GLARE ASSESMENT METHODOLOGIES AND THEIR APPLICATION TO THE OFFICE ENVIRONMENT:

A STUDY FOR THE CLIMATE OF SYDNEY, AUSTRALIA

by

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CONTENTS

FIGURES

TABLES

Abstract

In recent years there is resurgence in the use of daylighting in office environments. This resurgence is partially being driven by the recognition of the benefits of daylight access to humans; partially through advances in facade technology; and partially through the growing use of green building tools such as Green Star, LEED and BREEAM.

This growing use of daylight has many benefits including health benefits, productivity benefits, financial benefits, and ecological benefits. However, the use of daylight in offices must be carefully considered with it also potentially increasing the carbon cost of operating a building and negatively influencing the internal work environment through the introduction of glare.

This paper will primarily focus on the issues surrounding daylight glare - glare associated with indirect light from the sun - in the office environment and its assessment. Two glare metrics have been selected; daylight glare index (DGI), the recognised standard in the assessment of glare from large glares sources such as windows, and daylight glare probability (DGP) a recently developed metric for the assessment of glare that it is hoped will overcome some of the universally identified limitations of the DGI.

The use of Radiance, a backward ray tracing software tool has been utilised in the assessments, based on a theoretical model where the two glare indices have been compared to help identify any similarities between them and to better understand some of the limitations of the tools available to the building designer.

Further, a scripting tool has been developed to allow the visual representation of glare over the floor plate of a room, giving valuable feedback to the design team in the initial stages of a building design and the impact of various design options on occupant visual comfort.

The comparison between DGI and DGP ahs shown there to be a degree of correlation between the two metrics in areas toward the rear of a daylit room, but that this correlation does not hold as we approach areas of extreme light levels, or where the

observer has a large sky view. This lack of correlation has made it difficult to draw any conclusions on any comparison between the tools and it has been proposed that further study, using a more realistic representation of an office environment may help to determine which glare metric is pointing toward the correct response.

Chapter 1 Introduction

Light is the basic stimulus for vision, the richest of the human senses. For lighting to reach an optimal level it needs to be compatible with the physiological laws of vision, eye muscles and colour vision.

Daylight is one of the principal environmental synchronisers that triggers the human body's cycle of alertness and sleep. To keep this cycle balanced, it is crucial to make the most of the daylight available particularly because artificial lighting, to which many of us are subjected, never delivers the same lighting quality as daylight.

This paper will focus on issues surrounding daylight, and in particular glare associated with daylight in office environments. There has been resurgence in recent years in the use of daylight in lighting office environments. This is, in part, due to the benefits that good daylighting design can bring to the energy performance of the building and its benefits to occupants, including their health and increased task performance. However, successful integration within a buildings design requires that the impact of the solar radiation on both the thermal and visual environments be assessed.

There are many sophisticated dynamic thermal assessment programs that are commercially available. These have the ability to accurately predict the internal thermal environment based on external conditions which can be related back to human comfort, for example, through the work of P.O. Fanger or the ANSI/ASHRAE Standard 55-2004, Thermal Environmental Conditions for Human Occupancy.

Additionally, there are calculation tools for the assessment of daylight penetration and access. But these find it difficult to identify or asses the impact of potential glare sources in the visual field and are highly dependent on the location and orientation of any viewer to the glare source. Combined with this is the almost constant high degree of variation in external light levels and sky conditions.

There are many calculation methodologies for the determination of glare. Of these, most have been developed for the analysis of small glare sources such as artificial lighting. The daylight glare index (DGI) (or the Cornell equation assessment method) was developed with the use of fluorescent lighting behind diffusing screens and is generally taken as the industry benchmark for the assessment of daylight glare. A number of studies have indicated that the correlation between the perceived glare from large angle glare sources, such as that presented by windows, and that predicted by the DGI glare assessment methodology is not strong.

Other daylight glare assessment methodologies are currently under development and it is the intension of this report to carry out a desk top review of the currently accepted daylight glare assessment methods and those being developed to give some insight on how the methodologies vary from each other and what effect these variations might have. The calculations carried out have used the 'Radiance' software tool and have focused on two assessment methods, the Daylight Glare Index (DGI) and the Daylight Glare Probability (DGP) which have been performed for a number of locations within a standard office environment to better understand how their predictions vary. Two glare evaluation algorithms, 'findglare', crated by G.W. Larson and 'evalglare', created by Wienold and Christoffersen, have been used in the assessment of glare within the virtual environment. The two algorithms have both been used to generate values for DGI for a series of three viewing locations in the room viewing directly at, and then viewing at 90 degrees to the glazed façade. These results have then been used to determine what correlation there is between findglare and evalglare. Secondly, the evalglare tool has been used to generate values for DGP for the same views with the overall trends in glare likelihood compared to those calculated for DGI. Finally, in order to create a tool that gives the user a better understanding of how the glare indices vary over the entire floor plate, in the hope that this can help give guidance on façade geometry and glare likelihood in the initial stages of a building design, a tool has been developed to generate an image map of glare ratings over the floor plate of the room.

This technique of image mapping has then been applied to the climate of Sydney, Australia where Green Star, the Australian centric green building assessment tool comparable to LEED in the United States or BREEAM in the United Kingdom, sets targets on the limitation of glare in the office environment through the limitation of direct solar access to the working plane. The tool has been applied to see if the use of this technique has merit in reducing glare within the office environment, while an assessment of the daylight factor reduction, due to these measures has also been used to better understand potentially detrimental effects on the office environment.

Although the DGP assessment method is not validated, calculations have been undertaken using it to better understand the application of this tool, to understand the effect of particular variables within it and to help 'benchmark it' against the DGI method. It is hoped that this paper will give a better understanding of the limitations of these methodologies and highlight any areas of ambiguity within the results generated by Radiance.

Chapter 2: Daylighting

Effective daylighting has many benefits. It can significantly reduce energy consumption and greenhouse gas emissions, while improving occupant comfort and satisfaction. Financial benefits include reduced energy costs for lighting and cooling, and increased worked productivity (Kats, 2003).

Daylight has numerous beneficial physical and psychological effects on people. Effects include increased production of vitamin D3 (Holick, 1982) vital in the absorption of calcium, suppression of Melatonin production and hence the setting of the circadian cycles. Daylight can efficiently provide high levels of illumination that can contribute to good health, comfort and productivity.

Galasiu and Veitch (*et al* 2006) in there literature review of occupant preferences and satisfaction in daylit offices note that, irrespective of any health benefits that access to daylight or an external view might provide, there is a consistent and strong preference for daylight. Coupled to this, Farley and Veitch (*et al* 2001) note in there literature review of the effects of windows on work and well being that windows also presented the benefits of: increased job satisfaction; interest value of the job; perception of self productivity; perceptions of physical working conditions; life satisfaction; decreased intensions of quitting; and reduced recovery time of surgical patients.

Other benefits of daylight:

- The spectral content of daylight covers a wider frequency range, ensuring that we get a better colour rendering of the objects that we are looking at.
- Daylight is diffuse, arriving from all directions of the sky dome while artificial light is highly directional.
- Daylight levels vary in both the short and long term.
- Daylight is free to use and has the highest efficacy of all the lighting technologies meaning less heat build-up, see Appendix A: Efficiencies of standard lighting types)

- Daylight is free
- Can reduce lighting and cooling energy use, reducing greenhouse gas emissions and operating costs

Light and Humans

The human sensory system welcomes variety, or some degree of randomness based on "contrast pattern recognition" or "sensory variability" (Heerwagen, 1998). If there is no variation in lighting levels in a work environment, the workforce may be able to focus on their task but will be faced with a rather dull, boring environment. Complex lighting patterns will ensure that people are stimulated. Properly designed brightness contrast control systems increase performance and decrease physiological fatigue (Grandjean, 1985).

The complexity of the work environment needs to be considered in terms of the complexity of the view as well as that of the lighting. Workers subject to stressors recover faster from such events and/or work strains when provided with a view of the natural environment. The "Attention Restoration Theory" (Kaplan and Kaplan, 1995), supports the idea that people prefer a view of a natural environment to one of a built environment. For maximum benefit, the view should include the horizon and show movement and change over time.

The daylight that we can see within the built environment is made up of several components. Daylight comprises:

Figure 1: Constituent parts of daylight

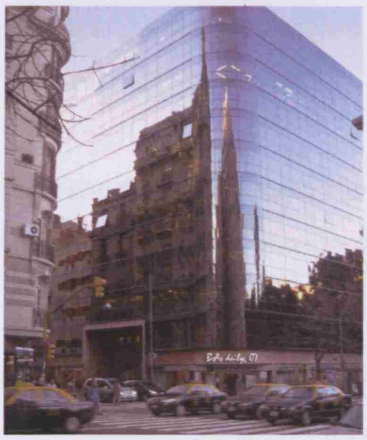
- Sunlight

The directional light from the sun which is intense and bright

- Skylight

The diffuse light directed from the sky where sunlight has been reflected off particles in the atmosphere

- External Reflections



Light that is reflected from other surfaces outside of the building, and typically includes other buildings, the ground and surrounding vegetation

- Internal reflections

Light that is reflected off internal surfaces, such as tables, walls, ceilings and floors

It is indicated in much of the existing research on the use of windows that the primary purpose of windows is their ability to create a sense of connection between the interior and the exterior (e.g., Galasiu, 2006 and Webb, 2006). However, C Reinhart and S Selkowitz (*et al* 2006) suggest in their paper that this interest is often beyond the energy efficiency concerns of the past decades. Instead, that a new emerging school of daylighting design has become more concerned with answering questions such as how we can better serve to satisfy occupant needs for health and comfort.

A R .Webb (*et al* 2006) points to recent research into the effect of daylight on the human body identifying a direct connection between the eye and the suprachiasmatic nucleus (SCN), the circadian pacemaker within the mammalian brain.

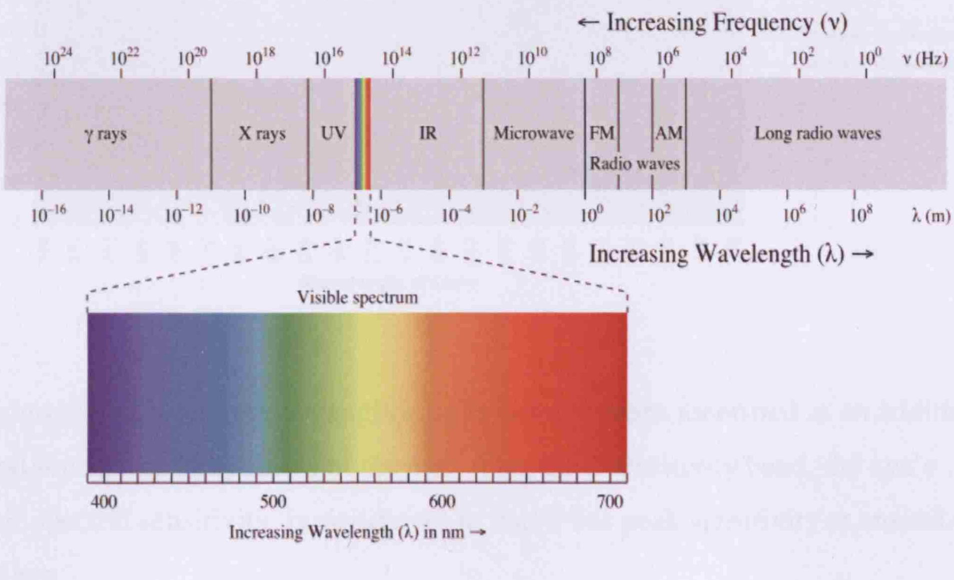
The article discusses the primary visual cells within the human eye as being the rods and cones that are active in different light detection areas for vision. The cones are responsible for depth and colour perception of the human eye. Rods are merited with an increased light detection capability to the cones. Additionally, melanopsin, a light sensitive protein found within the retinal ganglion cells of the eye has recently been identified as an additional light detection cell type within the eye. These cells have been shown to be linked to the SCN;

> *"The non-visual photoreceptor may provide for new methods of lighting to benefit health and well-being"* A. Webb, Energy and Buildings, 38, pp722

The Physical Make-up of Light and Human Response

Electromagnetic (EM) radiation, also called light, is a self-propagating wave in space with electric and magnetic components. Electromagnetic radiation is classified into types according to the frequency of the wave;

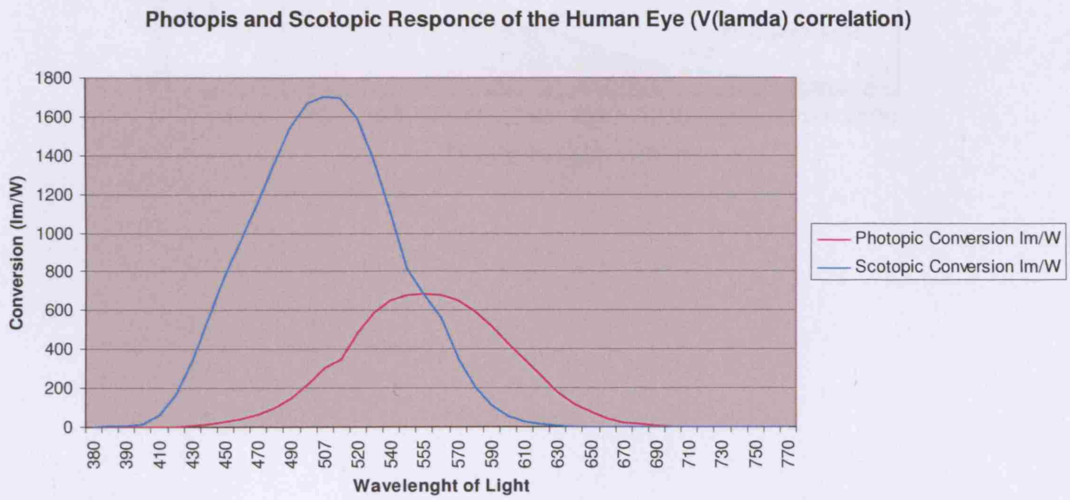
Figure 2: Spectral Distribution Photopic and scotopic spectral efficiency of the human eye using the V(λ) correlation (http://en.wikipedia.org/wiki/Image:EM_spectrum.svg)



The human eye responds to the visible portion of the electromagnetic spectrum, from approximately 780 nm down to 390 nm. Scotopic (dark-adapted) and photopic (light-adapted) sensitivities differ; scotopic peak sensitivity (of the rod cells) is 507 nm, while photopic sensitivity (of the cone cells) peaks at 555 nm. It is this photopic sensitivity range of the eye that has traditionally been focused on by lighting designers.

The V(λ) function provides the traditional conversion of the radiant power of light in Watts, to lumens, the standard measure of human visual response to light. This function takes account of the varying sensitivity of the human eye to the various frequency bands of light. The V(λ) function has been used by lighting practitioners for the last hundred years in the design of artificial lighting systems and predicts a peak spectral response of the human eye at 555nm.

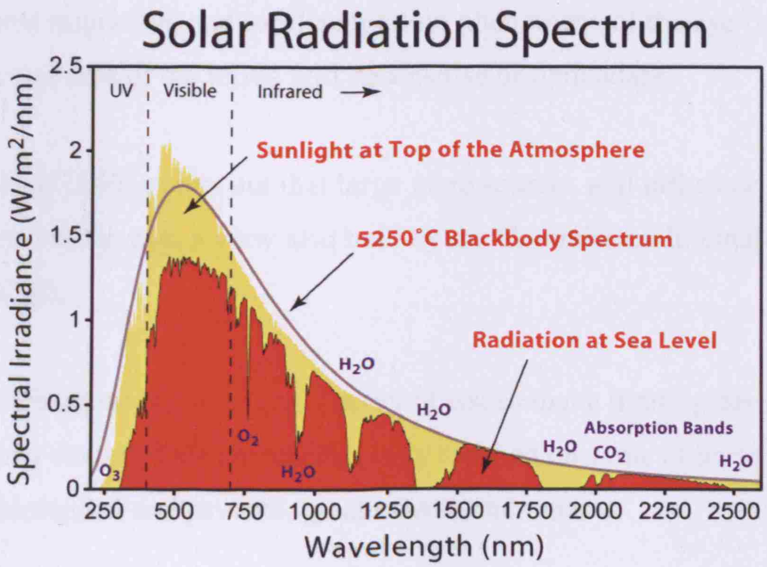
Figure 3: Photopic and scotopic spectral efficiency of the human eye using the V(λ) correlation



Melanopsin within the retinal ganglion cells has now been identified as an additional spectral sensitivity mechanism of the eye. This third sensitivity band, the eye's cirtopic spectral sensitivity, is significant in that it has peak sensitivity at around 446 to 488 nm.

Figure 4 indicates the solar intensity of light at various wavelengths. Approximately half of the solar energy is emitted in the visible spectrum with the other half divided between the ultraviolet (UV) (~10%) and infra red (IR). Access to the UV spectrum is essential in humans for the production of Vitamin D, vital for the metabolism of calcium needed for a healthy skeleton (Holick, 1982), while over exposure to UV can cause sunburn (erythema) (MacKinley, 1987) which in turn has been linked to skin cancer (Veierod, 2003)..

Figure 4: Sunlight intensity in the various solar spectrums noting the absorption bands due to atmospheric water and carbon dioxide



It is not known whether this photopic spectral tuning (V(λ) function) is to the detriment to the circadian cycles of the human body and has been identified as an area for future investigation (A. Webb, 2006).

Adaptation level of the eye

Outdoor daylight illuminance can vary from 120,000 lux for direct sunlight at noon, to less than 5 lux for the thickest storm clouds with the sun at the horizon. This means that the human eye needs to adapt in what is likened to a logarithmic progression. Kim and Koga (*et al* 2004) identify that the human eye adapts to the local or background luminance through a series of mechanisms:

- pupil response where the iris of the eye shuts down, limiting the amount of light entering the eye;
- the dual (photopic and scotopic) receptor system ;
- pigment migration; and local adaptation phenomena of the eye (where a particular area of the retina will desensitise or light adapt).

Hopkinson (*et al* 1960) points out that large glare sources will influence the adaptation level of the eye, a view also held by the Commission Internationale de l'Eclairage (CIE).

As we have seen above, there is a vast array of issues that a lighting designer needs to consider in their design. This chapter has only touched on some of these and how light has both physiological and psychological effects on humans.

Chapter 3: Lighting Design

There is a diverse, but highly interrelated set of building design elements that influences occupant performance. Natural lighting and the aspect to the outside environment afforded to internal work spaces is determined by the façade and fenestration, skylights and/or atria, floorplate shape and orientation, floor to floor heights and ceiling and window head heights all have an effect.

There are growing commercial forces for designers to optimise daylight to minimise the carbon cost associated with electric lighting. Green Star, the Australian green building design tool, is becoming increasingly common, with the Property Council of Australia requiring minimum Green Star ratings.

These requirements place additional constraints on lighting and façade engineers. This chapter describes some if those constraints and how the market is responding, through compliance with green building tools, and specification of façade performance. Design guidance from regulatory bodies is also investigated.

Green Star

There is resurgent interest in the use of daylight as a means of lighting the office environment. This interest is sparked both by recent research on the impact of light on human health and by the growing influence of green building rating schemes (Reinhart, 2006) - such as LEED in the United States, Green Star in Australia, or the European Energy Performance Directive (EEPD).

Green Star is a holistic, Australian centric, design methodology for ecologically sustainable building design. Is has been developed by the Green Building Council of Australia and is currently the leading assessment methodology for green buildings in the Australian building market.

Exerts from the Green building Council of Australia's web site (http://www.gbca.org.au/) have been presented below to give a better understanding of the Green Star assessment tool:

Green Star is a comprehensive, national, voluntary environmental rating scheme that evaluates the environmental design and achievements of buildings.
Green Star covers a number of categories that assess the environmental impact that is a direct consequence of a projects site selection, design, construction and maintenance. The nine categories included within all Green Star rating tools are:

- *Management*
- *Indoor Environment Quality*
- *Energy*
- *Transport*
- *Water*
- *Materials*
- *Land Use & Ecology*
- *Emissions*
- *Innovation*

These categories are divided into credits, each of which addresses an initiative that improves or has the potential to improve environmental performance. Points are awarded in each credit for actions that demonstrate that the project has met the overall objectives of Green Star.

The following Green Star Certified Ratings are available:

- *4 Star Green Star Certified Rating (score 45-59) signifies 'Best Practice'*
- *5 Star Green Star Certified Rating (score 60-74) signifies 'Australian Excellence'*
- *6 Star Green Star Certified Rating (score 75-100) signifies 'World Leadership'*

Two of the credits available are specifically aimed at the daylit environment within the office environment, one stipulating a particular daylight factor across a proportion of the net lettable area (NLA), and the other focused on the avoidance of glare.

The credit on glare avoidance is complied with when;

- *Where, for each typical glazing configuration or atrium, fixed shading devices shade the working plane 1.5m in from the centre of the glazing of direct sun at desk height (720mm AFFL) for 80% of standard working hours;*

OR

- *Where blinds or screens are fitted on all glazing and atriums as a base building provision and meet to following criteria;*
  - *Eliminate all direct sun penetration;*
  - *Are control with an automatic monitoring system;*
  - *Are equipped with a manual override function accessible by occupants; and*
  - *Have a visual light transmittance (VLT) of <10%.*

It is now a standard commercial requirement for new commercial buildings in Australia to be Green Star certified, which is driving a great deal of market transformation. A large component of the points available within the Green Star assessment come form the energy assessments. These take the form of a standardized simulated energy assessment methodology, the Australian Building Greenhouse Rating (ABGR), and drives the specification of much building envelope and mechanical system design.

Glazing Specification in Sydney Australia

There is a growing prevalence in the Sydney market for clearer glazing to be used. Where, until recently, glazing with and visible light transmission (VLT) in the region of 20-40% may have been used, glazing with a VLT in the region of 50-70% is now being used. Examples of this include the soon to be built Chifley Tower in Sydney, the recently completed NRMA building in Melbourne, and the recently refurbished Stocklands Headquarters in Sydney. The thermal transmission of the glazing (solar heat gain coefficient, SHGC) is important in helping to achieve thermal comfort of the occupant, and while in many instances it would be technically possible to achieve thermal comfort with high SHGC the energy performance of the building needs to be considered with recommendations within the City of Sydney's '*Draft Ecologically Sustainable (ESD) Development Control Plan (DCP)*'[1] being to achieve a minimum Green Star rating of four stars and ABGR of four and a half stars.

The movement toward using high VLT glazing is possible due to advances in glazing technology, where a high VLT can be achieved while also achieving a low SHGC. This shift toward higher VLT glazing, whilst bringing increased daylight, also increases the propensity for glare problems, and has the potential to increase occupants use of glare limiting blinds and hence the use of artificial lighting.

Daylighting Guidance

Guidance from regulatory bodies on the design on interior lighting is abundant but tends to focus on the use of artificial lighting. The following guidance has been taken from some of the relevant international standards and advisory bodies.

AS1680.1-1990, Interior Lighting Part 1: General Principles and Recommendations

Recommendations are provided for limiting veiling reflections in VDU screens

Assessment of visibility of visual tasks, and impact of veiling reflections, can be assessed:

- Using the Contrast Rendering Factor (CRF). Refer CIE publication nos 19.2, 29.2.
- Publication 19.2 unavailable, 29.2 superseded by ISO8995 below – CRF not mentioned

Recommendations provided for reducing glare from windows

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[1] http://www.cityofsydney.nsw.gov.au/Council/documents/meetings/2007/CSPC/061207/071206_CSPC_ITEM05.pdf, City of Sydney, Accessed 2008

CIE Unified Glare Rating (UGR) system, as described in CIBSE TM10

- UGR applicability – large rooms (room index > 2) / difficult visual tasks requiring:
    - sustained visual attention
    - view at or above horizontal for significant periods
    - room surfaces and equipment are abnormally dark coloured or poorly lit
- Calculated GI should be rounded to the nearest whole number of 13, 16, 19, 22, 25, 28
- Maximum recommended GI 19 for normal range of tasks or interiors, 16 for exacting visual tasks including screen based equipment (SBE) office areas

AS1680.2.2-1994, Interior Lighting Part 2.2: Office and Screen-based Tasks

Recommendations provided for limiting veiling reflections in VDU screens:

> "*Where the interior contains screen-based tasks that require sustained attention, discomfort glare from the electric lighting should only be assessed by the use of the glare evaluation system described in … AS1680.*1"

Recommendations provided for controlling glare from windows:

> "*Tasks surroundings which have an average luminance less than about one quarter that of the task itself (including any hard copy items) can cause considerable dissatisfaction if work is continuous.*"

> "*The glare evaluation system is appropriate only for interiors which utilize a regular array of the same type of luminaire.*"

- Maximum GI of 16 recommended for screen-based task areas, 19 for conference rooms / boardrooms

ISO8995:2002(E), Lighting of Indoor Work Places

"The discomfort glare rating of the lighting installation shall be determined by the CIE Unified Glare Rating (UGR) tabular method"

- UGR formula provided – refer CIE 117-1995

Recommendations provided for reducing risk of veiling glare:

"To reduce glare from windows, screening shall be provided."

- Maximum UGRs provided for a range of applications – 19 for writing, reading, typing, data processing, filing, copying, circulation, CAD, conference / meeting rooms; 16 for technical drawing

CIE 117-1995, Discomfort Glare in Interior Lighting

- UGR formula defined
- Table of position indices provided

"The domain of the data used to develop the UGR system was limited and restricted to sources which have a maximum subtense at the eye of 0.1 steradian (say, a 1m square luminaire, seen from about 3m). Further, discomfort glare for very small sources is determined by intensity rather than by luminance, so the UGR system should not be used for sources smaller than 0,0003 steradian (say, an incandescent downlight seen from about 10m)."

- UGR tabular and graphical methods presented

CIBSE TM10, The Calculation of Glare Indices, 1985

- Recommended procedure for evaluation of GI for a lighting installation is provided
- GI formula presented
- All presented in terms of luminaire design and layout

IESNA, Lighting Handbook, 8th edition, 1993

- Threshold discomfort luminance (BCD) as function of background luminance presented. Figure 3.23, P. 80, appropriate for interior lighting, small source, on line of sight. Impact of glare source size (< 0.2 sr) presented in Fig. 3.25. Impact of glare source position presented in Fig. 3.27.
- Visual Comfort Probability (VCP) method presented.

"By consensus, discomfort glare will not be a problem in lighting installations if all three of the following conditions are satisfied:

- the VCP is 70 or more;
- the ratio of the maximum luminance (luminance of the brightest 6.5 cm2 area) to the average luminaire luminance does not exceed 5:1 at 45, 55, 65, 75 and 85° from the nadir, crosswise and lengthwise; maximum luminance's of the luminaire crosswise and lengthwise do not exceed the (values in table on P. 81)."

"(The VCP) system was tested and validated using lensed direct fluorescent systems only."

"VCP should not be applied to very small sources such as incandescent and high intensity discharge, to very large sources such as the ceiling in indirect systems, or to non-uniform sources such as parabolic reflectors."

"Although VCP can be applied to virtually any situation, extrapolation to significantly different visual fields has not been validated."

- Recommendations by which to reduce the risk of daylight glare provided (P. 368)

IESNA, Lighting Handbook, 9th edition

As for 8th edition, plus:

- UGR formula presented

"(The UGR) formula is limited to those situation where 0.0003 < w < 0.1." w represented solid angle of luminaire subtended to the observer.

CIBSE, The Society of Light and Lighting, Code for lighting

- The uniformity of illuminance within the immediate task area should be similar to that acceptable with electric lighting (10:1) although there may be differences in the level of daylight in different parts of an interior.

The above recommendations give very little guidance on the use of daylight within offices. However, further recommendations based on the guidance of researchers in the field of daylight glare is given in Appendix B: Overviews and Reviews on Limiting Glare from Daylighting.

Successful use of daylighting requires carful consideration of many design elements. The task of the buildings designer is to integrate these elements to provide adequate lighting while avoiding excessive glare and heat gains. There are many reliable tools to help them understand the thermal performance but a reliable tool for the evaluation of glare also needs to be identified.

Chapter 4: Glare

Glare is highly subjective and related to a variety of physiological and psychological factors. People are more likely to tolerate glare from a window than from an artificial source and further are more likely to tolerate glare if there is a pleasant view (Chauvel, 1982). An individual may experience glare either from excessive illumination or from excessive contrast of illumination.

The Lighting Handbook of the Illuminating Engineering Society of North America (IESNA) defines glare as:

> *"the sensation produced by illuminance within the visual field that is significantly greater than the illuminance that the eyes are adapted to causing annoyance, discomfort or loss in visual performance and visibility"*

Osterhaus (*et al* 2005) further notes that glare can be further divided into two types:

Disability glare:

> *The effect of stray light in the eye whereby visibility and visual performance are reduced. Noted as a physiological effect.*

And

Discomfort glare:

> *or glare that causes discomfort. Discomfort glare does not necessarily interfere with visual performance or visibility. Noted as a psychological effect.*

Disability glare is encountered in situations of reduced contrast between an object and its immediate background. For example, high beam car headlights reduce visibility for oncoming drivers at night due to light scattering within the eye.

Discomfort glare is a sensation causing annoyance or pain, caused by extreme brightness or a significantly non-uniform distribution of brightness. Discomfort glare plays a very important role in natural lighting design, as luminance ratios vary considerably with location, daylight penetration and window size. Daylight levels are typically high directly adjacent to the window and fall off rapidly with distance from the window wall. Thus, conditions of high brightness are encountered near the window, while contrast between the window and its surrounds increases with distance from the window.

Veiling glare is another form of glare. Depending on severity, this can rate as a form of either disability of discomfort glare. It occurs where a reflection in an object reduces contrast and degrades visibility. It is an important form of glare in offices in which computers are used, where it often refers to reflections in computer screens.

Glare from windows is most commonly experienced when direct sunlight enters through the window and shines in to occupants eyes (sunlight glare). Additionally, it can arise as a result of high window luminance, usually caused by external reflections such as a view of the sky (daylight glare). However, the movement of the sun is a well understood pattern in our sky. This allows us to predict the hours of direct sunlight penetration to the occupants and guard against it. The diffuse light from the sky, caused by sunlight reflected from the sky turbidity or cloud cover is far more variable and more difficult to predict.

Background to Glare Assessment Indices

Glare has been studied by vision and lighting researchers for the past 80 years. In this time the process of disability glare has become well understood, however, discomfort glare is still not fully understood. (Osterhaus, 2005)

A review of documentation from various advisory bodies with respect glare has been performed. These recommendations are often based around good design practice in order to minimise the risk of glare. This, in some way, indicates the difficulties associated with glare assessment methodologies.

> *"Several formulae have been developed in order to predict glare response, typically relating the luminance, position, apparent size of the glare source*

and the adaptation level (or background luminance) of the eye" (Osterhaus, 2005).

The general form of these formulae has been expressed by Boyce (*et al* 1981):

$$\text{Glare sensation} = \frac{(\text{luminance of glare source})^{m} \times (\text{angular substance of glare source at the eye})^{m}}{\text{Luminance of background})^{x} \times (\text{deviation of glare source from line of sight})^{y}}$$

The formulae have generally been developed assuming small, high intensity glare sources. These glare sources are considered bright glare sources but actually deliver very little light to the observer's eye. Osterhaus (*et al* 2005) suggests this to be a reliable assumption for electric lighting, but cannot be applied when daylight plays a significant role in interior lighting where the large glare source window delivers significant levels of illuminance to the observer's eyes, affecting the eyes adaptation level.

A brief background to the glare assessment methods is presented below and is largely based on Osterhaus' paper 'Discomfort glare assessment and prevention for daylight applications in office environments'.

Visual Comfort Probability

The Visual Comfort Probability (VCP) method was derived from the work of Lukiesh and Holladay (*et al* 1925) and Luckiesh and Guth (*et al* 1949). From this, Guth developed the Discomfort Glare Rating (DGR):

$$\text{Discomfort glare rating (DGR)} = 0.5 \frac{L_s \quad Q}{P \quad F^{0.44}}$$

Where:

L_s	=	Source luminance
Q	=	Parameter specifying solid angle of source as seen by the observer
P	=	Factor expressing the change in glare with change in glare-source position in azimuth and elevation
F	=	Parameter defining the background luminance of the installation, including the source

The overall equation took the form:

$$DGR = \left(\sum_{i=1}^{n} DGRi \right)a$$

Where:

- $a = n^{-0.0914}$
- n is the total number of glare sources in the calculation

The final form of Guth's DGR formula was used to define the number of people who would find the installation acceptable and was termed the Visual Comfort Probability (Perry, 1993). The VCP Method is still used to this day and is the method described in the IESNA Lighting Handbook for assessment of discomfort glare; however, the method is not applicable large or non-uniform sources of glare.

British Glare Index

The British glare index (BGI) system (also known as the IES glare index) is based on the work by Hopkinson and Bradley (1926, 1929), Hopkinson (1949, 1963) and Hopkinson and Collins (1963). Through their work, an empirical function was derived:

$$\text{Glare Constant (g)} = \frac{L_s^{1.6} \quad \omega^{0.8}}{L_b^{1.0} \quad P^{1.6}}$$

This formula is then summed to determine the total perceived glare from a series of glare sources giving the Glare Index:

$$\text{Glare Index} = 10 \log \left(0.5 \sum_{i=1}^{n} gi\right)$$

Where :

- L_s is the Luminance of the glare source
- ω is the solid angle of the source as seen by the observer
- L_b is the background luminance
- P is a factor expressing the change in glare with change in glare source position in azimuth and elevation
- n is the number of glare sources

Petherbridge and Hopkinson note that the formula "will hold for most artificial lighting fittings and for small windows, but that it will not apply to large windows of high brightness.

The key differential between the VCP and the BGI is that the VCP includes a term that defines the luminance at the observers eye, including the glare source (Perry, 1993). This is not in agreement with the paper by Osterhaus (*et al* 2005).
G. W. Larson also notes[2] that Guth poorly defines the term for the background luminance and so has taken it to exclude the luminous effect of the source in the VCP calculations within Radiance[3].

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[2] See LBNL web site: http://radsite.lbl.gov/radiance/refer/Notes/glare.html (accessed 2008)

[3] a backward ray tracing analysis engine developed by Ward

European Glare Limiting Method

The European Glare Limiting Method (originally termed Luminance Curve Method) was developed by Sollner (*et al* 1965). The underlying philosophy of the system was that it should be simple to use. His studies indicated that four principal components influenced the level of perceived discomfort glare, being

1. Luminance of the luminaire
2. Room length and luminaire mounting height
3. Adaptation luminance
4. Type of luminaire, particularly the presence or absence of luminous side panels

Sollner derived a set of luminance limiting curves from his work. The system was, in its original form, unsuitable for use as a lighting design model and was later modified by Fischer (*et al* 1972).

Further development of the Glare indices

All but the Glare Limiting Method are still seen as useful in the appraisal of ceiling mounted arrays of lighting. But all tend to encounter problems when dealing with extreme luminance levels, evaluation of large sources, or sources that are not mounted in or close to the ceiling plane (Osterhaus, 2005).

CIE glare index (CGI)

The CIE glare index (CGI) was developed by a technical committee of the CIE (*et al* 1983). It attempts to combine the best points of all the existing formulae.

Osterhaus (*et al* 2005) states that:

> *"Compared to the other methods (the CGI) includes the glare source contribution to the adaptation of the observer in the description of the luminous environment of the room. This is an advantage when assessing large area glare sources surrounding or adjacent to an observer's visual task"*

The CGI calculation took the final agreed form of:

$$\text{Glare index (CGI)} = 8 \log 2 \left[\frac{(1 + E_d/500)}{E_d + E_i} \Sigma \frac{L^2 \omega}{p^2} \right]$$

Where:

- E_d is the direct vertical luminance at the eye due to all sources
- E_i is the indirect luminance at the eye
- L is the luminance of the luminous parts of each luminaire and the direction of the observers eye
- ω is the solid angle of the luminous parts of each luminaire at the observer's eyes.
- p is Guth's position index for each luminaire, which relates to its displacement from the line of sight.

Unified Glare Rating (UGR)

The Unified Glare Rating (UGR) method was further developed by the CIE in 1995 to simplify the calculation. It incorporates features of the Einhorn (CGI) and Hopkinson (BGI) formulae, with the Guth position index used in the formula.

The main objective of the committee was to create "a practical glare evaluation system" and to that end three methods of glare evaluation were developed:

1. The basic Unified Glare Rating (UGR) formula; and
2. The derived tabular method which enables the easy comparison of different lighting situation; and
3. The derived luminance limiting curve method to assist the design of luminaires and to give designers rough guidance on the suitability of luminaire choices

The UGR method equation takes the form:

$$\text{Unified Glare Rating (UGR)} = 8 \log \left[\frac{0.25}{L_b} \sum \frac{L^2 \omega}{p^2} \right]$$

L, ω and p are the same terms, defined in the CIE Glare Index above.
L_b is defined by the CIE as "that uniform luminance of the whole surroundings which produces the same illuminance on a vertical plane at the observer's eye as the visual field under consideration excluding the glare sources" (CIE publication 117). It is determined from the formula:

$$L_b = \frac{E_i}{\pi}$$

Where:

E_i is the indirect illuminance at the eye of the observer.

The main simplification within the formula is the exclusion of glare sources in determining the adaptation level of the observer:

> *"For practical purposes, (the exclusion of the direct luminance at the eye) will have limited effect when the formula is applied to rooms with illuminances within the usual range recommended for working interiors"* (CIE publication 117).

The UGR scale has had operators applied to it to give agreement with the BGI scale. It is recommended that the glare rating be rounded to the nearest 1.5 in the range 13, 16, 19, 22, 25, and 28. This illustrates the low level of precision provided by glare index.

The table below indicates the range of UGR rating and how this correlates to the perception of glare:

Table 1: UGR and it's correlation to human glare perception

Glare Criterion	UGR
Imperceptible	Below 10
Perceptible	10 - 16
Acceptable	16 – 18.5
Just Comfortable	18.5 – 22
Uncomfortable	22 – 28
Intolerable	Above 28

The original form of the equation had a number of limitations. One of these was that it was limited in its application to glare sources between 0.0003 steradian (say, an incandescent downlight seen from about 10m) and 0.1 steradian (a 1m square luminaire seen from about 3m). The UGR is gaining increasing use throughout the world and is the method of assessment recommended by a number of the guidance documents (e.g. CIBSE code for light and lighting 2006).

A number of the limitations of the UGR formula are addressed by the CIE 2002 document (CIE publication 147). These are commented on by Osterhaus (*et al* 2005, p143).

Overview of glare indices

The glare indices presented above were developed with electric lighting design in mind. The CGI method includes a term for all luminance sources, which should make it more applicable to its use in daylight glare calculations. Additionally, there is some discussion as to whether the VCP calculation includes all light sources (including glare sources) in the assessment of the eye's adaptations level.

There is general consensus amongst the papers presented that there is a degree of correlation between the various methods and; that there is some correlation between subjective response and the predicted glare values, reported on by Boyce (*et al* 1980)

Discomfort Glare Prediction from Windows

As noted above glare indices have generally been developed for electrically lit environments and are non-applicable to daylit situations. Osterhaus (*et al* 2005) notes that this is mainly because the size of daylight openings generally exceeds 0.01 steradian. Kim and Konga (*et al* 2004) also note that the two most prominent glare indices for electric lighting, UGR and VCP, exclude any expression that accounts for the effect these large glare sources have on the adaptation of the observers eye.

Chauvel (*et al* 1982) notes that the difference between the glare experienced from a large source of artificial light and that from the same subtended area of sky is due to the psychological differences in the visual content of the field of view. His paper also notes that the basic studies of glare by Luckiesh and Guth and by Petherbridge and Hopkinson looked at relatively small sources of glare that that there was some evidence that source size increase did not give the results predicted. It is noted that this is *"(the unexpected results are)likely to be due to the effect of the glare source occupying a large part of the visual field raising the adaptation level of the eye, thus reducing the visual response and the glare sensation"*

Additionally, Chauvel notes that since the glare source occupies a large proportion of the visual field, it would not be correct to simply assign a position factor at the centroid of the a large glare source.

Daylight Glare Index

Work was carried out between the Building Research Station (BRS) in England and at Cornell University in the USA in 1963 with the result that the 'Cornell formula' was derived empirically to describe glare from large area glare sources. The formula was essentially a modification of the original BRS glare formula (BGI):

$$\text{Glare constant, } G = K \frac{L_s^{1.6}\,\Omega^{0.8}}{L_b + 0.07\omega^{0.5} L_s}$$

Where:

- K is a constant depending on the units;
- L_s is the source luminance;
- L_b is the surrounding luminance;
- ω is the solid angle subtended by the source as seen from the observers eye; and
- Ω is the solid angle subtended by the source modified for the effect of position in the observer's field of view.

The total predicted glare sensation will then be given by:

$$\text{Glare Index} = 10 \log \Sigma G$$

In the original work Ω is modified according to the proposed method by Petherbridge and Longmore, however, this has been modified slightly in that it is now generally accepted to use the Guth position index (Kim, 2007 and Wienold, 2006). Ω is then calculated using:

$$\Omega = \int \frac{d\omega}{P^2}$$

Where P is the Guth position index as determined by:

$$P = (35.2 - 0.31889\tau - 1.22e^{-2\tau/9}) \times 10^{-3}\sigma + (21 + 0.26667\tau - 0.002963\tau^2) \times 10^{-5}\sigma^2$$

In his review of this work Chauvel (*et al* 1982) notes that the work by Aubree and Markus indicates that there are other factors that affect the perceived glare associated with the appearance of the window. The view to outside; the degree of secular surfaces; and the windows surrounds (e.g. curtains and the form of the windows reveals) all have bearing. However, Chauvel indicates that the correlation between the Cornell formula and perceived glare was strong enough to draw two conclusions:

1. The degree of discomfort glare due to the sky seen through a window can be predicted from a glare index based on the Cornell large source glare formula;
2. There appears to be a greater tolerance of mild degrees of glare from the sky seen through windows than from a comparable artificial lighting situation with the same value of glare index, but this tolerance does not extend to severe degrees of glare.

Given that the basis of the DGI was the BGI, analysis of the results from the DGI formula lead to the simplified numerical relationship between the BGI and DGI. This relationship was given by the formula:

$$\text{Daylight Glare Index (DGI)} = \frac{2}{3}(\text{BGI} + 14)$$

This lead to the recommendation within the Illumination Engineering Society (IES) Code for 1973 that limits be set on daylight glare. This is presented below indicating the relationship between the UGR (noting that it is weighted to give answers that correlate to the BGI) and DGI.

Table 2: Correlation between UGR, DGI and human glare perception

Glare Criterion	UGR	DGI
Imperceptible	Below 10	Below 16
Perceptible	10 - 16	16 – 20
Acceptable	16 – 18.5	20-22
Just Comfortable	18.5 – 22	22-24
Uncomfortable	22 – 28	24-28
Intolerable	Above 28	Above 28

A computer program was written for the purposes of determining a tabularised method of DGI calculation. The program served to confirm that the area subtended by a large source has little influence on the glare sensation that it causes. Importantly Chauvel notes that, for the purposes of giving design guidance, the windows size and the observers distance could be ignored. The result of these findings led Chauvel to the following recommendations:

- the sighting of work places so that there is no direct view of the sky by the occupant;
- the reduction of the luminance of the window by curtains, blinds or tinted glazing;

- the reduction of sky view by appropriate louvered blinds, overhangs, canopies, etc.;
- the provision of light coloured surfaces around the window and the detailing of the sill, head, reveals, frames and window bars to produce a graded contrast, rather than a sharp one, with the sky seen through the window.

Limitations of DGI

DGI is the accepted standard by which to asses daylight glare from windows (Osterhaus, 2005) with several studies indicating that there is a degree of correlation between predicted and measures glare response (eg Chauvel, 1982). However, a number of limitations of the calculation have been also been identified. Iwata (*et al* 1990/1991) and Boubekri (*et al* 1992) both note that the correlation between the values predicted by the DGI and those measured under real sky conditions was not good.

Kim (*et al* 2007) notes that the degree of discomfort glare perceived was higher for uniform as opposed to non-uniform glare sources like those seen in real sky conditions, while it is noted that the DGI was developed using uniform glare sources. Further, it has been identified that varying the subdivision of a glare source leads to differing glare results (CIE, publication 83). Nazzal (*et al* 2005) notes that it is necessary to have the solid angles of the source to the power of one (1) to allow their summation, something that is not present within the DGI formula.

Above all, the terms used in the calculation of the DGI are somewhat ill defined. There appears to be some differing information in the papers presented and the calculation tools available as to how the various terms are calculated. In particular, the background and source luminance have been calculated in varying ways by different people (Larson[4]; Osterhaus, 2005; Perry, 1993).

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[4] See LBNL web site notes on findglare algoithm: http://radsite.lbl.gov/radiance/refer/Notes/glare.html (accessed 2008)

Further Glare Analysis Tools

A series of glare assessment methodologies have been proposed in recent years with various claims of giving better correlation between predicted and measured glare response from windows, while a new technical committee of the CIE is currently charged with advancing the knowledge about discomfort glare from daylight (CIE technical committee 3-39: Discomfort glare from daylight in buildings).

New Daylight Glare Index

Ali Nazzal (*et al* 2005) presents a new methodology for the determination of perceived glare. The method is based on the existing DGI and has been adapted to overcome the existing limitations. Further he has better defined the calculation methodology for the terms within the formula:

$$DGI_N = 8\log_{10} \{ 0.25 \{ \frac{[\sum(L^2_{exteriour}\Omega_{pN}}{[L_{adaptation}+0.07(\sum(L^2_{window}\omega_N))^{0.5}]} \} \}$$

Where:

L_{window} is the vertical luminance of the window, and is read from the sensors positioned within the room

$L_{adaptation}$ is the average vertical luminance of the surrounds

ω is the solid angle of the source.

Ω is the corrected solid angle of the source

Both ω and Ω have been more clearly defined by Nazzal in his earlier work (*et al* 1998) and here have been designated as ω_N and Ω_{pN}.

Nazzal notes that the DGI behaves counter to expectations in that it decreases as the vertical illuminance on the window increases. He has proposed that the formula be applied for use in daylighting control systems and has used the methodology created by Christoffersen and Velds (1998) to divide the room up into three specific lighting regions where shielded daylight sensors will be located.

The method is orientated toward the control of glare in a practical setting, where perhaps automated glare control blinds may be operated based on the algorithm presented by Nazzal and as such will not be used in this theoretical setting.

Daylight Glare Probability

Wienold and Christoffersen in their 2006 paper present their work in assessment of glare perception with the use of CDD (charged couple device) cameras in the assessment of glare response in test facilities in Denmark and Germany. There work comprises the development of a new glare evaluation algorithm, 'evalglare', which used the Radiance image format to identify the sources of glare within the image. The algorithm was tested for a series of parameters for the identification of glare sources:

- Calculate the average luminance of the entire picture and count every section as a glare source that is x-times higher than the average luminance
- Take a fixed value and count every section as a glare source that is higher than the fixed value
- Calculate the average luminance of a given zone (task area) and count every section as a glare source that is x-times higher that the average luminance of this zone.

All three glare identification algorithms have been implemented into the tool.

The analysis of the glare, based on the 349 responses to glare sensation that they obtained from users performing work related tasks in the test rooms, resulted in them developing a new glare assessment methodology, the Daylight Glare Probability scale. It is noted by them that their respondents were given a choice of two answers to their perception of glare; that they were uncomfortable or dissatisfied in the space, or that they were comfortable.

$$DGP = 5.87 \times 10^{-5} E_v + 9.18 \times 10^{-2} \log \left(1 + \sum \frac{L_{s,i}2\ \omega_{s,i}}{E_v^{1.87} P_i^2} \right) + 0.16$$

Where:

- E_v is the vertical eye illuminance (lux)
- L_s in the luminance of the source (cd.m^2)
- ω_s is the solid angle of the source
- P is the position index

We see that the basic form of the formula holds true to that described at the start of this chapter with the exception of two points. Firstly, that the illuminance at the users eye is used, including any contribution from the source it's self; and secondly the form of the position index used in the equation.

For the purposes of calculating the DGP, Wienold and Christoffersen us a combination of the Guth position index and, Einhorn's expression for glare sources that are below the viewer's line of sight.

This chapter has illustrated the progression of glare assessment over the last 80 years, where early testing and glare rating systems were based solely on the glare perceived from fixed lighting systems, to the modern day use of HDR images to expedite, and, hopefully, add a degree of rigor to the calculation performed by non-academic practitioners. However, there have been a range of issues raised in the discussions with various researchers highlighting the need for a reliable tool for determining the likelihood glare sensation, with the correlation between commonly used glare indices and measured glare perception from daylighting installations being poor. The following chapter seeks to look at two of the glare indices, DGI widely regarded as the benchmark daylight glare metric, and DGP, recently developed by Wienold and Christoffersen, to see how they compare.

Chapter 5: Methodology

As we have seen previously there are many tools at our disposal in the assessment of glare. Also previously noted is that the DGI is recognised as the industry standard with limiting values described in the IESNA Code.

It is intended to compare DGI values to the DGP, where, some correlation may be found, or help to identify aspects of either method that is counter intuitive and potentially in argument with what we subjectively believe to be the case.

Secondly, the contrast ratios of the scenes will be assessed. The Society for light and lighting describes that a daylit office should adhere to the same limitations as one where artificial lighting is used, specifically, that the surrounds of the work area should not be less than one quarter that of the task area; and that the maximum contrast ratio should not exceed 10:1.

Computer simulation has been used for the analysis due to the equipment and human resources needed in real office environments. Also, it is intended that some understanding in an artificial environment will be applicable to the design of offices in the concept stages.

Glare Assessment Comparison

A range of observer locations and various sky brightness's[5] have been used to understand the variation in DGI and DGP with location, and the observers orientation. Both methods of assessment are carried out using Radiance software, the industry standard for lighting analysis. A more detailed description of the calculation engine and further reading and resources may be obtained through the Radiance web site[6].

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[5] Sky brightness have been selected at 25klux, 50klux, 75klux and 100klux.

[6] http://radsite.lbl.gov/radiance/ , LBNL, Accessed 2008).

It is noted by Larson[7] that the Radiance glare calculation process follows a two step process, where:

> *"(glare assessment methods) all require more or less the same input, which is difficult to compute, it makes good sense to create a two stage glare calculation. The first stage computes the locations, sizes and brightness's of the light sources and the background luminance level, and the second stage computes whatever glare index is desired."*

For the purposes of comparison a generic office model has been created. The model comprises a typical office layout plan, a total depth of 22 meters and a column grid at 8 meters by 10 meters. The floor to ceiling height is 2.7 meters and the spandrel goes from floor level to 0.9m with glazing from this level to soffit. The Image below demonstrates a plan view with typical table locations. Three viewing locations are shown, with each viewing location having a view directly at (1a, 2a and 3a), and one at 90 degrees, to the window (1b, 2b and 3b).

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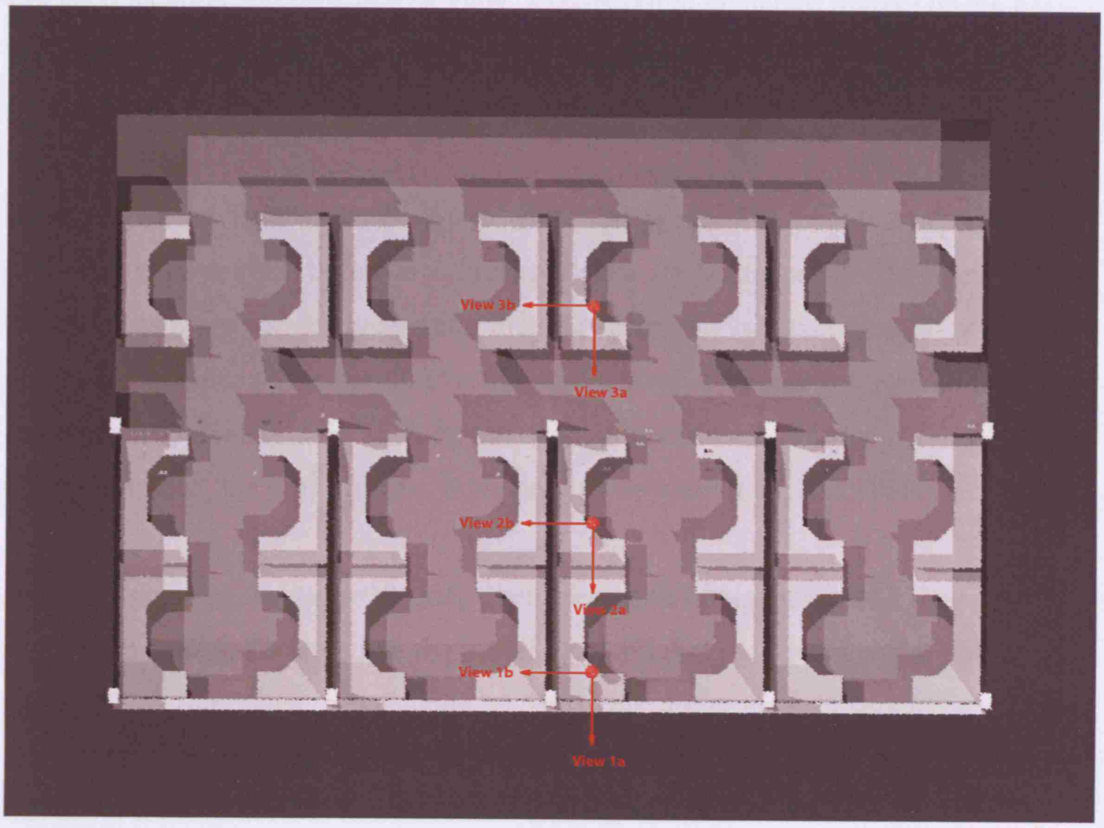
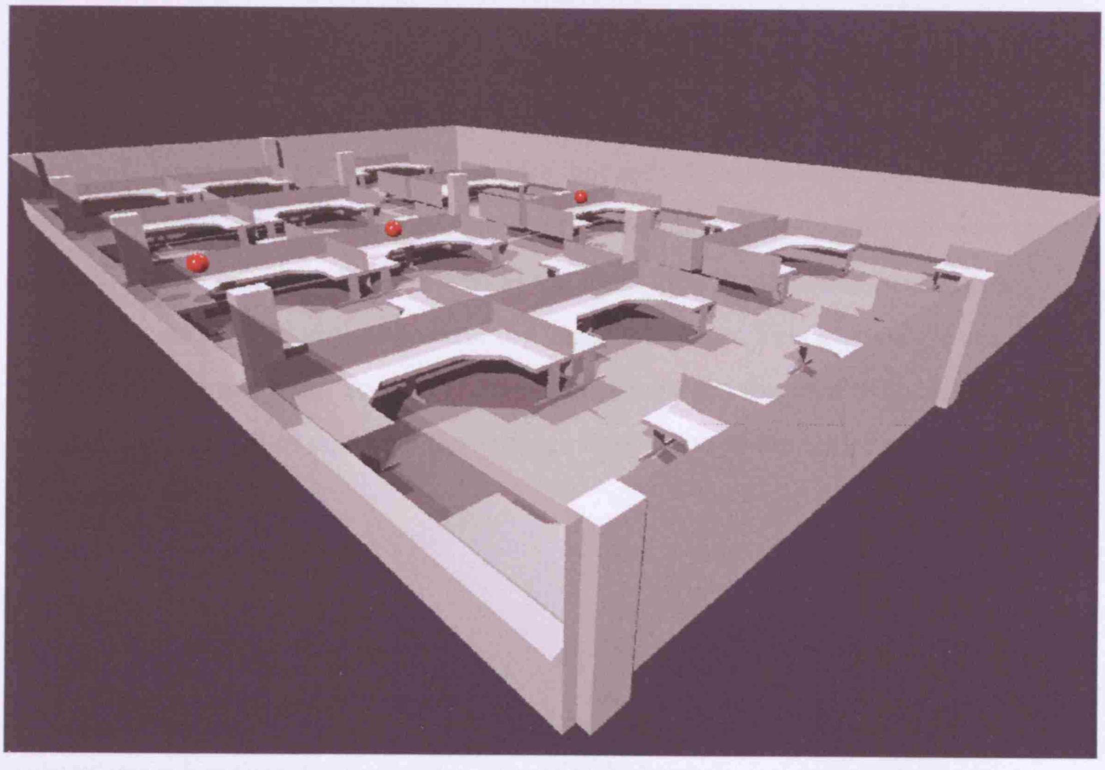
[7] LBNL Radiance web site on glare assessment http://radsite.lbl.gov/radiance/refer/Notes/glare.html (Accessed 2008)


View 3b
View 3a
View 2b
View 2a
View 1b
View 1a



For each location and direction of view, a HDR (High Dynamic Range) image has been generated. The image contains radiance values across the full spectral sensitivity of the human eye.

From this image, Radiances 'findglare' algorithm is run. The findglare algorithm identifies glare sources based on a threshold value (defaulted at 7). Glare sources are identified as ranges which are greater than the threshold value multiplied by the average luminance of the scene. The adaptation level of the eye is based on the indirect vertical luminance, excluding any direct contribution from the glare sources. Once computed, the outputs from findglare can be used to analyse DGI.

findglare gives the ability to identify the background luminance over a range of viewing directions (centered on the initial view direction) allowing a glare rating for each of these directions to be calculated. With this ability the user should be able to specify a single location and then determine the desired glare index for any viewing direction. It is intended to test this method of calculation.

The DGP metric has been developed into an evaluation tool 'evalglare' to evaluate a rage of glare indices (DGP, DGI, UGR, VCP & CGI). The tool includes a series of additional descriptors not seen in findglare, but uses the same basic input of a Radiance format HDR image file[8]. The user is then able of describing the viewing location within the image file[9] as well as the focal area in steradian around this viewing location for evalglare to base it's calculations on. This gives a greater degree of control in the analysis. To give comparability between the results obtained, evalglare will be left to compute the average luminance of the entire scene with the threshold set to 7.

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[8] It should be noted that the image input to the 'evalglare' tool differs in it's input in that a angular projected image is generated of the scene as opposed to the hemispherical one used by 'findglare'

[9] Measured as a function of pixel resolution in positive x and positive y directions from the bottom left of the image

Further to the analysis of glare from the three viewing locations, an additional script has been developed so that the glare indices can be assessed over the entire floor plate of the test room. This has been done as a visual aid, to allow us to better understand how the glare indices vary.

Sky Description

The sky will be the only source of luminance, and is key to the results generated. There are no recommendations on the type of sky that should be used in assessment of glare.

There are a multitude of sky descriptive models exist.. The CIE sky definition model includes an array of luminance distributions for overcast, clear and intermediate skies. In order to reduce some of the complexities associated with the orientation, a standard CIE sky description will be used in the modelling.

Material Properties

The reflectivity of materials will be specified in accordance with those recommended in The Society of Light and Lighting's Code for lighting and lighting. Average reflectance's of the various surfaces have been specified in Radiance and have been assigned using a grayscale representation.

Table 3: Modelled surface reflectivity

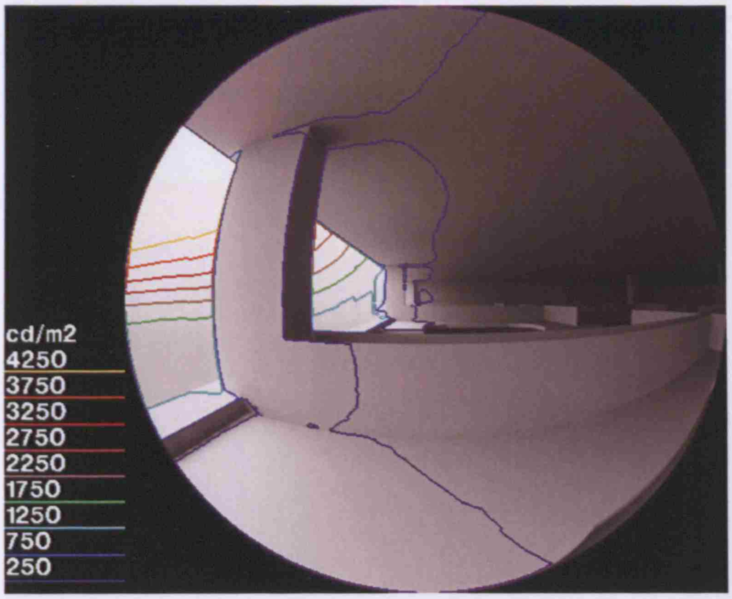
Object	Surface Reflectivity
Walls/Columns	0.50
Floor	0.20
Ceiling	0.70
Tables	0.30

Glazing

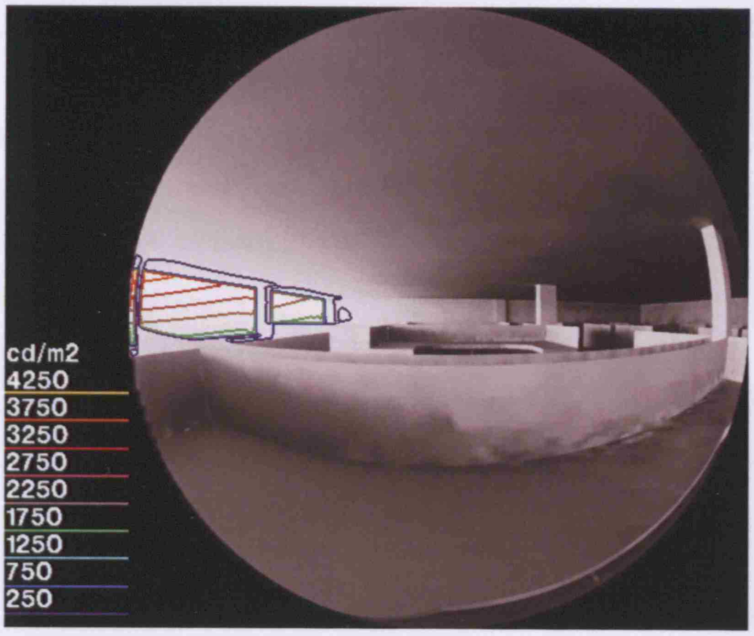
This assessment will not focus on the type of glazing that is used as the assessment is interested in the variation between the various methods of glare assessment. Glazing has been excluded from the model for the purposes of this comparison. A fully description of the modelling process can be seen in Appendix C: Modelling procedure and analysis settings.

Optical File Parameters

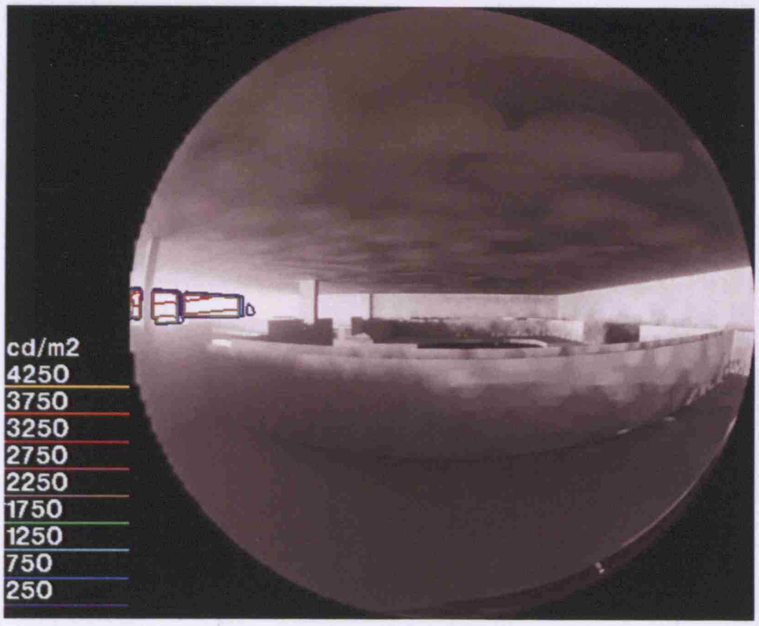
Figure 5: 'Falsecolor' luminance images for views 1B, 2B, & 3B demonstrating the effect of poor parameter settings in the calculation



View 1B



View 2B



View 3B

The images above are examples of some initial HDR images generated using the falsecolor command in Radiance and indicate the luminance values as seen from view point 1b, 2b and 3b, viewing at ninety degrees to the window. These are the initial images generated by Radiance using standard settings with high QUALITY, DETAIL and VARIABILITY settings[10]. In the images generated at the front of the space, where there will be large amounts of daylight and a large view angle of the sky, show a reasonable quality of resolution with a relatively smooth gradation over surfaces. However deeper into the room (view 3B) the more broken this gradation becomes, and, the less we might be inclined to trust the results. Even though the images have been calculated using high optical settings, Radiance still generates poor results.

Ideally, we might expect to set all parameters to a very high degree of refinement, and this would give the most accurate results. However, the cost of this is the speed of the calculation. We need to find a medium between accuracy and processing time.

Focusing on the ambient parameter settings within the optical file, a parametric study has been carried out to better understand the influence they have in generating a reliable radiance map for use in the glare analysis. This can be seen in Appendix D: Optical file settings, a parametric study.

For speed of calculation the model has been used without the desks represented. This will also allow us to better understand of variation in the glare indices without the additional complexity of the desk layout reflection and shading.

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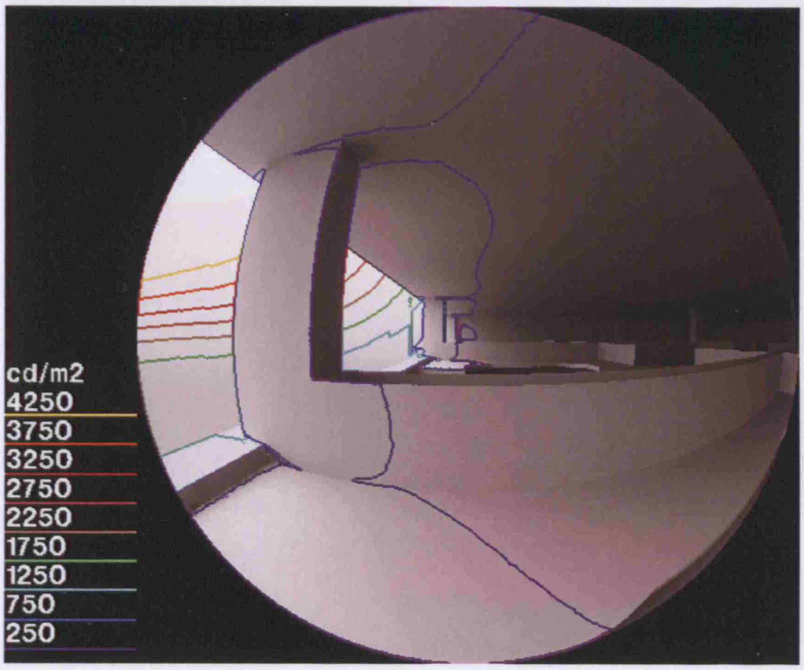
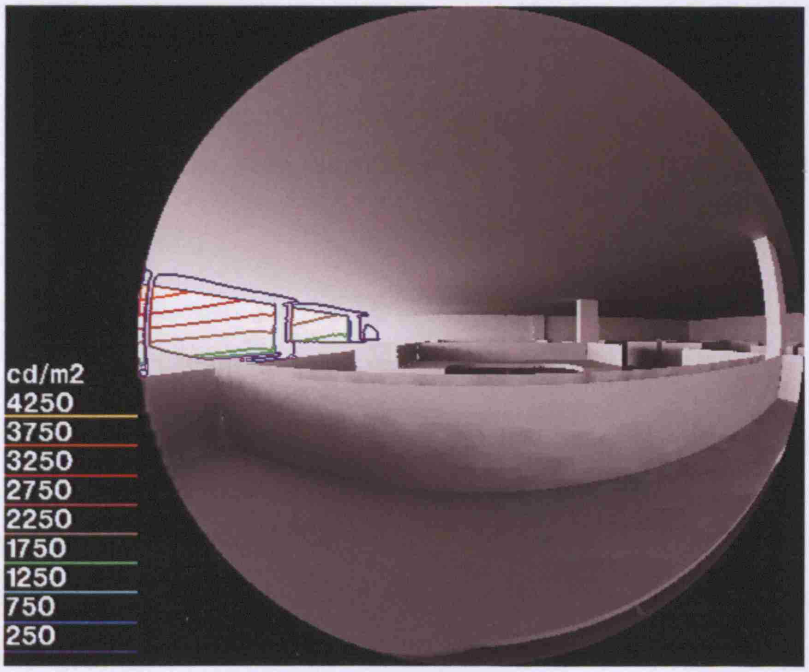
[10] note that a *.rif file was used to generate the initial optical file settings

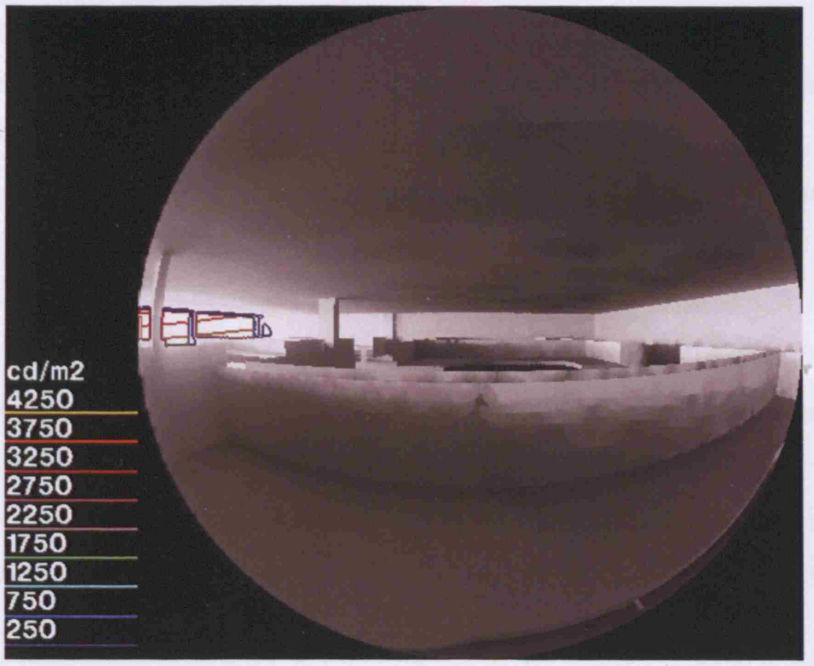
Figure 6: 'Falsecolor' luminance images for views 1B, 2B, & 3B demonstrating the effect of improved parameter settings in the calculation



View 1B



View 2B



View 3B

Note that the images given in Figure 6 above are improved in the accuracy of the results over the field of view which has been investigated more fully in Appendix D: Optical file settings, a parametric study. The image at the rear of the room still shows a greater degree of variation in the gradation of surface renders. While the error associated with this has been minimised as far as possible, for the sake of calculation expedience, this error has been allowed.

Comparison Between the Glare Algorithms

The findglare algorithm does not output any information on DGP, and was developed prior to the advent of this glare metric. However, as noted previously, evalglare does calculate the DGI. It is intended that these two outputs (DGI from findglare, and DGI from evalglare) be compared with each other to identify if there is a degree of agreement between them. Based on this, it is intended to draw some conclusions on DGP, and how we might use this metric to describe limits of acceptability.

To summarise:

- Modelling has been carried out using findglare and evalglare to compute DGI and DGP
- The modelling algorithm parameters have been set as a compromise between accuracy and speed of calculation
- The models internal reflections have been specified in accordance with recommendations of the Society of Light and Lighting, Code for Lighting (2002).
- Glazing parameters have been calculated to account for Radiances calculation of the transmissivity of glass
- The sky type used on the calculations is base on the standard CIE overcast sky
- Calculation of indices will be done to help identify if underlying trends in glare ratings over the floor plate exist
- Comparison of findglare and evalglare DGI outputs to determine if the two algorithms are comparable
- Based on the comparison of outputs of DGI, draw conclusions on acceptable limits of DGP.

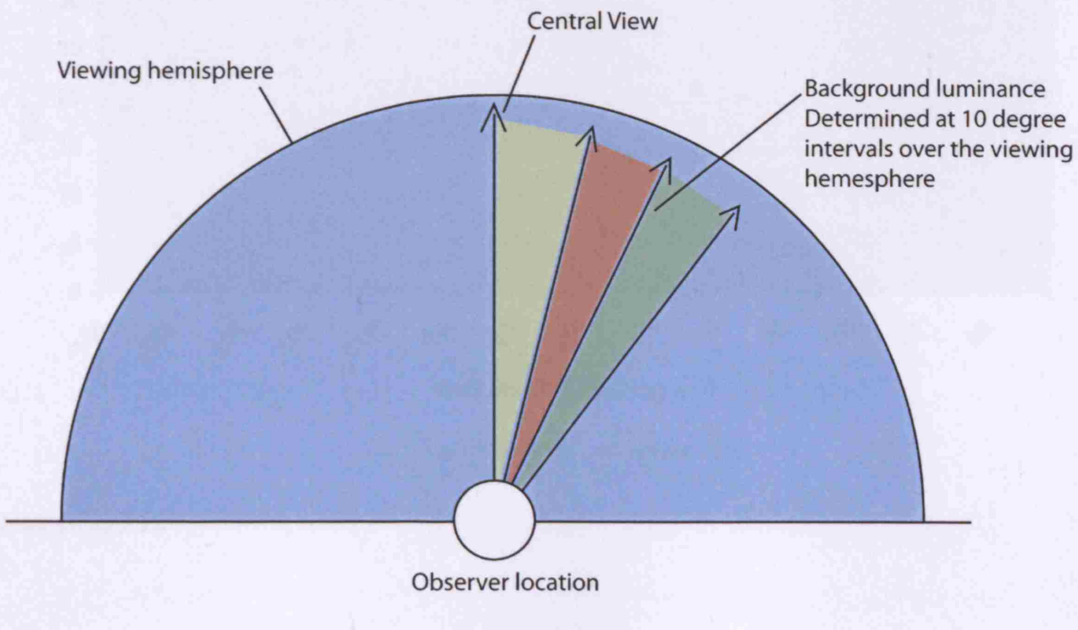
Chapter 6: Results

Analysis has been carried out to better understand underlying trends and to give comparison between the DGI and DGP metrics. To do this all inputs to the previously described glare evaluation algorithms has been kept as constant as possible. The results presented below demonstrate that there is a degree of consistency between the different glare evaluation tools understanding the recommendation to round DGI to the closest 1.5 in the ranges 13, 16 19, 22, 25, and 28.

Findglare and viewing direction

Within findglare it is possible to specify a single observer location and viewing direction, then calculate the background luminance for a series of offset angles from this central view. By doing this it should be easy for the user to specify a single location and then determine the glare index from any orientation of the viewer. To test this, for each of the view locations and for each of the view direction (1a, 1b, 2a, 2b, 3a, and 3b), findglare has been used to determine the background luminance in 10 degree steps over a 180 degree viewing angle, shown in Figure 7 below.

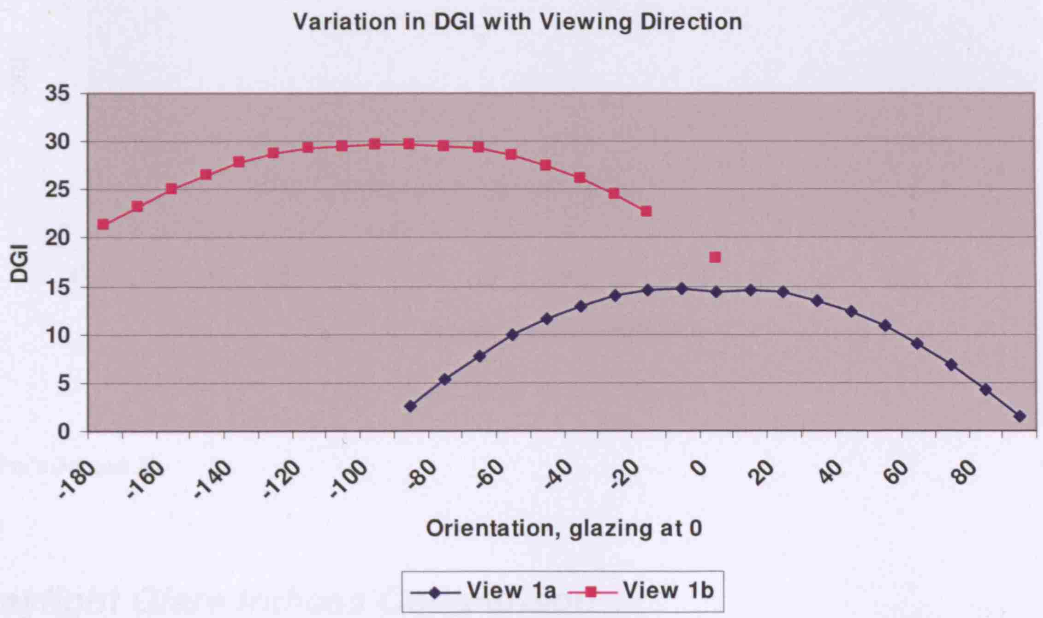
Figure 7: findglare calculation over hemisphere of view



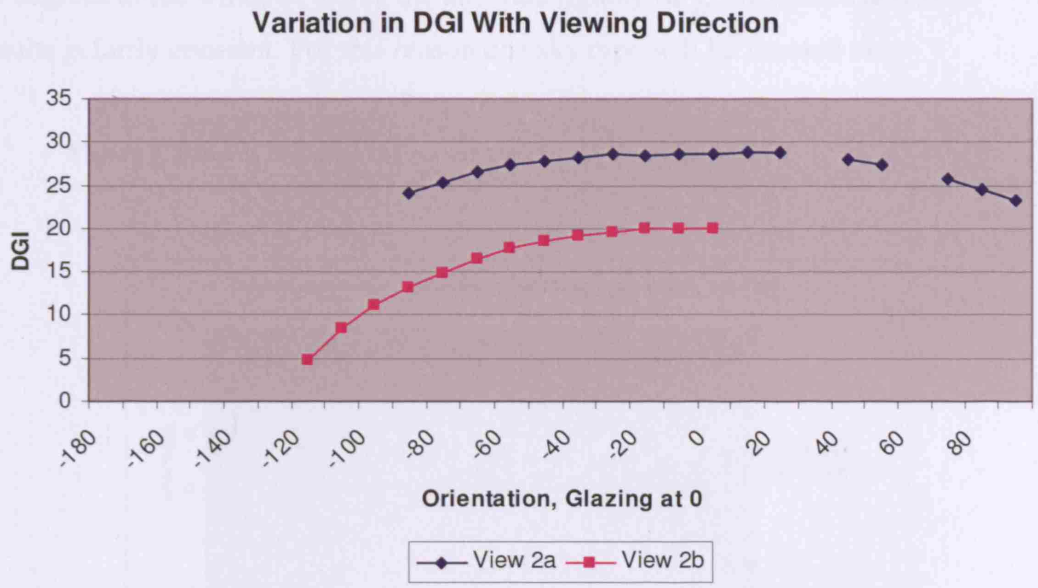
Below is plotted the results for each observer location, with viewing angles over a 180 degree viewing hemisphere. Based on the description of the algorithm by it's creator, G. Larson findglare's results should tally with each other for the same viewing direction even though we start from a different central view. However, as can clearly be seen from the results below, this is not the case at the front of the room (View's 1a and 1b), with there being a far greater degree of agreement from the observer location furthest from the glazing (View's 3a and 3b). This suggests that it is not acceptable to simple output a series of glare values from a central view and calls into question one of three things;

1. the parameters used in the assessment; and
2. how the findglare algorithm works and it's validity on the assessment of glare; and
3. if how the parameters used within the DGI are appropriate in assessing glare.

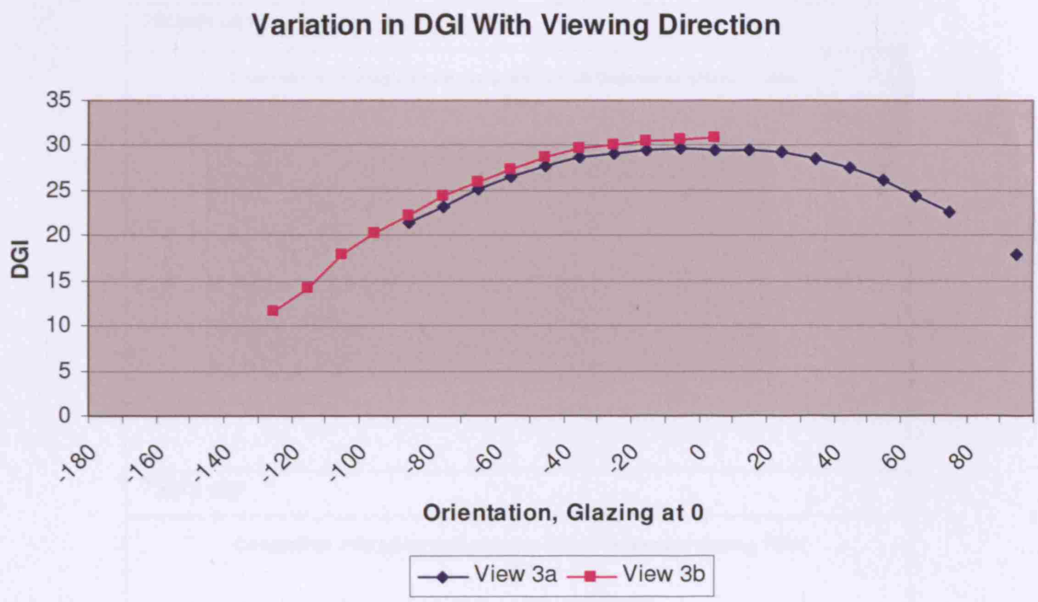
Figure 8: Variation in DGI output from findglare with variation from central view for differing central view's



Views 1a and 1b



View's 2a and 2b



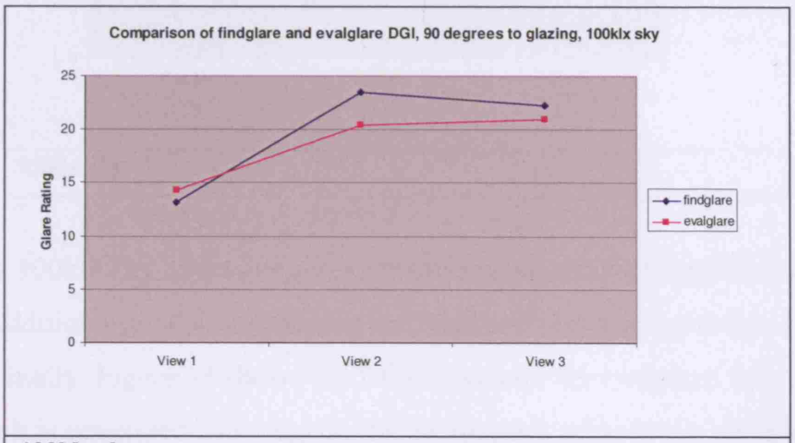
View's 3a and 3b

Daylight Glare Indices Comparison

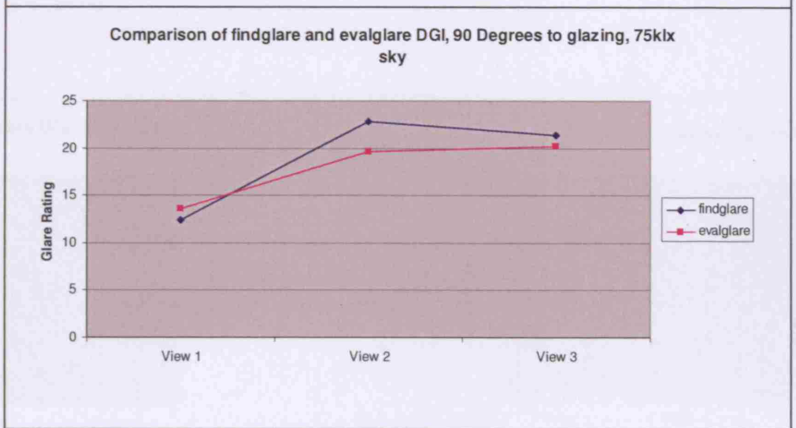
For the six views and for 25klx, 50klx, 75klx and 100klx skies, DGI and DGP have been generated. The results all show a high degree of similarity in the patterns with all sky types. Below is a comparison of findglare and evalglare DGI for occupants facing

90 degrees to the window. While the absolute figures vary, the pattern across all results is fairly constant. For this reason one sky type will be focused on.

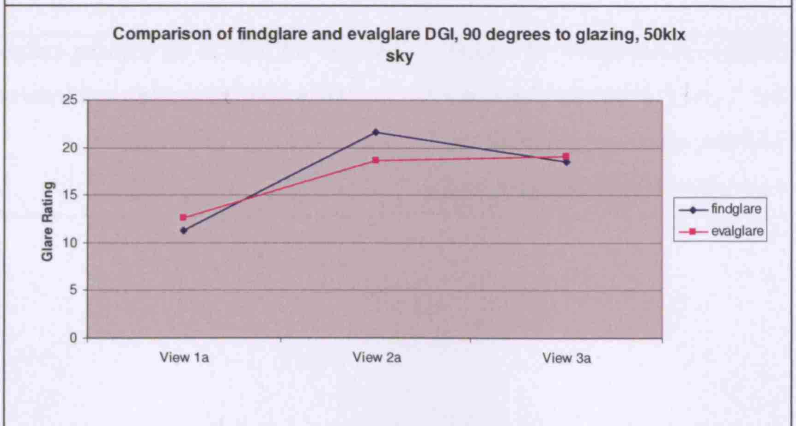
Figure 9: Patterns in glare indices over various sky illuminances



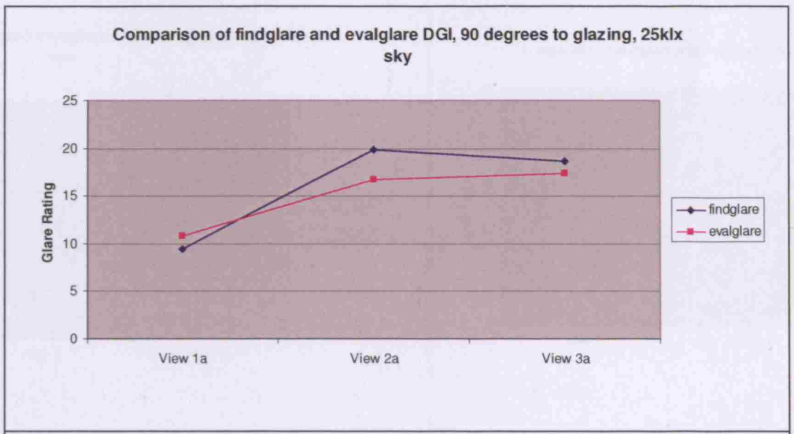
100klx sky



75klx sky



50klx sky



25klx sky

Below, for a 100klx sky, plots are given for DGI generated by findglare and for evalglare. Additionally, plots comparing the results of the two algorithms have been generated. Finally, Figure 14 shows the DGP generated by evalglare. It is noted that an error result is generated by evalglare for the location adjacent to, and facing the window.

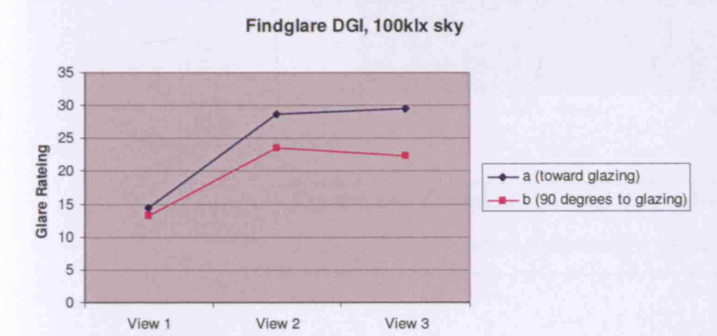


Figure 10: Variation in findglare predictions of DGI for viewing locations 1, 2 and 3. View toward the window (a) and at 90 degrees to the window (b)

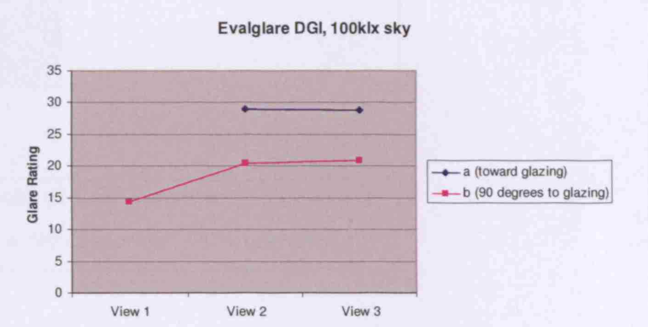


Figure 11: Variation in evalglare predictions of DGI for viewing locations 1, 2 and 3. View toward the window (a) and at 90 degrees to the window (b). Note, error given for locations immediately adjacent to window.

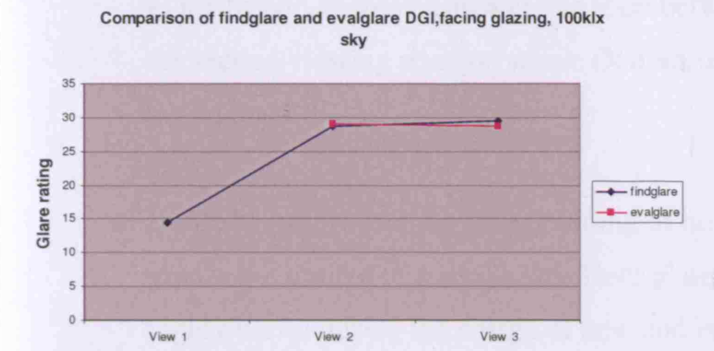


Figure 12: Variation between findglare and evalglare predictions of DGI for viewing locations 1, 2 and 3. View toward the window (view direction a). Note, evalglare returns error for locations immediately adjacent to window.

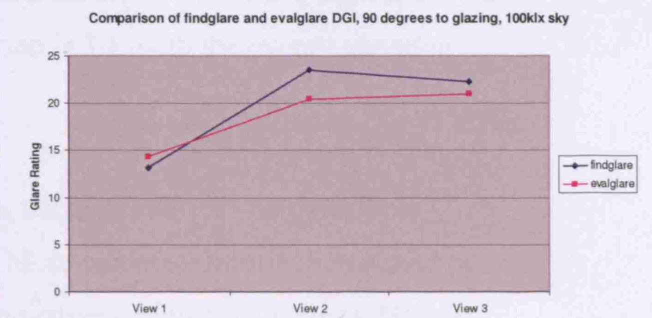


Figure 13: Variation between findglare and evalglare predictions of DGI for viewing locations 1, 2 and 3. View at 90 degrees to the window (view direction b).

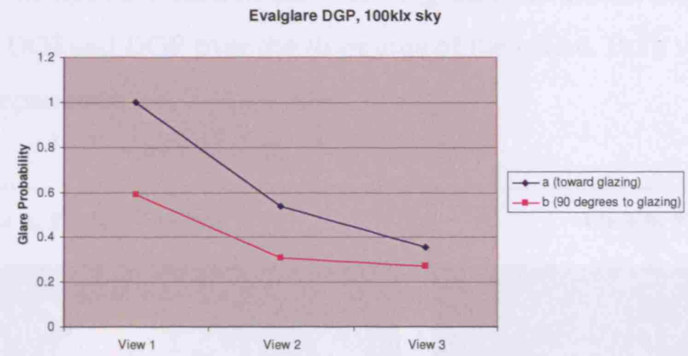


Figure 14: Variation in evalglare predictions of DGP for viewing locations 1, 2 and 3. View toward the window (a) and at 90 degrees to the window (b).

We see from Figure 10 and Figure 11 that there is a reduction in DGI of 4.6[11] when occupants are positioned facing at 90 degrees to the window. Both the algorithms see a similar pattern with a very low DGI adjacent to the window, a rapid increase as we move into the room, and a fairly constant value deeper within the room. The DGP sees an average decrease of 0.2 when comparing the viewing directions.

For occupants facing the window, DGI from the two algorithms are similarity with the variation between DGI values averaging 0.3. For occupants positioned at 90 degrees

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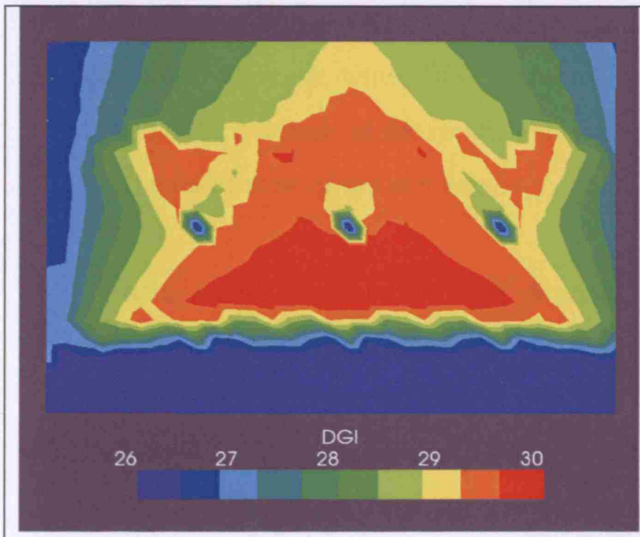
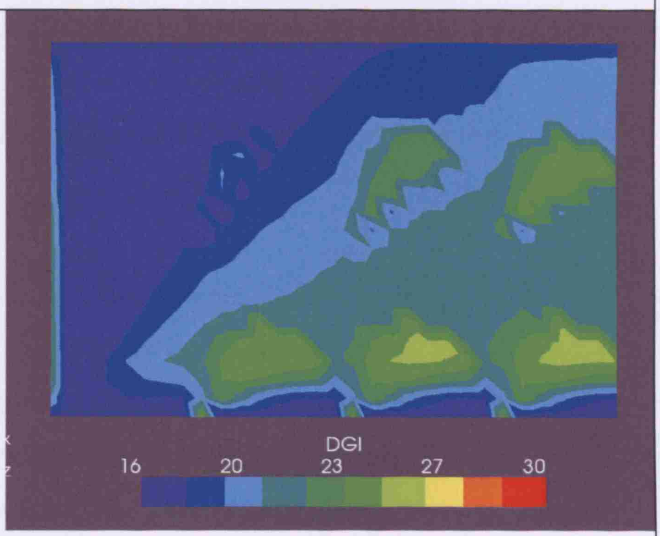
[11] A reduction in DGI of 4.6 is seen for both DGI and DGP

to the façade, there is a greater variation between the algorithms, most significantly at the second viewing position where DGI variation is 3.1, with the overall variation averaging 1.8.

While helpful to gain an understanding of how the glare indices compare, these graphs are limited to a slice of the floor plate. More complete information would be highly useful during the design of new and innovative building geometries. Here a more complete analysis will help identify the variation between DGI and DGP.

Figure 12 and **Figure 13** have shown there to be a reasonable level of correlation between the DGI generated by both findglare and evalglare. To simplify the process, evalglare alone has been used in the following analysis. Below are plots of the variation in DGI and DGP over the floor area of the office. Both viewing directions have been represented.

	View a, Facing Window	View b, 90 Degrees to Window
DGI		
	Figure 15: Daylight Glare Index (DGI) represented over a viewing plane at 1.5m from floor level. All occupants facing the window, 100klx sky	**Figure 16:** Daylight Glare Index (DGI) represented over a viewing plane at 1.5m from floor level. All occupants facing 90 degrees to window, 100klx sky

DGP

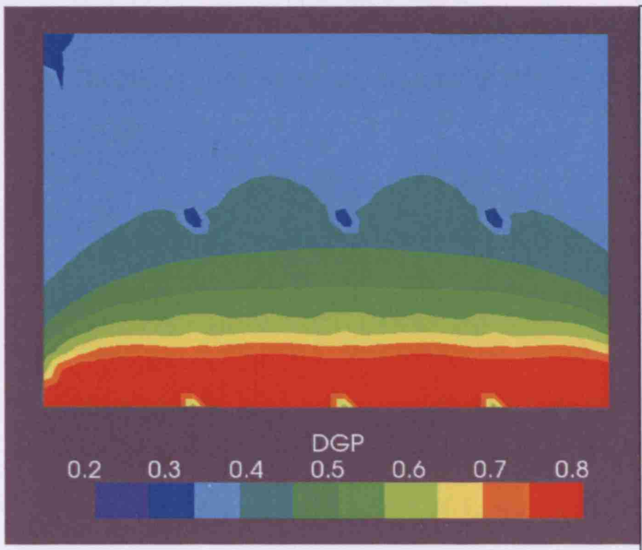


Figure 17: Daylight Glare Probability (DGP) represented over a viewing plane at 1.5m from floor level. All occupants facing the window, 100klx sky

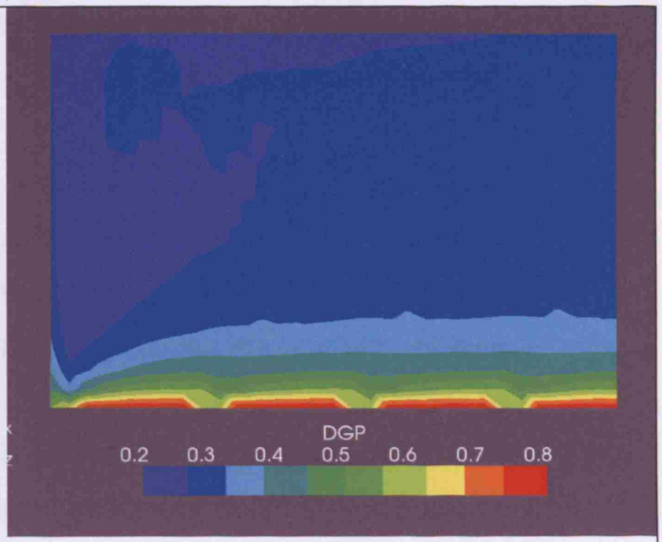


Figure 18: Daylight Glare Probability (DGP) represented over a viewing plane at 1.5m from floor level. All occupants facing 90 degrees to window, 100klx sky

The patterns identified in the previous graphs can also be seen here, with the DGI significantly decreasing next to the windows, increasing in the intermediate zone, then slightly decreasing toward the rear of the room. Adjacent to the windows, DGI is shown to decrease, while DGP increases. Both DGP and DGI show a similar pattern around the columns in the room, with a drop in the DGI and DGP, assumed to be due to the restriction of the sky view.

Where occupants are facing at 90 degrees to the window (toward the left of the images, Figure 16 and Figure 18) the tendency for DGI to decrease next to the window is also apparent. Ignoring the local effect immediately adjacent to the windows for the time being, the overall patterns from both indices are similar. Both indicate an elevated glare rating at the front of the room, a slight decrease in the middle of the room, and then again; a rise in the rear third of the room. This rise is more localised with DGI and seems to be driven by locality to the columns. It is thought that this is due to the columns blocking a component of the light from the windows, reducing background luminance, and hence adaptation level.

While there is some correlation between the figures presented, the DGI results contain localised 'hot-spots' compared to the far smoother gradations and gradual decline of DGP.

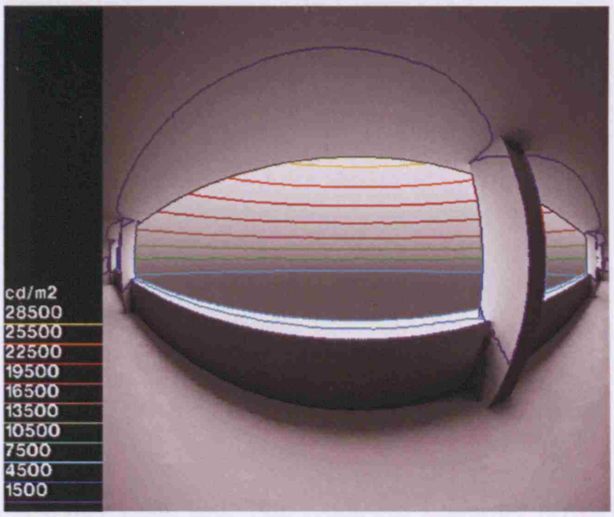
The lack of correlation between the two indices adjacent to the window poses some questions on which glare assessment is correct. We might take anecdotal evidence from our own perception on glare, but this is highly subjective and calls into question influence of such things as internal lighting, or a semi restricted view of the façade by internal partitions and privacy barriers. High luminance ratios are highlighted by both the IESNA and the Society of Light and Lighting as causing discomfort and it is suggested that these luminance ratios be used to give guidance on glare adjacent to the windows.

Luminance Ratios

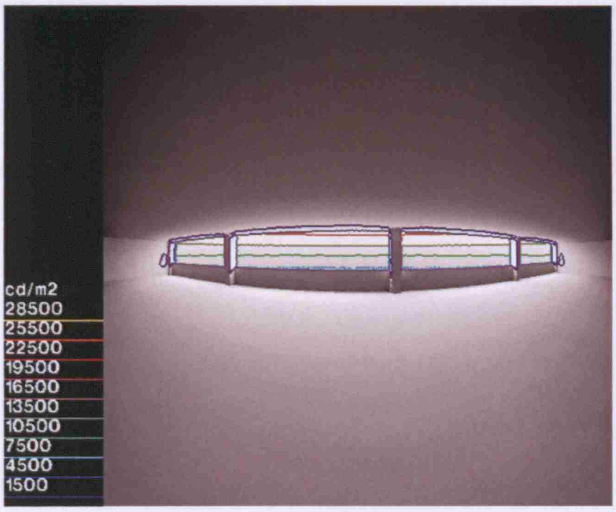
It is recommended by the Society of light and lighting (2002, pp33) that a maximum luminance ratio of 10:1 be used between the task area and area immediately surrounding it. Below is a falsecolor image of the scene seen from View 1a with a 100klx sky.

From the findglare algorithm it has been determined that the indirect component of luminance would be 21000cd/m2, 1200cd/m2 and 260cd/m2 for viewing positions 1a, 2a and 3a. Hence we see that the contrast ratio between the indirect and direct is 1.4, 13 and 40 respectively, suggesting that glare will be an increasing problem toward the back of the room.

Figure 19: Falsecolor images for views 1a 2a and 3a noting that the maximum window luminance is approximately 30,000cd/m^2, 16,500cd/m^2, and 10,500cd/m^2 respectively



View 1a



View 2a

View 3a

It should also be noted, however, that The Code for Lighting remarks that luminance that is too high will also give rise to glare, but no guidance is given on limitations. Added to this it needs to be recognised that most office based activities are orientated around visual display units (VDU) which typically have a luminance of 250-350cd/m^2 altering what we might define as the task are a luminance. Extreme luminance, like that seen next to the windows in this example, will have a tendency to introduce veiling reflections.

Chapter 7: Case study

A case study has been performed for Sydney, Australia (located at 33°52'S, 151°13'E). It is intended that the analysis performed previously can be applied to a generic office in the Sydney market letting us understand the effect of changing the façade geometry on DGI and DGP.

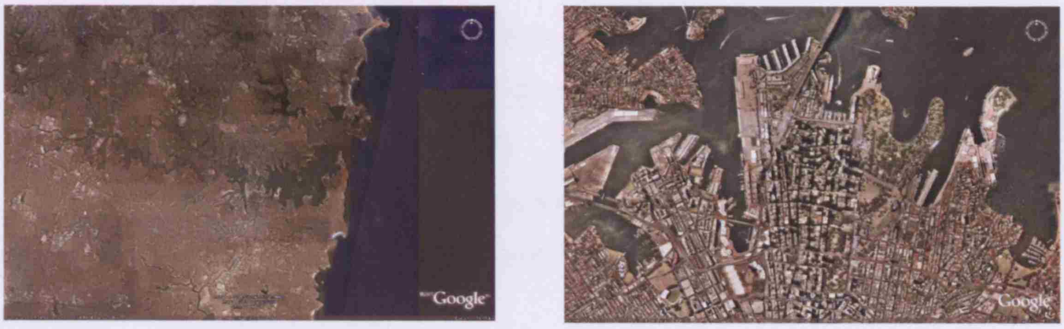
Green Star has become a wide spread tool for use in the analysis of green buildings in Australia. Credits are available within Green Star for the limitation of glare, with one of the options for the limitation of glare being façade treatment to limit daylight penetration to the working plane. It is intended to use the methods previously developed in this document to better understand if this method of glare limitation reduces the propensity of glare.

Sydney's Solar Climate

The analysis of Sydney's prevailing solar climate has largely been based on the weather file for Sydney's representative meteorological year (RMY) obtained from the United States Department of Energy[12].

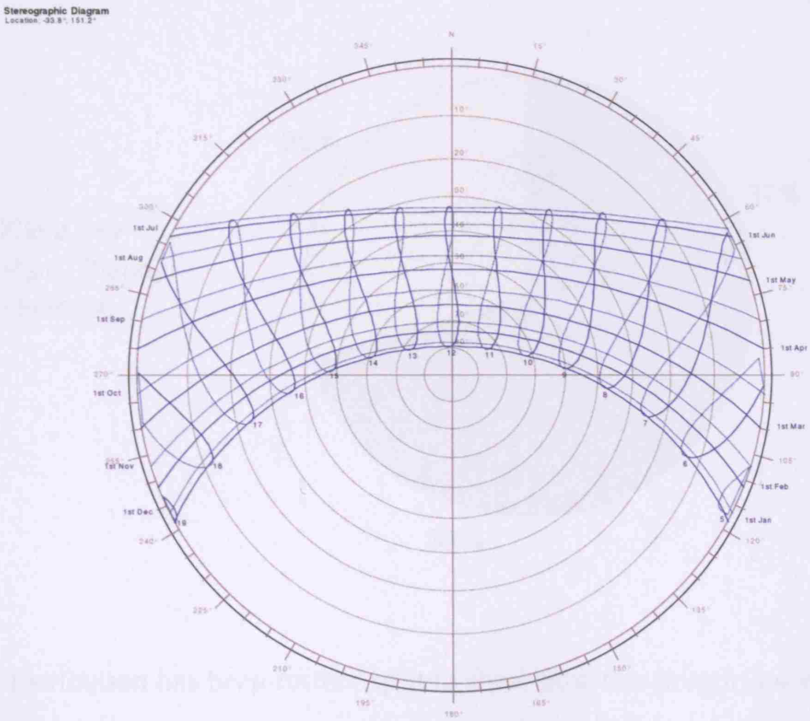
[12] http://www.eere.energy.gov/buildings/energyplus/cfm/weather_data3.cfm/region=5_southwest_pacific_wmo_region_5/country=AUS/cname=Australia

Figure 20: Macroscopic and local view's of Sydney and it harbour, Images taken from Google maps (http://maps.google.co.uk)



Below is a stereographic diagram for Sydney's skies showing the solar azimuth and altitude throughout the year. The solar altitude ranges from around 33 degrees maximum altitude in the winter, to around 80 degrees in the peak of summer.

Figure 21: Stereographic diagram for Sydney, Australia. Generated using Ecotect.



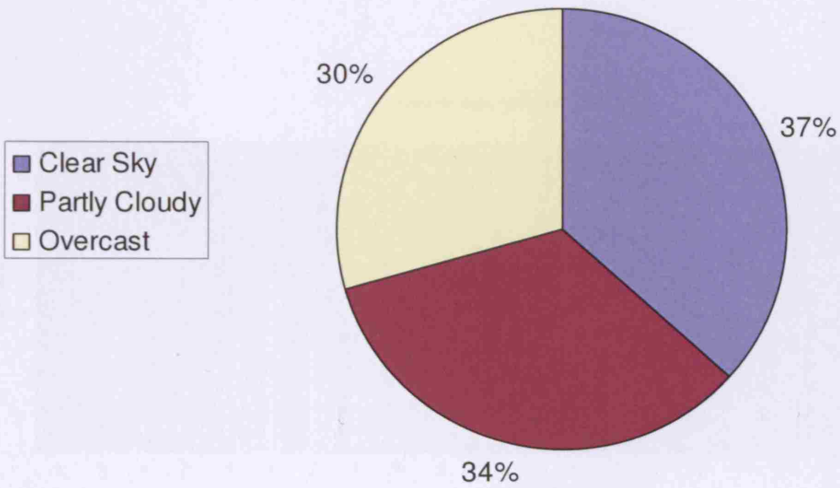
Distribution of Sky types

Analysis of the sky conditions for Sydney has been performed to better understand the distribution and probability of each. This analysis has broken the sky conditions into the CIE Sky types of overcast, intermediate and clear. The data has been broken down, in accordance with IESNA (pp 8-5) recommendations, such that:

- clear sky if cloud cover is < 30%
- intermediate sky if cloud cover is > 40% and , 70%
- overcast sky if cloud cover is > 80%

The graph below shows the percent proportion over the year for clear, overcast and intermediate skies, demonstrating a very even distribution.

Figure 22: Proportions of sky cover type for Sydney, averaged over the year.



This distribution has been further split to show how this proportion varies over the year and the day.

Figure 23: Monthly sky type distributions for Sydney, Australia

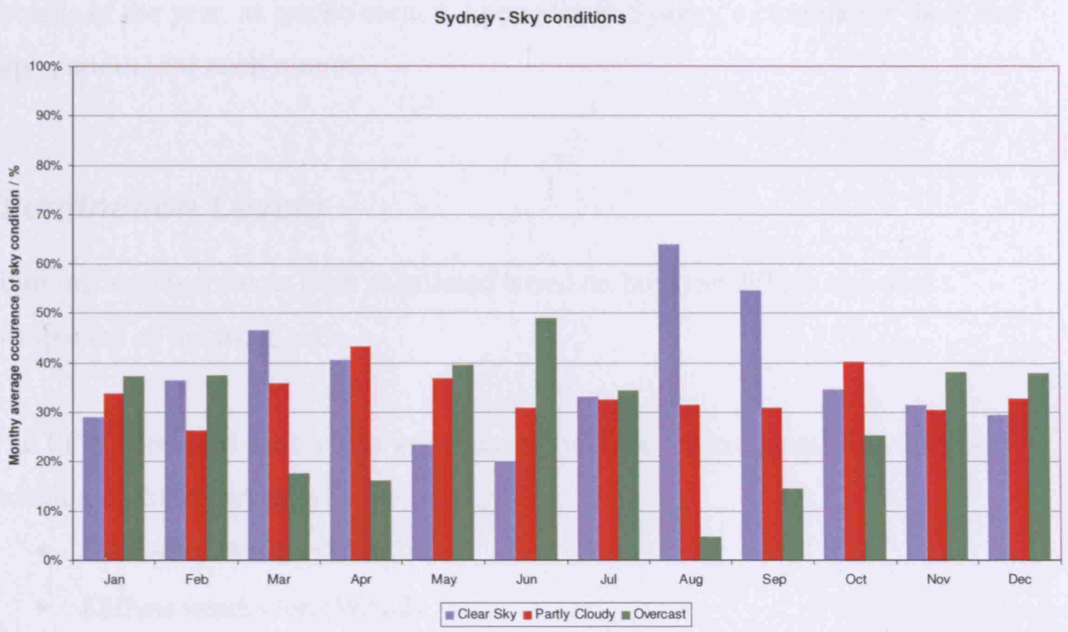


Figure 24: Cumulative hours for all sky types over the day for January. Demonstrating no obvious pattern in daily cloud cover

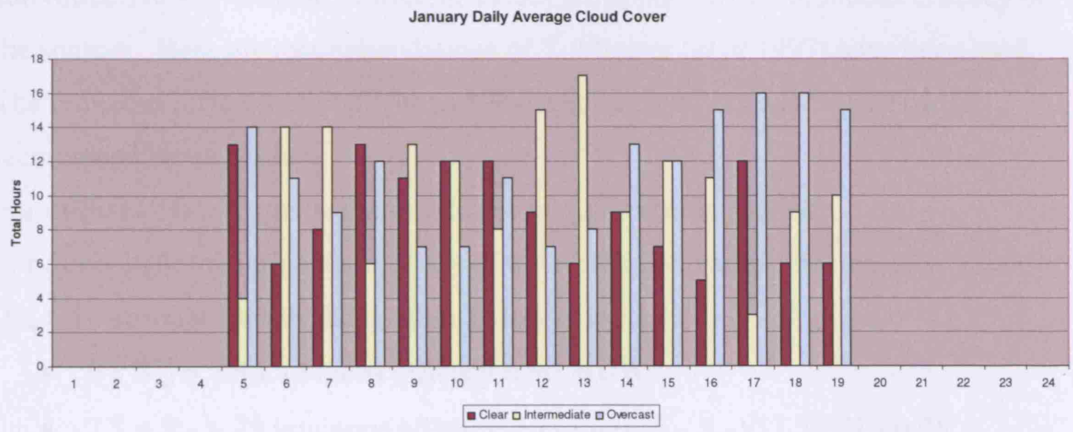


Figure 23 above indicates the sky distribution over the course of the year, showing a dip in the overcast conditions in the spring and autumn with the lowest proportion of clear sky conditions in the winter months, May and June, and peak clear sky conditions in the spring months, August and September.

Figure 24 illustrates the average daily sky distribution for January. It is difficult to identify any trend in daily cloud profiles. This lack of trend is also evident in all other months of the year, as can be seen in Appendix F: Sydney's cumulative daily sky type patterns for each month.

Illumination Levels

Illumination levels have been calculated based on both the diffuse and direct component of the irradiation.

The EPW files used for the analysis present the solar environment of Sydney as a function of three variables[13]:

- Global irradiation (W/m2)
- Diffuse irradiation (W/m2)
- Cloud Cover (%)

To understand what this means in to the human eye we must first convert these irradiation values into lux values. Depending on whether the irradiation is from the sun (direct) or sky (diffuse), different values are applied to the luminous efficacy of the sources. Here the recommendations of T. Muneer (*et al* 1997) have been used. The luminous efficacy of sunlight and skylight has been assessed based on the recommendations below:
For diffuse light a single weighting factor of 125lux/W is applied
For direct light the luminous efficacy of the irradiation varies with the solar altitude (S_{alt}). To account for this the formula below is used:

- $0 < S_{alt} > 7.5$ Luminous efficacy = 90 lux/W
- $7.5 < S_{alt} > 25$ luminous efficacy = $117 - ((25 - S_{alt})/17.5)*27$ lux/W
- $25 < S_{alt}$ luminous efficacy = 117lux/W

[13]The weather analysis files that are available from the United State Energy Department include data on the illumination through the year. Within this report these figures have been disregarded in favor of applying Muneer's proposed illumination model.

Figure 25: Mean hourly illuminance (Lux) on the horizontal plane for each moth of the year

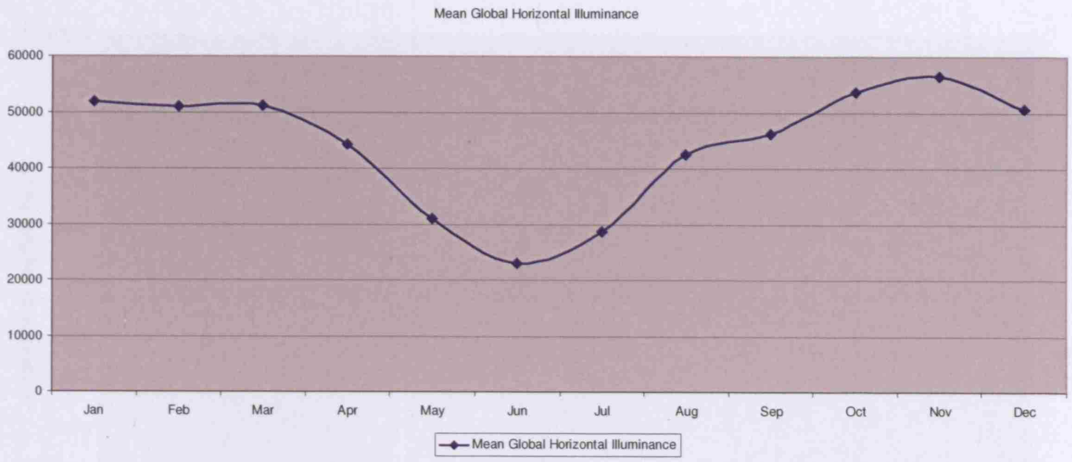
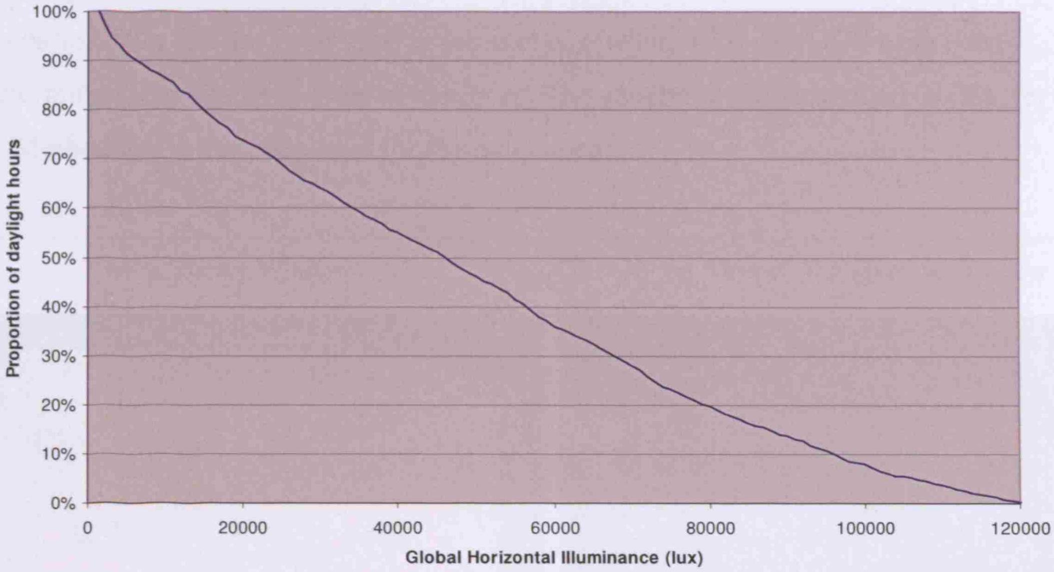


Figure 25 above demonstrates the variation in global horizontal illumination levels over the course of the year. There is a large reduction in the average available light through the winter months. There is a sudden rise/fall in the available light in the intermediate seasons with a relatively flat curve over the summer season. This might could be explained by the prevalence of intermediate and cloudy skies compared to the spring and autumn.

The sky brightness is not dominated by either sun light of sky light. Figure 26 below illustrates the sky brightness as a percentage of daylit hours. This shows how often particular sky brightness is exceeded. For instance, the median sky brightness (exceeded through 50% of daylight hours) is 42,000 lux. Sky brightness's greater than100,000 lux are exceeded through 8% of daylight hours.

Figure 26: Global horizontal illumination as a proportion of daylight hours in Sydney, Australia



The table below demonstrates the percentile for the global horizontal illumination on the unobscured working plane

Table 4: Accidence of annual horizontal illumination

Percentile	Horizontal Illuminance
10%	2333
30%	18961
50%	42018
70%	65350
90%	94553

Glazing

For this assessment glazing with a 40% VLT has been specified in keeping with standard design practice in Sydney at this time.

Glare Sensation

In order to understand the propensity for glare in the Australian climate the analysis techniques developed in the previous chapter have been applied. A worst case scenario 95klx sky has been used in the analysis, where DGI and DGP have been determined over the floor plate of the room. The generic model described in Chapter 5: Methodology, has been used for the assessment.

DGI

View a, Facing Window

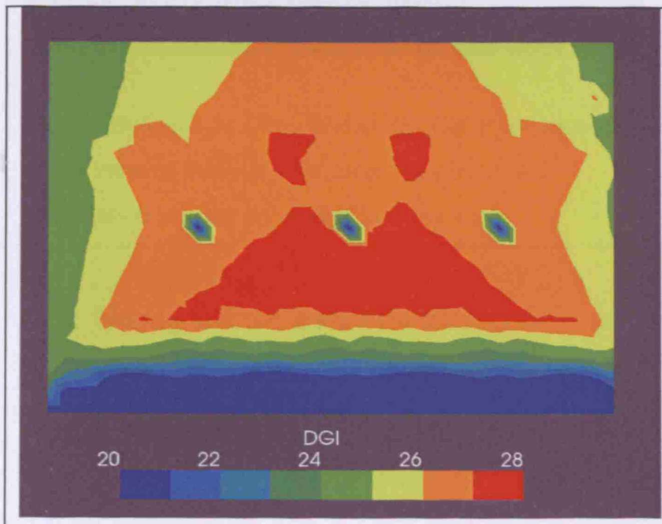


Figure 27: Daylight Glare Index (DGI) represented over a viewing plane at 1.5m from floor level. All occupants facing the window, 95klx sky

View b, 90 Degrees to Window

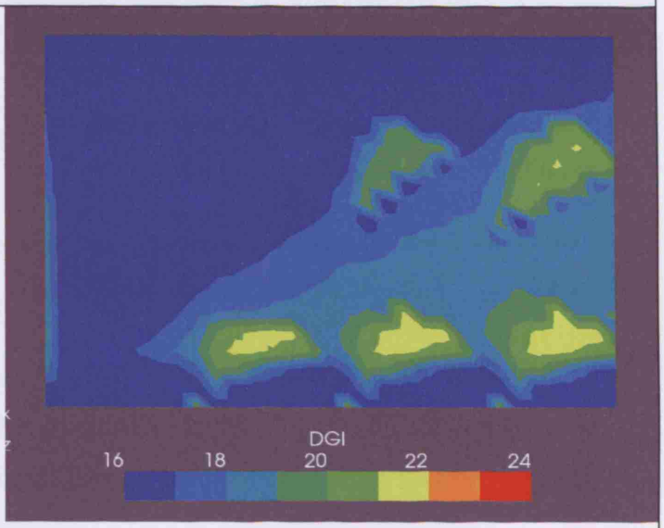


Figure 28: Daylight Glare Index (DGI) represented over a viewing plane at 1.5m from floor level. All occupants facing 90 degrees to window, 95klx sky

DGP

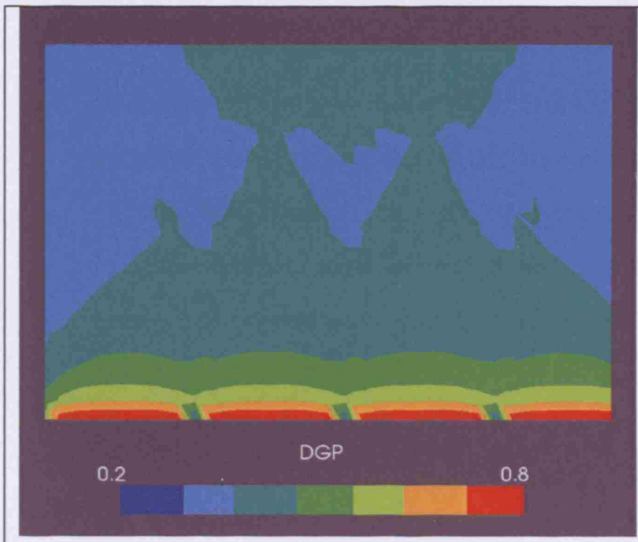


Figure 29: Daylight Glare Probability (DGP) represented over a viewing plane at 1.5m from floor level. All occupants facing the window, 95klx sky

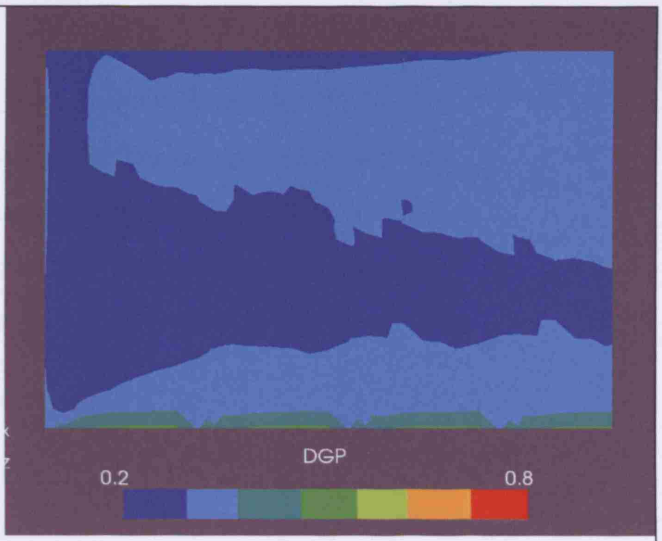


Figure 30: Daylight Glare Probability (DGP) represented over a viewing plane at 1.5m from floor level. All occupants facing 90 degrees to window, 95klx sky

Noting that the glare criterion for DGI are; acceptability below 22 and intolerable above 28, we can see that for occupants facing the glazing that the intermediate zone is worst effected, with a large proportion of this area reaching into the intolerable range. As with the analysis in Chapter 6: Results, there is a tendency toward a very low glare rating at the front of the room.

For occupants facing the windows, we see the DGI across the floor plate is typically in the region of 27, corresponding to a DGI rating of uncomfortable. In the corresponding DGP graph, we might be able to summate that this corresponds to a value of around 0.5.

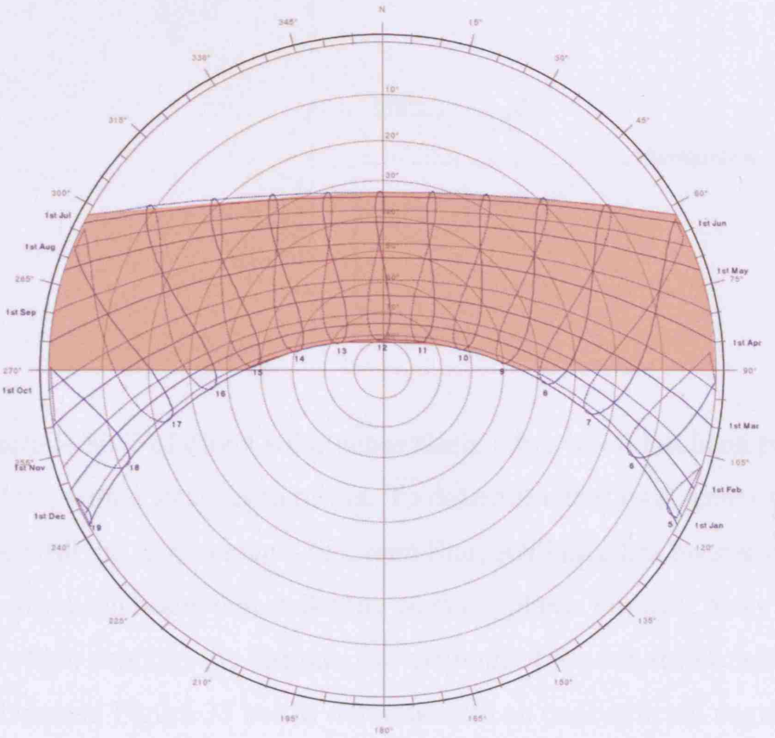
For occupants facing at 90 degrees to the glazing, the typical rating is below 19, corresponding to a rating of perceptible. However, there are localised areas where this increases to around 22, on the limits of acceptability. In the areas corresponding to a DGI of 19, we see that that DGP shows a value in the region of 0.3.

Again, for all plots we see the discrepancy between DGP and DGI close to the façade.

Green Star

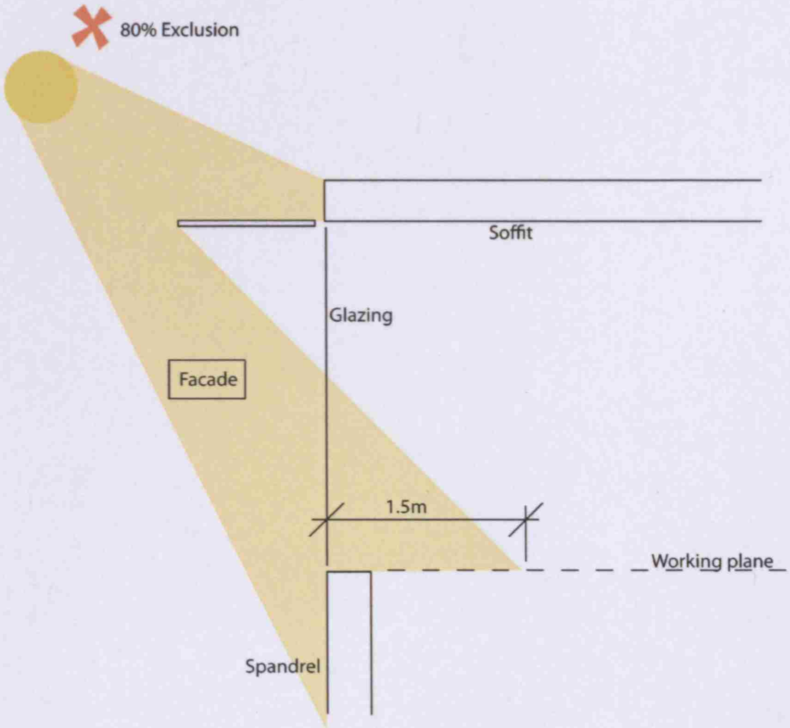
In order to comply with the requirements of Green Star and obtain the credits associated with the limitation of glare in the office, the façade must be designed to exclude 80% of direct sunlight penetration onto the working plane (0.722m AFFL). In this instance a north facing façade has been chosen as a worst case. Figure 31 below demonstrates the area of exclusion deemed a requirement by the Green Star credit.

Figure 31: Area of solar exclusion for Green Star illustrated on a stereographic diagram for Sydney



The solar exclusion may be done by two methods; the base building installation of glare limiting blinds, or, façade treatment or fixtures that exclude 80% of sunlight striking the working plane at a distance of 1.5m from the façade.

Figure 32: Solar exclusion from the working plane for compliance with Green Star glare control credit



In order to exclude 80% of direct solar penetration, a bre soleil has been positioned over the window, with a total depth of 2m. To determine that total solar exclusion is in compliance with the requirements of Green Star, Radiance has been used to determine the total sun hours that strike the working plane. For this, a sky file has been created which contains the altitude and azimuth of the sun for each hour the sun in above the horizon. Figure 33 below demonstrates an unobstructed angular projection of this sky, where we can immediately recognise the similarities to the stereographic projection shown earlier.

Figure 33: Annual hourly solar pattern for an un-obstructed sky view

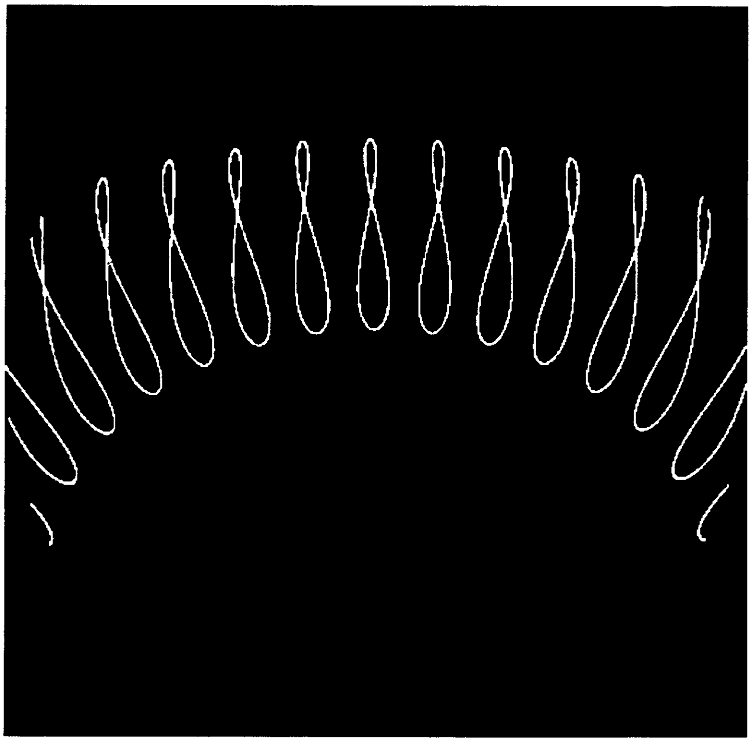
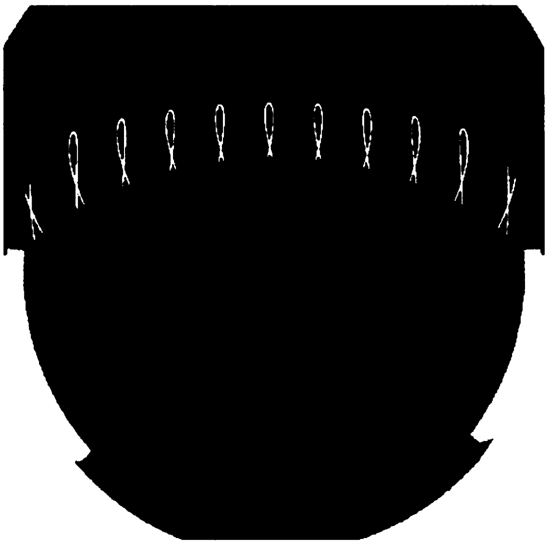
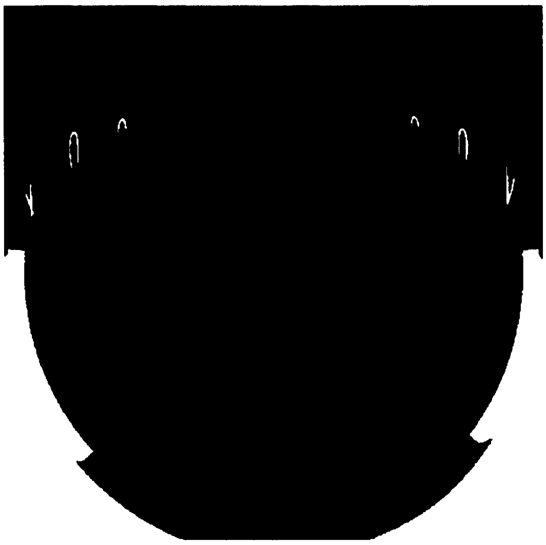


Figure 34 below demonstrates this same sky file only now with the shielding influence of the generic office model around it, and then further with the 2 meter bre soleil projection.

Figure 34: Annual solar pattern seen from within the test room, with and without a 2 meter overhang



View without bre soleil



View with bre soleil

- Ignoring any obscuration, we see a total of 4369 hours of direct solar penetration onto the working plane.
- Without the bre soleil, total hours of direct solar penetration is 1641, or 62% exclusion
- With the bre soleil, total hours of direct solar penetration is 417, or 90% exclusion

The use of the overhang to shade the internal surfaces represents a reduction of 75% of hours of direct solar penetration on to the working plane at a depth of 1.5 meters.

While we have demonstrated compliance with the requirements of Green Star for the alleviation of glare, it is not understood what effect this has on the glare rating induces within the office. Additionally, the use of a bre soleil will reduce the opportunity for daylight access to the space, potentially increasing the proportion of the year that artificial lighting will be used.

Effect of Bre Soleil on Internal Daylight Access, DGI and DGP

In order to asses the impact of adding an overhang on the glare perception within the office DGI and DGP have been calculated again with the overhang. The figures below demonstrate the effect of this on the glare metrics.

View a, Facing Window | **View b, 90 Degrees to Window**

DGI

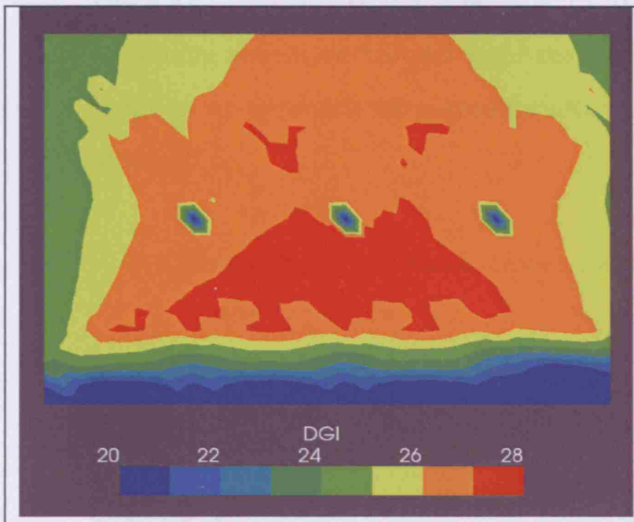


Figure 35: Daylight Glare Index (DGI) represented over a viewing plane at 1.5m from floor level. All occupants facing the window, 95klx sky

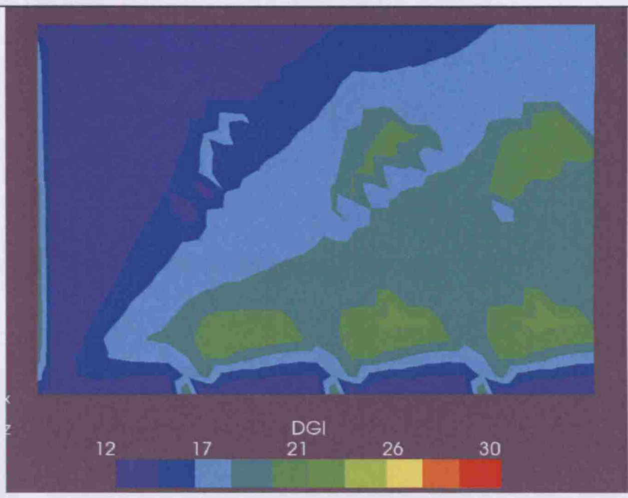


Figure 36: Daylight Glare Index (DGI) represented over a viewing plane at 1.5m from floor level. All occupants facing 90 degrees to window, 95klx sky

DGP

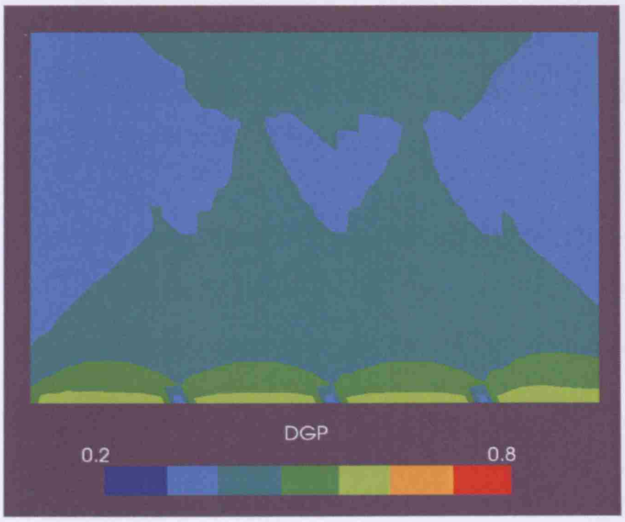


Figure 37: Daylight Glare Probability (DGP) represented over a viewing plane at 1.5m from floor level. All occupants facing the window, 95klx sky

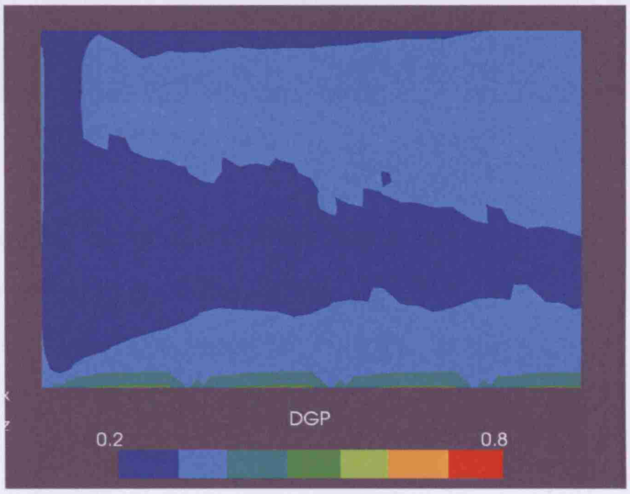
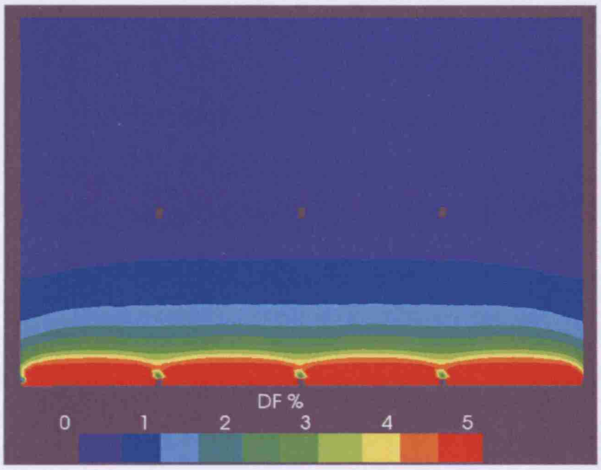


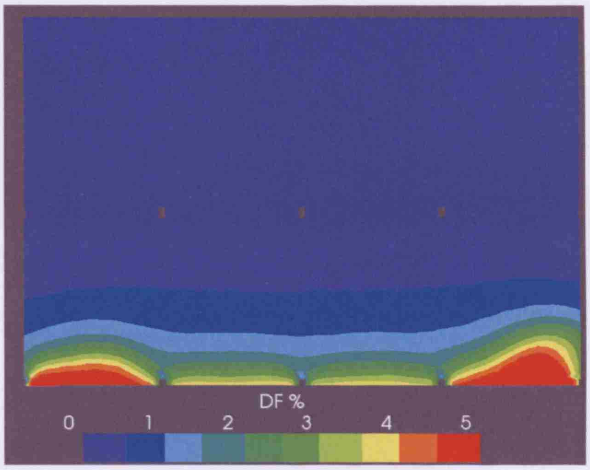
Figure 38: Daylight Glare Probability (DGP) represented over a viewing plane at 1.5m from floor level. All occupants facing 90 degrees to window, 95klx sky

The figures above show a very similar pattern to those presented earlier in this chapter with glare ratings at the rear of the room the same as without the bre soleil. However, it is also noted that the localised spots calculated for the DGI have diminished in their value for occupants facing at 90 degrees to the façade. Additionally, the DGP, whilst remaining almost unchanged at the rear of he room, shows a marked decrease in the index as we approach the glazed façade, with values dropping from over 0.8, to around 0.6.

Figure 39: Daylight Factor variation for working plane for office with and without 2m overhang



DF % without overhang



DF % with overhang

The assessment of the effect of the overhang on the internal light levels has been demonstrated with the use of a daylight factor percentage (DF%), or the ratio of internal to external light on the horizontal plane. Green Star points are awarded on the basis of the total area of the floor plate that has a DF in excess of 2.5%.

The figure above demonstrates the variation in the DF on the working plane for a room with and without the 2 meter bre soleil. In accordance with the recommendations of Green Star, taking a 2.5% daylight factor as the minimum, we see that the total floor area over 2.5% is 10.7% when the overhang is not included, and with is 6.7%, a reduction of 37%. However, we also have to consider the usability of the light delivered where a DF in excess of 10% is considered unusable and potentially detrimental to the indoor environment. It is noted that the DF reaches an extreme of 11% when the overhang is not present but only 7% when it is.

Chapter 8: Discussion

It has been shown that there are a plethora of benefits in the use of daylighting in the office environment including health benefits, improved productivity, and reduced carbon cost. But while there are many benefits to the use of daylight it is also noted that building designers must be careful in mitigating the potential problems associated with thermal comfort, and glare perception of the building occupants.

The human eye is adapted to respond to the spectral output of electromagnetic radiation from the sun (light), with different photo receptors in humans being tuned to differing spectrums. Continuing research in this field is casting into question some of the traditionally accepted concepts on this spectral sensitivity. Recent discoveries point to new photo receptors which are directly linked to the SCN, the previously identified driver of our circadian cycles, calling into question how lighting systems and glazing may be developed in the future to deter fatigue in office environments

The human eye and our perception of light is extremely complex; and is a combination of physiological and psychological response, making it very difficult to subjectively measure some of the effects that cause our sensation of glare.

Various metrics of human perception of glare and how we will respond to extreme light contrast have been developed over the last 100 years. These have traditionally focused on the perception of glare from artificial lighting. Glare from large non-uniform sources, such as that observed from windows is still little understood with various researchers demonstrating that the correlation between the recognised standard in daylight glare response, the Daylight Glare Index (DGI), and measure human response being poor. Kim (et at 2007) notes that the degree of discomfort glare for non-uniform sources of glare is lower than that for uniform sources, used for the formulation of the DGI. The result of this is that the DGI may not be applicable to glare from window, where we see a non-uniform distribution of luminance.

Combined with this different practitioners in the field of lighting research appear to have differing opinions on how to calculate the variables in the same glare equation. It is remarked by G. W. Larson that the terms in the equations are often ill defined. This results in confusion in the industry and calls into question the validity of the glare indices and causing confusion of building designers. It is noted that the Commission Internationale de l'Eclairage (CIE) technical committee 3-39: Discomfort glare from daylight in buildings is attempting to address this issue and it will be interesting to see the results of this.

The analysis of glare indices has focused on a generic, virtual office model where parameters have been set in accordance with recommendations of regulatory bodies and kept as constant for he sake of comparison. Radiance, a backward ray-tracing software has been used for the analysis and two glare identification algorithms, findglare and evalglare, have been used in calculating the DGI and Daylight Glare Probability (DGP). DGP has recently been developed by Wienold (et al 2006) and little information is available on its performance.

Both the DGI and the DGP use modifications of the basic glare formula:

$$\text{Glare sensation} = \frac{(\text{luminance of glare source})^{m} \times (\text{angular substance of glare source at the eye})^{m}}{\text{Luminance of background})^{x} \times (\text{deviation of glare source from line of sight})^{y}}$$

The main variation between the two formula is that DGP substitutes the vertical illuminance at the observers eye , for the luminance of the background, and how they weight the deviation of glare sources from the line of sight; where DGP includes a term for glare sources that are perceived blow the line of sight in accordance with the findings of Einhorn. This may have significant bearing on the assessment of glare adjacent to windows where semi specular surfaces may act to bounce excessive light into the occupants eye.

Chauvel (*et al* 1982) notes when dealing with large glare sources such as those from windows, it would not be correct to simply asses a position factor at the centre of a glare source. Additionally, Nazzal comments on the inability to add the results of the DGI since it does not raise the solid angles of the glare sources to one (1), making it impossible to subdivide large glare sources and assign a position factor to specific areas. This suggests that the DGI will struggle the closer we get to the windows, and the sky angle increases in size. Like Nazzal's work, Wienold and Christoffersen appear to have identified this, and solid angles are raised to the power of one(1) in their formula. It is not immediately obvious of evalglare takes advantage of this ability, subdividing particularly large glare sources, and applying an appropriate position factor.

The findglare algorithm works by identifying glare sources in the viewer's field of view. We have seen that the orientation of the viewer is crucial in determining this, and that it is potentially not appropriate to simply calculate the glare perception over a range of angles. This is confusing and potentially shows an error in the findglare algorithm. The documentation available from the LBNL web site suggest that the output file from the find glare command contains information on the adaptation luminance in each of the requested directions. Given that this is the case, then we should not see a variation in the glare results for the same absolute angle. It is unknown at this time whether this variation in the results is a function of poor scene description or settings on the users behalf, or whether it is a problem with the way in which the adaptation level of the eye is calculated. However, this effect is seen over all outputs from findglare.

Although this variation is not in line with what is described in the documentation, it is however, what we might expect to happen in real life, i.e. if a user of the space, who is normally positioned with their head at ninety degrees to the window, turn their head toward the window, it is likely that they will perceive a greater degree of glare sensation than someone who is normally facing the window. This said, it is highly unclear how predictable the results from Radiance are, and the results are at odds with how the calculation is reported to work. It is therefore not possible to use the results in a reliable manner.

It has been noted by Osterhaus that the lighting patterns within a room vary significantly depending on location. While at the front of the room, extreme brightness may be the main driver for discomfort glare, extreme contrast between the window and the task area may be the main driver for discomfort glare toward the rear. This potentially suggests that two assessment methodologies may be required, depending on the physical make-up of the room.

The identification of glare sources in the findglare and evalglare algorithms is noted as using the average luminance of the scene, including luminance from the glare source. This suggests that the contribution of the glare sources is, in part considered in the calculation since a higher average luminance values will impact on the identification of glare sources.

It has also been reported in Chapter 6: Results, that there is a strong deviation between the DGI and DGP immediately adjacent to the glare source. It is thought that the DGI goes down because the contrast ratio between the glare source and the background luminance goes down. It should be noted that based on the luminance ratios and the recommendations of regulatory bodies[14] the DGI tendency to decrease next to the window is correct. However, based on circumspect evidence, we also know that we can have difficulty adaption to the high light levels presented to out eye on sunny days. Additionally, the ubiquitous use of VDU in office environments will affect our answer. This said, we have not considered this in the calculations, but instead have simply assessed for an occupant adapted to the local luminous environment, which, next to the window is very high. Taking these two arguments into account, it is difficult to simply rationalize what the correct response is, and it would be best to investigate an office with a known glare problem to see.

We have looked at the application of glare indices in a typical office environment in Sydney, Australia where we have seen for a worst case scenario that the average DGI response was one of

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[14] The Society for Light and lighting (2002, pp 33) recommendations for limiting luminance ratios.

Chapter 9: Conclusions

Glare is a very difficult thing to measure and apply a definitive metric to say whether a space will be comfortable or uncomfortable to work in. There is limited guidance on what metrics there are, and this advice can at times be conflicting, resulting in confusion of practicing Engineers.

To alleviate this problem a reliable and benchmarked method is needed, which, may result in several methodologies being applied in different parts of the room/varying situation, or, be a result of years of personal practice in the design of buildings. However, at this stage there is a lack of either.

There is still progression in our understanding of how humans relate to light, with new discoveries causing us to rethink how we approach an old problem. The implied connection between our eye and our circadian cycles my seem obvious, but by now better understanding the mechanism behind this, Engineers and designers can apply this understanding to improving the working environment.

In doing this comparison between the daylight glare index and the daylight glare probability, it was not possible to draw any definitive comparison between the two metrics. This is largely due to the variation between them adjacent to windows, and it is not simple to rationalise which metric is correct (given the modelling that we have performed). To further this investigation it would be beneficial to investigate 'real life' scenarios, where we create a virtual environment as close to what we might expect in a real office. From personal experience, it might then be possible to interpret the results.

The development of a tool for the visual display of glare indices should allow the expedience and comparability of various façade and layout options in the initial design phases of a building design. However, the analysis should be used with caution as the results given by the metrics are highly dependent upon many parameters, with many questions being raised in this investigation about the validity of the tools.

Additionally, the use of Radiance as a tool for analysis has highlighted that a good degree of experience with it is essential for getting reliable results.

The application of the glare indices in the Australian climate has demonstrated that there are benefits to the reduction of glare through the recommendations of Green Star. However, the inclusion of these measures alone will not preclude glare in the office and a combination of this and good office design should be used in tandem, where we see that by simply orientating the occupants at 90 degrees to the façade results in a far greater reduction in the glare metrics than the inclusion of a bre soleil. To this end it is advisable in office situations to follow the recommendations of Chauvel and others to provide:

- A line of sight to the external, including a view of the horizon and movement
- the sighting of work places so that there is no direct view of the sky by the occupant;
- the reduction of the luminance of the window by curtains, blinds or tinted glazing;
- the reduction of sky view by appropriate louvered blinds, overhangs, canopies, etc.;
- the provision of light coloured surfaces around the window and the detailing of the sill, head, reveals, frames and window bars to produce a graded contrast, rather than a sharp one, with the sky seen through the window.

In this carbon conscious age, the development of reliable, descriptive glare tools is paramount in the design of innovative buildings. Within this report we have attempted to look at the implications of reducing glare in a holistic sense, where the limitation of glare needs to be balanced with the access to daylight. Further to the development of a benchmarked tool for the assessment of glare, a continuation of this may push us to an optimised solution, where various façade elements including internal and external shading and glazing type may be tested to give the best compromises between aesthetic motivations; daylight access, minimising the propensity to use artificial lighting; and, glare control, where excessive daylight may again increase the use of artificial lighting through over uses of glare blinds.

Chapter 10: Glossary

Luminance vs. illuminance:

Lux (lx) is a measure of the amount of light energy falling on any given surface and is based on the candela. The candela (cd) is one of the base system international (SI) units. It gives a measure of the luminous intensity of the light source in any given direction and hence is a vector. The luminous flux or lumens (lm) of that light source is a measure of how much luminous energy is being emitted by that light source per solid angle (or steradian (sr)). The difference between lumens and lux is the same as that between luminance and illuminance. Luminance, measured in candela per square meter, gives a measure of the density of luminous energy that is emitted in any given direction. Illuminance, or lux, is a measure of the total luminous energy per meter squared that falls on a given surface.

"As an example, if you form a demagnified image with a lens, the luminous power is concentrated into a smaller area, meaning that the illuminance is higher at the image. The light at the image plane, however, fills a larger solid angle so the luminance comes out to be the same assuming there is no loss at the lens. The image can never be "brighter" than the source"

It should be noted at this time that the luminous energy and radiant energy are not the same. The luminous energy is a corrected value to take account on the human eyes sensitivity to the different light wave bands, where the later is the total energy output of the source.

The relationship between the three measures is given thus:

1 lm = 1 cd•sr = 1 lx•m2

Visual Comfort:

Glare is highly subjective and related to a variety of physiological and psychological factors, including age, illness and view. An individual may experience glare from either excessive illumination or from excessive contrast of illumination. Glare is generally defined in two ways:

Disability glare – causing the occupant to be unable to perform a task such as reading or writing

• Discomfort glare – causing discomfort or irritation

Lumen (lm)

The energy radiated by a light source (candela) per solid angle (steradian), corrected for the human eyes response to the various wave lengths of light ($V(\lambda)$ function).

Luminous Intensity - I, candela (cd)

Luminous Intensity (I) is the power of a source to emit light in a given direction, and is measured in candelas, one of the SI systems base units. The luminous intensity measures

One candela is equal to one lumen per steradian - 1cd = 1lm/sr

As it is defined in a particular direction and is a vector

$I = dF/dw$

Luminous Flux - lumen (lm)

Luminous Flux is the total light emitted by a source or received by a surface in all directions, and is measured in Lumens. The luminous flux is not the same as the radiant flux in that it is adjusted to account for the human eye's sensitivity to the different wavelengths of light.

Steradian (Sr)

One steradian is a unit solid angle subtending an area on the surface of a sphere equal to the square of the sphere radius

Illuminance - E, lux

Illuminance (E) is the quantity of light (luminous flux) arriving on a unit area of a surface, and is measured in lux

One lux is equal to one lumen per m^2 - 1 lux = 1 lm/m2

$E = dF/dA$

Local Adaptation

A process where localized retinal areas become desensitized to light stimulus. The effect can result in separate parts of the retina being desensitized to varying degrees.

Nadir

The nadir is the astronomical term for the point in the sky directly below the observer, or more precisely, the point in the sky with an inclination of −90°. In simple terms, if you are standing on the Earth, it is the direction "down" toward your feet.

Azimuth

The angle measured clockwise from the south point to the location of the celestial body, within this paper that will typically be the solar position.

Base Building
Base building refers to the core building services and fixtures installed within a building prior to a tenant fit out.

Daylight Glare Index (DGI)
Glare index developed between the Building Research Station (BRS) in England and at Cornell University in the USA in 1963. Used to describe glare from large area glare sources. Glare indices rounded to the closest 1.5 to give glare ratings of:

Glare Criterion	DGI
Imperceptible	Below 16
Perceptible	16 – 20
Acceptable	20-22
Just Comfortable	22-24
Uncomfortable	24-28
Intolerable	Above 28

Daylight Glare Probability (DGP)
Glare index developed by Wienold (*et al* 2006) based on glare response measured in 'real 'life' test facilities. Index returns a probability function of glare response for occupants, giving a % probability that glare will be perceived by occupants. No validation or benchmarking currently exists outside the testing carried out by Wienold.

Suprachiasmatic Nucleus (SCN)
The circadian pacemaker within the mammalian brain that drives daily wake-sleep cycles as well as certain hormonal levels.

Property Council of Australia (PCA)
Independent regulatory body, working with industry to set minimum standards and requirements on achieving various grades of building; including Grade C, Grade B, Grade A and Premium Grade. Standards relate to inclusions and features that tenants can expect as a minimum in renting a particular grade of building.

Green Building
A building that has included specific design features or systems to minimizing it's impact on the environment

Solar heat gain coefficient (SHGC)

The ratio of total incident solar thermal energy on the glazing to that transferred through the glazing

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Appendices

Appendix A: Efficiencies of standard lighting types

Indoors/Outdoors	Color Temperature (K)	Color Rendition Index (CRI)	Lifetime (hours)	Efficacy (lumens/watt)	Lighting Type
					Incandescent
Indoors/outdoors	2700–2800 (warm)	98–100 (excellent)	750–2500	10–17	Standard "A" bulb
Indoors/outdoors	2900–3200 (warm to neutral)	98–100 (excellent)	2000–4000	12–22	Tungsten halogen
Indoors/outdoors	2800 (warm)	98–100 (excellent)	2000–3000	12–19	Reflector
					Fluorescent
Indoors/outdoors	2700–6500 (warm to cold)	50–90 (fair to good)	7000–24,000	30–110	Straight tube
Indoors/outdoors	2700–6500 (warm to cold)	65–88 (good)	10,000	50–70	Compact fluorescent lamp (CFL)
Indoors			12,000	40–50	Circline
					High-Intensity Discharge
Outdoors	3200–7000 (warm to cold)	50 (poor to fair)	16,000–24,000	25–60	Mercury vapor
Indoors/outdoors	3700 (cold)	70 (fair)	5000–20,000	70–115	Metal halide
Outdoors	2100 (warm)	25 (poor)	16,000–24,000	50–140	High-pressure sodium
Outdoors		-44 (very poor)	12,000–18,000	60–150	Low-Pressure Sodium

Common lighting types typical properties. U.S. Department of Energy, http://apps1.eere.energy.gov/consumer/your_home/lighting_daylighting/index.cfm/mytopic=12030 (Accessed 2008)

Appendix B: Overviews and Reviews on Limiting Glare from Daylighting

LightLab International, Lab Notes, The Control of Glare by the AS1680 Systems

- "The Glare Index System tends to be a more sensitive indicator of a glare situation (than the Luminance Limiting System)"
- Maximum GI of 16 for screen based tasks
- "Tolerance of 1.5 GI units is quite tolerable"
- "Calculated Glare Index of up to 17.4 GI units is considered to be acceptable in Australia"

Hopkinson, R.G., Glare from Windows, Construction R & D Journal, 2(3), 98-105, 1970

- "Many factors not present in the artificial lighting situation, particularly those associated with the appearance of the window, the pleasantness or otherwise of the view outside, the effect of curtains and reveals around the window, and other factors, clearly affect judgement of discomfort under daylighting conditions."
- "The degree of discomfort glare due to the sky seen through a window can be predicted from a glare index based upon the Cornell large source formula."
- "There appears to be a greater tolerance of mild degrees of glare from the sky seen through the window than for a comparable artificial lighting situation with the same value of glare index, but this greater tolerance does not extend to severe degrees of glare."
- Relationship between IES glare index and proposed daylight glare index presented

Hopkinson, R.G., Glare from Windows 3: Using the Glare Index in Daylighting Design, Construction R & D Journal, 3, 23-28, 1971

- Glare index calculation procedure presented, using Cornell large source glare formula

- View divided into ground and sky components
- Design methods by which to reduce daylight glare presented

Hopkinson, R.G., Glare from Daylighting in Buildings, Appl Erg, 3(4), 206-215, 1972

- Cornell large source glare formula presented
- "The modified formula permitted a Glare Index to be computed for the daylighting of
- Interiors, where views of bright skies through large windows constitute the source of glare discomfort."
- "The Glare Index enables a numerical magnitude to be placed upon the probably degree of glare discomfort likely to be experienced in a daylit interior."
- "There is an underlying conflict in making an assessment in a highly glaring situation if the window has a pleasant view or one with a great deal of interesting information. In such circumstances, the observer would extend his tolerance level to discomfort, even though the view is not actually reducing the glare."
- "The brighter the sky the worse the glare"
- "The most sensitive region of the sky for glare is that immediately below the window head, at an angle of elevation to the observer above the horizontal of 20-30°."

Chauvel, P., Collins, J.B., Dogniaux, R., Longmore, J., Glare from Windows: Current Views of the Problem, LR&T, 14(1), 31-46, 1982

- "This paper discusses daylight glare as a source of visual discomfort in terms of glare from the unobstructed sky and not glare related to direct or reflected sunlight"
- "There is a difference between the glare experienced from a window and the glare experienced from a large source of artificial light of the same subtended area as the sky, due to the psychological differences in the visual content of the field of view."

- "Discomfort glare from a single window (except for a rather small one) is practically independent of size and distance from the observer but is critically dependent on the sky luminance"
- "The basic studies on discomfort glare by Luckiesh and Guth, and by Petherbridge and Hopkinson … produced formulae which appeared to describe the relationships up to a size which subtended a solid angle on the eye in the region of 0.01 steradian."
- Reviewed work by Hopkinson on the Cornell large glare source formula
- Application of the Cornell formula concluded that, "the principal means of meeting a specified limiting daylight glare index is by limiting the luminance, or visibility of the sky as seen through the window, by permanent means or by temporary means such as adjustable blinds or curtains"
- Experimental study by Aubree and Chauvel concluded that, "the most important parameters are: (1) the luminance of the glaring source, but it is necessary to reach a very low level – 2000 cd/m2 – to improve the situation; (2) the luminance contrast between the sky and surroundings, but a small amount of electric light, on a small area, seems enough"
- Design guidance provided for control of glare from windows
- "The assessment of discomfort glare conditions for (combined artificial lighting and daylight) cannot be expressed simply in a predictive equation."
- "The formula for large area glare sources derived from the results of experiments in the laboratory was found to produce a glare index which had a reasonable correlation with the average experience."
- Electric lighting levels recommended to ameliorate identified daylight glare

Waters, C.E., Mistrick R.G., Bernecker, C.A., Discomfort Glare from Sources of Nonuniform Luminance, JIES, Summer 1995, Pp 73-85

- "A nonuniform glare source produces more glare than a uniform glare source directly along the visual axis, and less glare at 10 and 20 degrees off-axis."
- "Existing discomfort glare models conservatively estimate the effect of nonuniform source luminance on the perception of discomfort glare."

Velds, M., Assessment of Lighting Quality in Office Rooms with Daylighting Systems, Technische Universiteit Delft, 1999

- "The majority of existing glare formulae are developed for the evaluation of discomfort glare from small artificial light sources, such as the Visual Comfort Probability system (VCP) …, the Building Research Station Glare Index (BGI) … and the Unified Glare Rating (UGR)"
- "Previous research has shown that these glare formulae cannot be used for the assessment of discomfort glare from windows"
- "Osterhaus … showed that the best correlation with perceived degree of discomfort glare was found for the direct vertical illuminance at the eye or the overall brightness in the visual field, instead of existing glare formulae."
- "A number of studies conducted by other researchers showed that the use of the DGI could lead to unreliable results"
- Predicted Glare Sensation Vote (PGSV) presented "The PGSV gives more plausible degrees of glare than the DGI does, but generally these values are still too high."
- "The PGSV … only aims at the evaluation of glare from windows located in the line of vision."
- "The discomfort J index … is a tool for establishing optimal visual comfort conditions at VDT work stations."
- J index can be calculated by Radiance – not anymore
- Stationary Virtual Reality (SVR) method presented
- "Comparison of assessments made in the virtual reality (SVR) and those made in identical offices showed that there is a good correspondence with respect to perceived glare and brightness"
- "The Daylight Glare Index and the Predicted Glare Sensation Vote give higher calculated degrees of discomfort glare than those perceived under real sky conditions … they are based on experiments with uniform light sources and it is not yet clear whether these indices can be used to represent the degree of discomfort glare in situations with a non-uniform luminance distribution within the window plane."

- "It seems to be infeasible to predict or measure the perceived degree of discomfort glare in a specific situation."
- Visual Comfort Evaluation (VCE) method presented
- "The Visual Comfort Evaluation Method is a method to appoint the degree of discomfort glare in daylit satiation under reproducible conditions, through assessments of subjects in a large scale model placed in front of an artificial sky"
- User Acceptance Studies presented
- "The perceived degree of discomfort glare near the facade is critically dependent on the visible sky luminance, when large windows are looked at"
- "The perceived degree of discomfort glare at the back of the room is not solely dependent on the luminance of the sky"

Appendix C: Modelling procedure and analysis settings

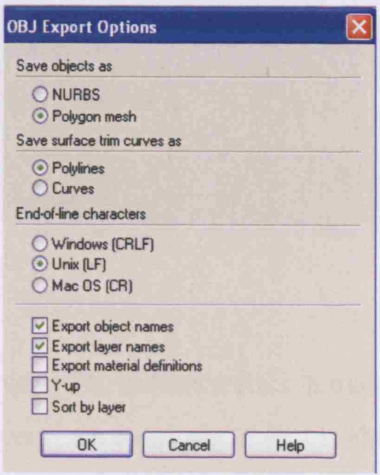
This is a brief summary documenting the procedures to set up a daylight model in Radiance to undertake daylight studies of glare. The initial stages of the document can be used generally for the procedure of exporting geometry files for use with Radiance, at which time a multitude of other analysis techniques may be used (see http://radsite.lbl.gov/radiance/)

The following steps have been followed:

- Create a 3D geometry in Rhinoceros (here after known as Rhino) (http://www.rhino3d.com/)
- Export as a wavefront obj file
- Use radiance to convert wavefront files to radiance files
- Creation of material files
- Creation of sky file description
- Creation of viewing points file
- Creation of optical file
- Description of the Radiance command line input.
- Image/results filtering

When modelling your building in Rhino the following procedures shall be adopted:

- A specific layer shall be created for each different material in the building.
- When exporting wavefront file be sure to export using the settings demonstrated below



Meshing settings should be appropriate for the level of detail and scale of the model. The denser the mesh created, the more computational power required, and the longer the analysis will take.

Surface reflectivity has been assigned in accordance with The Code For Light And Lighting 2002 (check!) and have been assigned been given a greyscale representation.

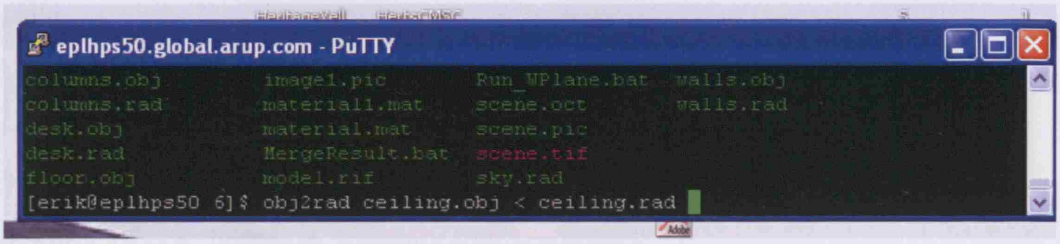
Object	Surface Reflectivity
Walls/Columns	50%
Floor	20%
Ceiling	70%
Tables	30%

The transmissivity of the glazing – used by Radiance - is not the same as the transmission of the glass as it does not include the addition of light that is reflected at interfaces. In this instance the Transmissivity of the glass will be entered 0.432 to account for this. No colour tint will be used within the glazing and the red blue and green spectral transmissivities.

Radiance

After exporting the wavefront model, the obj2rad command will be used to convert them into radiance files. This can be done in a batch process if using a windows based system such as Desktop Radiance or Cygwin Radiance.

The image below shows how this would be entered on a command line prompt.



Materials file

After all files have been converted to radiance files, a materials file must be created, giving a description of all layers. An example of this is shown below.

```
void plastic walls
0
0
5 0.5 0.5 0.5 0 0

void plastic columns
0
0
5 0.5 0.5 0.5 0 0

void glass glass
0
0
3 0.402 0.402 0.402

void plastic floor
0
0
5 0.2 0.2 0.2 0 0

void plastic ceiling
0
0
5 0.7 0.7 0.7 0 0

void plastic desk
0
0
5 0.3 0.3 0.3 0 0

```

Here, the plastic derivative has been used for most materials where five variables are entered, for the r, b and g reflectivities, the surface roughness and the secularity of the surface. Both roughness and specularity have been left at zero. The glas material has been used for the glazing, which, as stated previously has it's transmissivities set to 0.402 in the r, b and g.

Sky file

Next, a sky files for the description must be created. An example of this is again shown below. Here, the latitude, longitude and meridian of the site are so that radiance can determine the solar position for a give n date and time. The sky distribution takes the form:

!gensky 6 21 13 -c -a -33.53 -o -151.1 -m -150 -B 18.4

Gensky - internal radiance program for generating the sky description

6 - month of the year

21 – Day of the month

13 – time of day, based on a twenty four hour clock

-c – CIE sky type, other options include:

-c overcast sky

-s sunny sky (without sun)

+s sunny sky

-u uniform sky

-i intermediate sky (without sun)

+i intermediate sky with a subdued sun

-a – Latitude of the site

-o – Longitude of the site

-m – Closes standard meridian to the site

-B – Total irradiance of the sky. Radiance determines the contribution of each part of the sky based on this figure. It is the –B values that has been altered to generate the various sky brightness's.

-R – As with the –B option but radiance of the sky

There are a multitude of other settings which, if the reader is interested can be investigated further by reading Rendering with Radiance (Ward/Shakespeare, 199X)

In addition to the sky distribution, a description of both the sky and ground reflection must be entered. For this analysis the following has been used:

```
!gensky 6 21 13 -c -a -33.53
# Outside Paramaters.
skyfunc glow sky_glow
0
0
4 1 1 1 0
sky_glow source sky
0
0
4 0 0 1 180
skyfunc glow ground_glow
0
0
4 1 1 1 0
ground_glow source ground
0
0
4 0 0 -1 180
```

Combining the files

The files created must now be put together into an octree file using the oconv command:

$ oconv materials.rad element_files(eg floor.rad).rad sky.rad > model.oct

Note: the materials file must be placed prior to the various other elements or else an error will occur. This is because the files are opened in turn and each material must have been previously described before it is referenced elsewhere in the element files.

Optical file

The optical file sets a number of important rendering parameters for the ambient calculation in Radiance. An in depth review of these, including recommendations and formula on how to calculate some can be seen in the book ' Rendering with Radiance' (Ward/Shakespeare, 1998) a copy of which is available on-line (http://radsite.lbl.gov/radiance/) .

To set the -ar value (ambient resolution) get the dimension of largest plane inside your model and divide by the ar value to determine how often light bouncing off a surface is calculated. For example, if you wish to calculate light levels at a regular spacing of a meter the **size of model largest plane/ar=1meter**.

To do this go to the dos prompt and type **getinfo –d model.oct** to get the value for the model largest dimension. In this case 32.4 meters. The –ar value has been set based on a grid of a half meter.

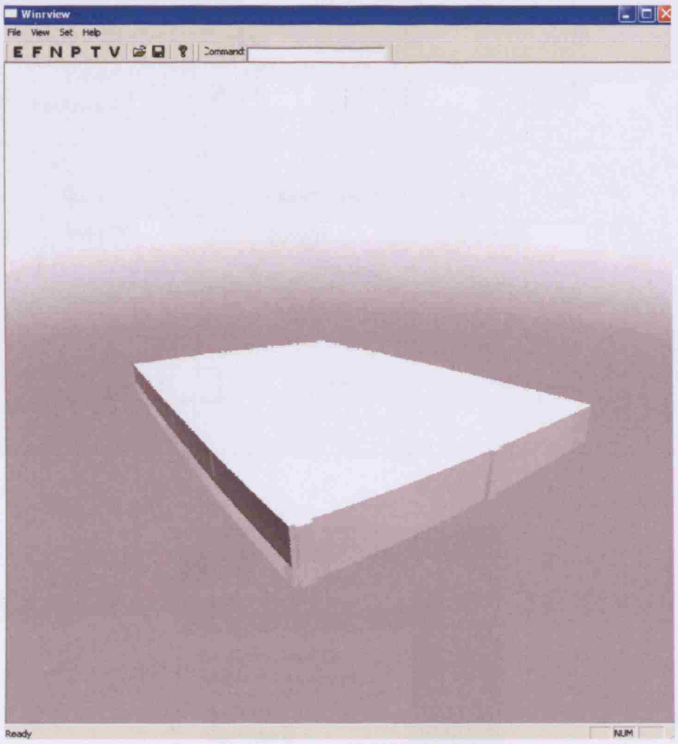
The –ab value (ambient bounces) has been set based both on the accuracy of the results required, and on the computational power required. Appendix D: Optical file settings, a parametric study, investigates the setting in more detail. A value of –ab 3 has been chosen in this instance as it gives reasonable results, while limiting the time associated with the calculation.

View file

Our viewing points describe the location and type of view that we want for each point of analysis. To set these, the rview command may be use to open our octree file in Winview thus:

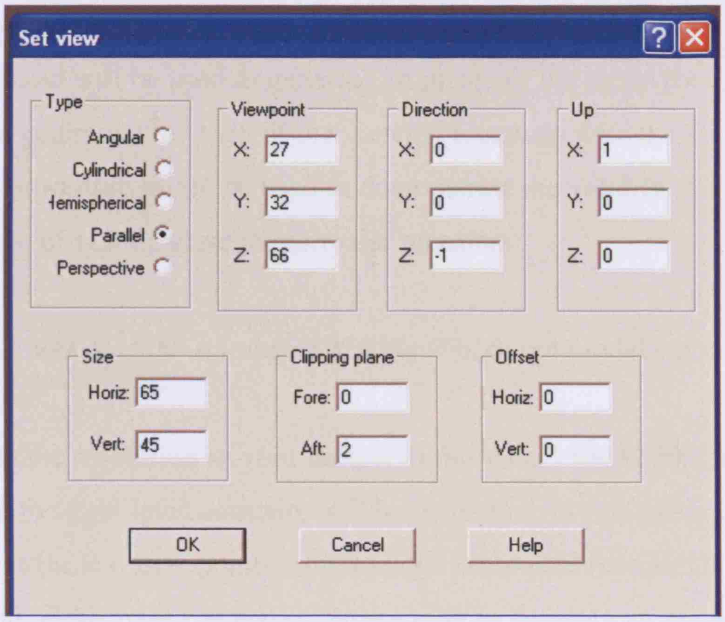
$rview model.oct

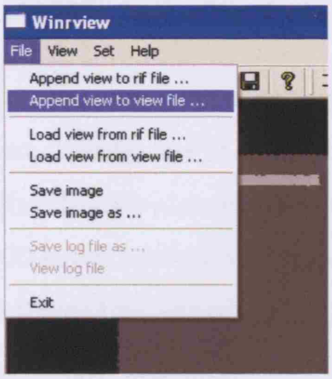
Use the window used to visualize the geometry file with all its components. Press V to set view.



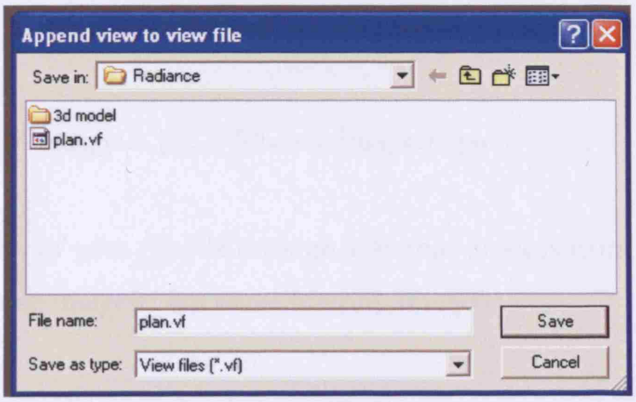
A window will pop up with options to set your view. The view point will determine the centre point of your view. Direction will determine the direction the view is facing. 1 or -1 means the view is looking in that direction. So X=0, Y=0 and Z=-1 means the view is looking directly down towards the Z vector (suited for plan view). Up will define which direction vector of the page will face up.

Clipping plane will clip everything above or below the location of the point. If aft is set to 2 it means that everything 2 meters below the viewpoint will be clipped out of the figure.





Save the file as append view to file



Parameters are set.

Image generation

The rpict command will be used to generate an image of the scene for display. One image has been generated for each of the viewing locations with the 90th percentile sky used. This procedure might be used to demonstrate the validity of a façade design for the limitation of veiling glare in computer monitors.

rpict -i –S 1 -x 1500 -y 1500 -o image%02d.pic @high.opt model.oct < view.vf

this line defines the resolution of your image, in this case 1500X1500 pixels, defines the view where the light level contours will be generated, in this particular case the view file defines the six view points, and the –S 1 command (combined with the %02d at the end of the *.pic file name) allows rpict to generate an image for all the valid viewing locations in the view file *.vf .

This command will be run twice, once with the –i setting and once without. The –i setting turns the calculation from illuminance to luminance (-i for illuminance). The luminance image will be used for the calculation of the windows vertical luminance (where a maximum value of 4000cd/m2 is recommended for the avoidance of glare). The illuminance image will be filtered (as shown below) for this luminance figures to be overlayed onto. This is done simple to generate an image that more closely represents that ween be the human eye.

Image filtering

pfilt -x /3 -y /3 -r 0.1 image01.pic > filtered_image01.pic

improves the quality of your pic file through anti alias process from version a to version b, in this case image01 becomes filtered_image01)

pcond -h filtered image01.pic > human_eye01.pic

adjust your pic file from antialias to a picture seen through human perception falsecolor -i luminance01.pic -p human_eye01.pic -cl –l cd/m2 -s 4000 -n 10 > final.pic

-s parameter defines the maximum luminance contour so it will show from 0 up to 4000cd/m2, if the maximum value desired is say 9000 then change s value to reflect. –n parameter determine the number of contours, so if the max luminance is 10,000cd/m2 and there are 10 contours there is a increase of 1000cd/m2 in each contour.

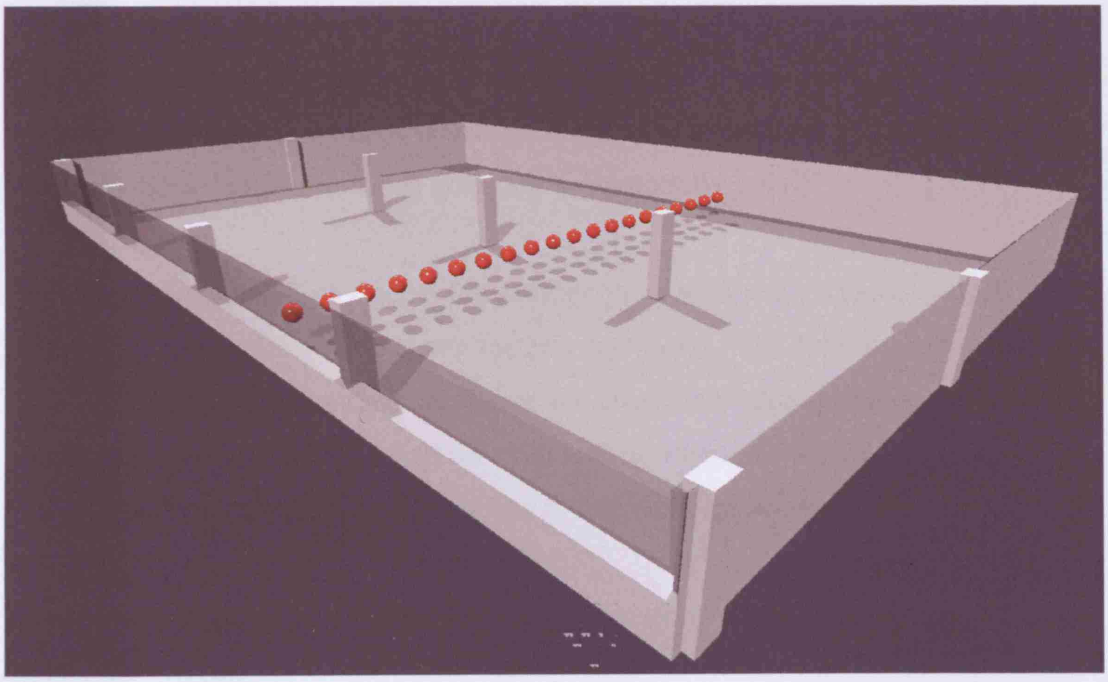
Visual Comfort Calculation

All three calculation methods use an image file input to identify the glare sources and all three use Radiance to calculate the glare sensation. However, the DGI uses the findglare algorithm, written by Larson, to identify glare sources within a prescribed field of view, while the DGP glare source algorithm has been written by Wienold.

The glare sensation methodology written by Larson can be further studied here: http://radsite.lbl.gov/radiance/refer/Notes/glare.html

Appendix D: Optical file settings, a parametric study

In order to test the effect of some of the many parameters that go into the Radiance calculation, a test model was created. The model, in order to ensure the results are as directly comparable to the model proposed for use in comparing glare metrics, is similar to that used for the glare calculations other than the desks have been removed. This has been done for expedience of calculation, and to help ensure a smooth and predictable declination in the light levels as we move away from the windows. Below is an image of the model used with the ceiling removed for demonstration purposes. For aid of description, red spheres have been added to the radiance octree at all measuring points. All the measuring points are described by their x, y, z coordinates and their normal direction nx, ny, nz. In doing this we describe their position (through the coordinates) and viewing direction (through the normals). During the calculations, all normals have been described as pointing straight up (0, 0, 1) and may be seen as having a hemispherical view of the area above them.



For the measuring points indicated above, several optical file settings have been investigated in order to get a reliable representation of daylight within the space. Show below are plots of the daylight factors at each of these points. The optical files settings used for each of the graphs is given to the right of the image. Daylight Factor percentage has been used as it is a commonly used unitless parameter showing ratio of internal illuminance to external illuminance.

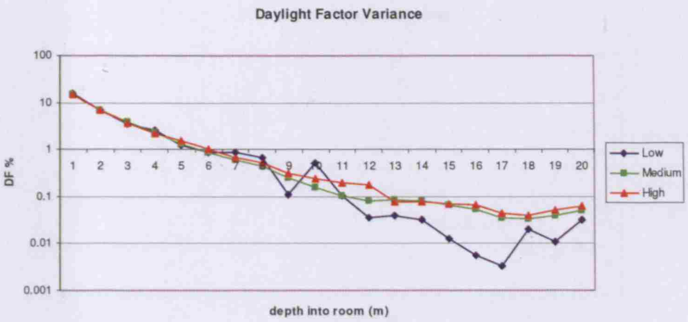
The optical files used in figure C.1 were generated based on the recommendations given within Rendering With Radiance (Larson/Shakespeare, 1996) for low, medium and high optical file settings. We see, next to the window where there is a large view angle of the sky and hence the luminance source, that there is low variation in the daylight factors predicted, and that all three graphs follow the anticipated declination pattern. However, the further into the room we go, the more erratic the predictions become, particularly with the low optical file settings. Both the medium and high optical file settings show a far lesser degree of variation. All plots in figure C.1 were generated using three ambient bounces. The ambient bounce setting might be seen as having one of the greatest effects on the accuracy of the results, and refers to the total number of bounces that a ray of light has before it stops. For example, if we were to sit in a room with a light bulb on; a ray of light travelling from the bulb directly to our eye would see no ambient bounces. If the ray of light were to bounce off one wall and then to out eye it would be seen to have one ambient bounce, and so on. The Greater the number of ambient bounces we allow, the greater the number of ray paths need to be calculated with the time taken going up exponentially.

Both the medium and high optical file settings show a limited variation between them, ranging from 14.9% to 15.1% at one meter's depth to 0.5% 0.45% at eight meters, and 0.066% to 0.55% at sixteen meters. There is a close correlation between the two optical files. To better understand the effect of the ambient bounces, both files have been further divided and analysed for one to four ambient bounces.

Daylight Factor Predictions using Radiance for various optical file settings

Optical file settings used

Low.opt Med.opt High.opt



-dp 64	-dp 512	-dp 4096
-ds 0	-ds .3	-ds .02
-dt .2	-dt .1	-dt .05
-dc .25	-dc .5	-dc .17
-dr 0	-dr 1	-dr 3
-sj 0	-sj .7	-sj 1
-st .5	-st .1	-st .01
-ar 120	-ar 480	-ar 960
-ab 3	-ab 3	-ab 3
-aa .4	-aa .2	-aa .15
-ad 64	-ad 400	-ad 768
-as 0	-as 64	-as 196
-av 0 0 0	-av 0 0 0	-av 0 0 0

figure D.1

Variation in DF predictions for Rendering with Radiance' recommended optical file settings

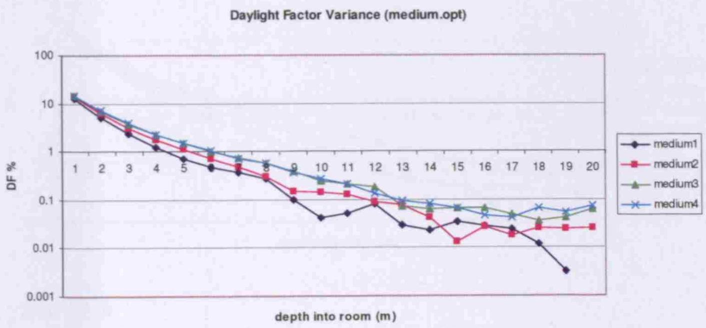


figure D.2

Variation in DF predictions for medium optical file settings with ambient bounces ranging from one to four

-dp 512
-ds .3
-dt .1
-dc .5
-dr 1
-sj .7
-st .1
-ar 480
-ab 1 through 4
-aa .2
-ad 400
-as 64
-av 0 0 0

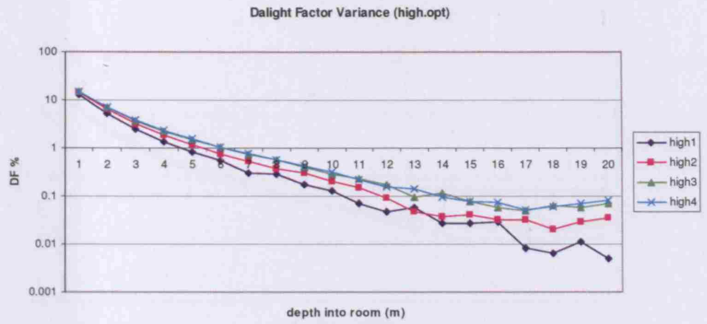


figure D.3

Variation in DF predictions for high optical file settings with ambient bounces ranging from one to four

-dp 4096
-ds .02
-dt .05
-dc .17
-dr 3
-sj 1
-st .01
-ar 960
-ab 3
-aa .15
-ad 768
-as 196
-av 0 0 0

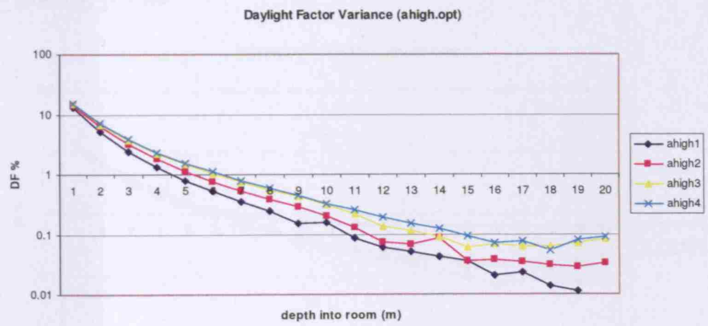


figure D.4

Variation in DF predictions for high optical file settings with ambient bounces ranging from one to four, modifications made to ambient divisions and ambient sampling to allow predictions deep within the room to accurately sample light coming from the sky.

-dp 4096
-ds .02
-dt .05
-dc .17
-dr 3
-sj 1
-st .01
-ar 64
-ab 1 through 4
-aa .15
-ad 2056
-as 1024
-av 0 0 0

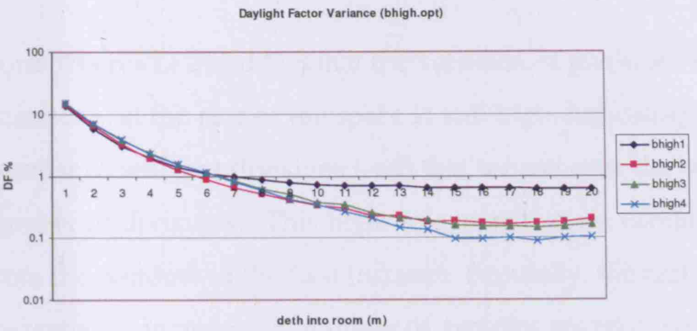


figure D.5

Variation in DF predictions for high optical file settings with ambient bounces ranging from one to four, modifications made to ambient divisions and ambient sampling to allow predictions deep within the room to accurately sample light coming from the sky. Ambient value increased to 0.28 to account for the adaptation associated with internal light level of 400lux on the working plane

-dp 4096
-ds .02
-dt .05
-dc .17
-dr 3
-sj 1
-st .01
-ar 64
-ab 3
-aa .15
-ad 2056
-as 1024
-av 0.28 0.28 0.28

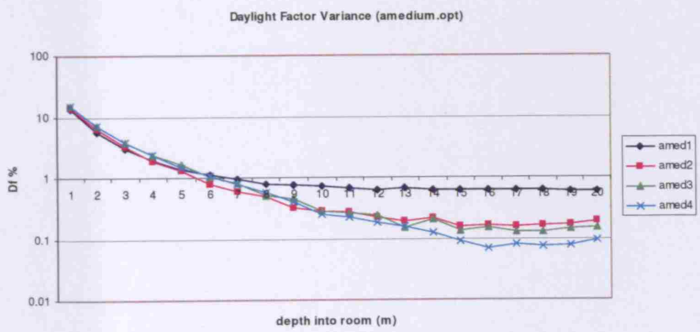


figure D.6

Variation in DF predictions for medium high optical file settings with ambient bounces ranging from one to four, modifications made to ambient divisions and ambient sampling to allow predictions deep within the room to accurately sample light coming from the sky. Ambient value increased to 0.28 to account for the adaptation associated with internal light level of 400lux on the working plane.

-dp 512
-ds .3
-dt .1
-dc .5
-dr 1
-sj .7
-st .1
-ar 60
-ab 3
-aa .2
-ad 1024
-as 256
-av 0.28 0.28 0.28

Form figures D.2 and D.3 that the variation in predicted light levels - for low ambient bounces - at the rear of the space is still high, indicating that we need to increase the number of ambient divisions (-ad) that we use over the hemisphere of view (total number of divisions). This helps to ensure that we capture the direct light coming from the window in the first instance. Secondly, the ambient supersamples (-as) are increased to increase the number of samples we take over areas with large bright and dark regions. Thirdly, in order to balance out the calculation time needed for the calculation, we reduce the ambient resolution (-ar).

These changes result in a smoothing of the curve toward the rear of the room while still maintaining accuracy of results across the area of investigation.

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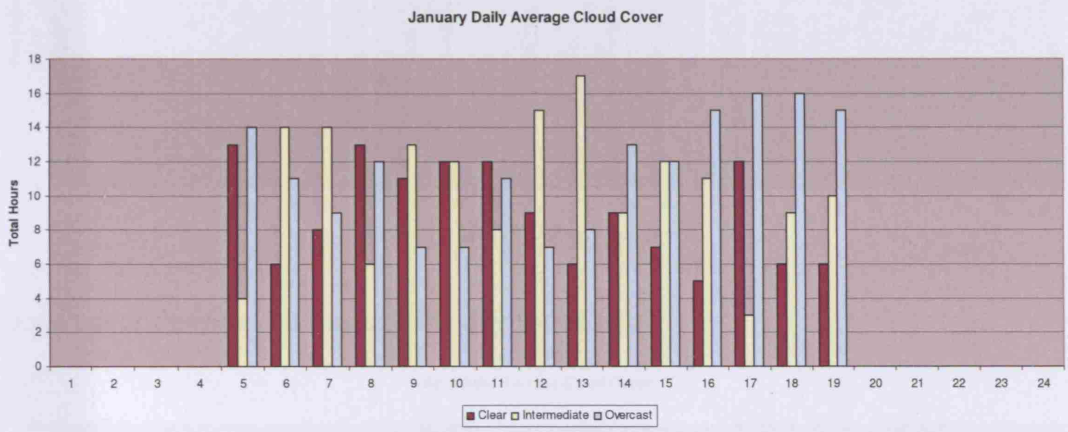
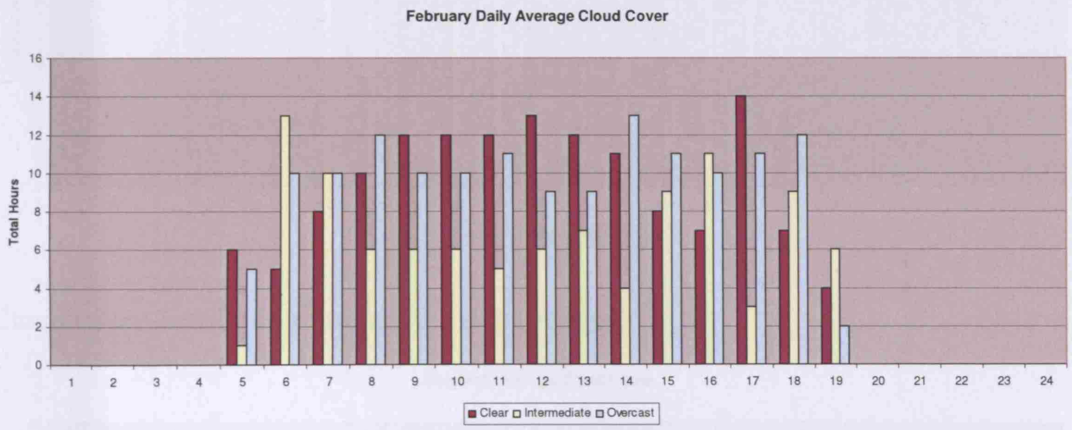
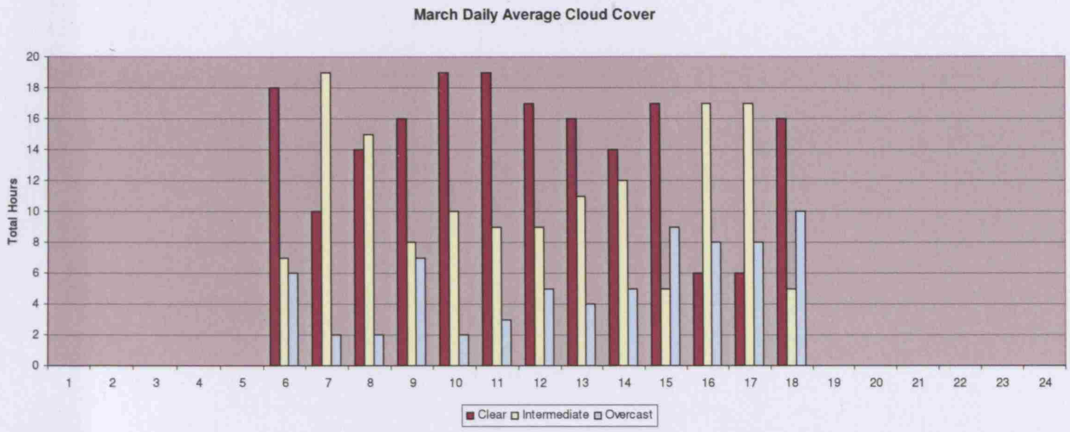
Appendix F: Sydney's cumulative daily sky type patterns for each month



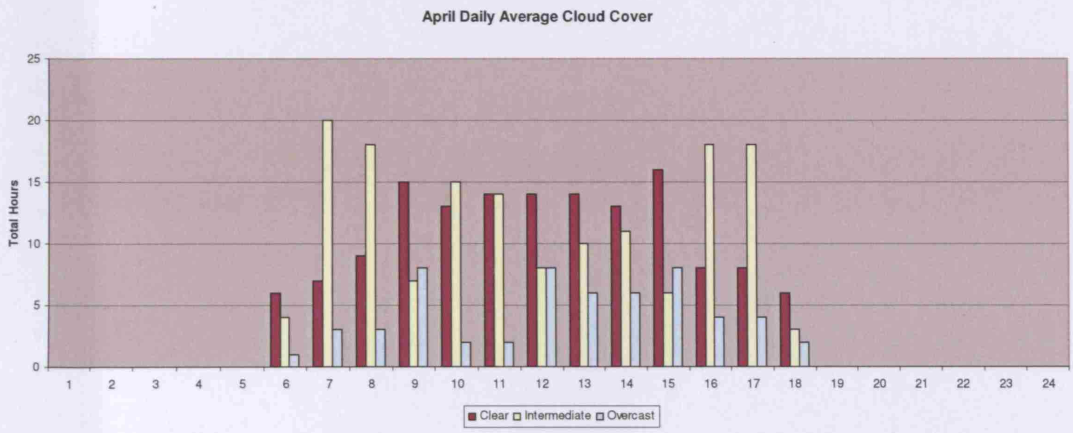
Cloud cover distribution through the day for January



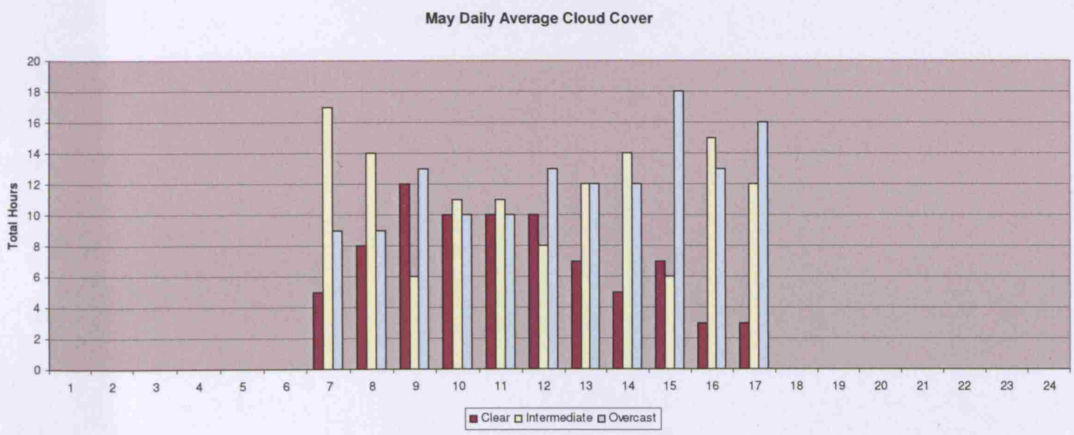
Cloud cover distribution through the day for February



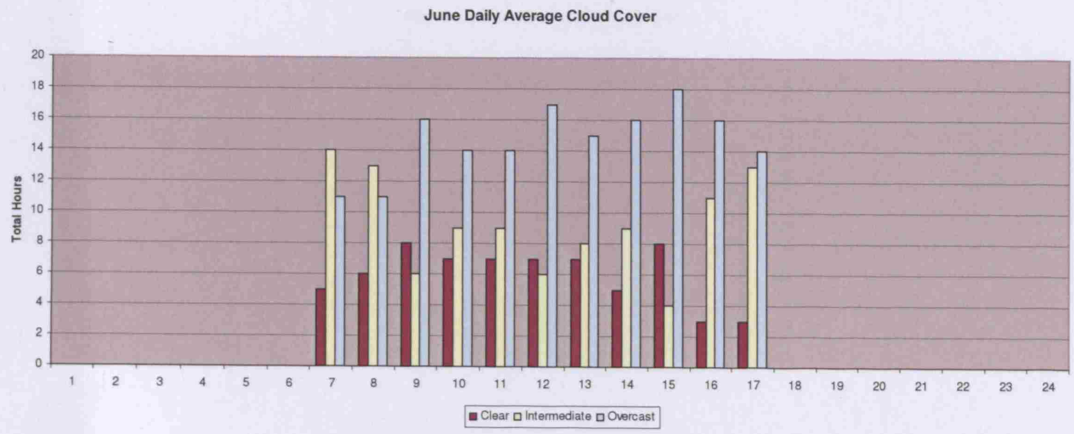
Cloud cover distribution through the day for March



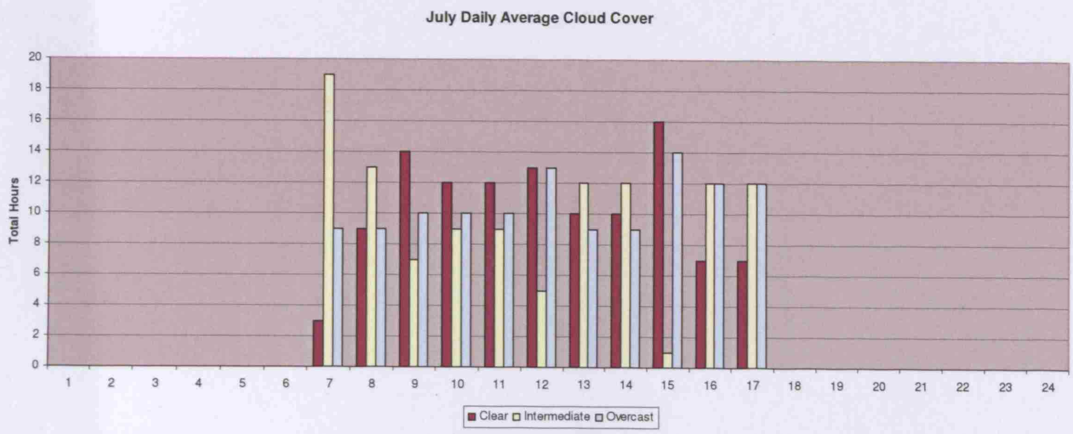
Cloud cover distribution through the day for April



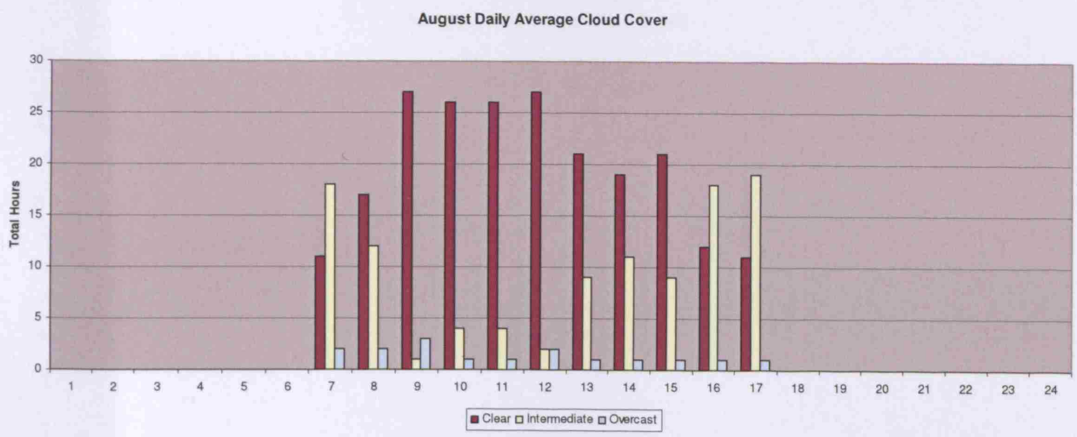
Cloud cover distribution through the day for May



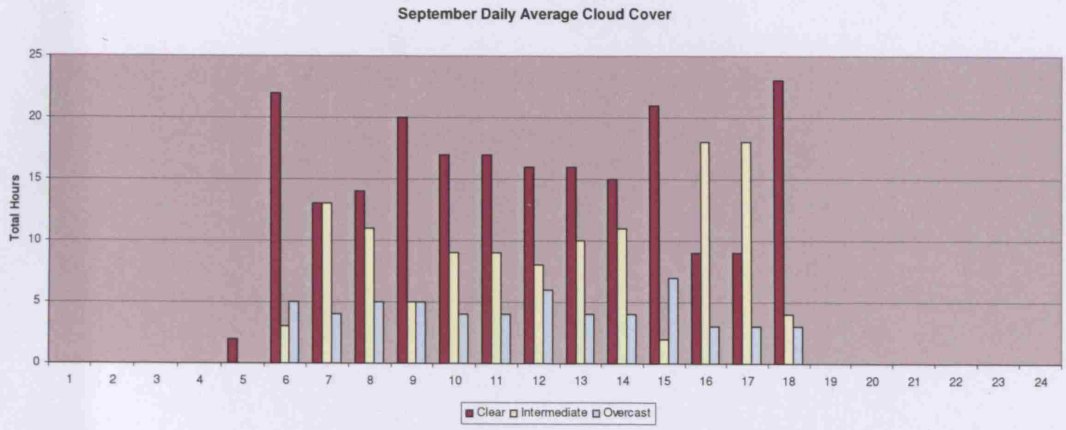
Cloud cover distribution through the day for June



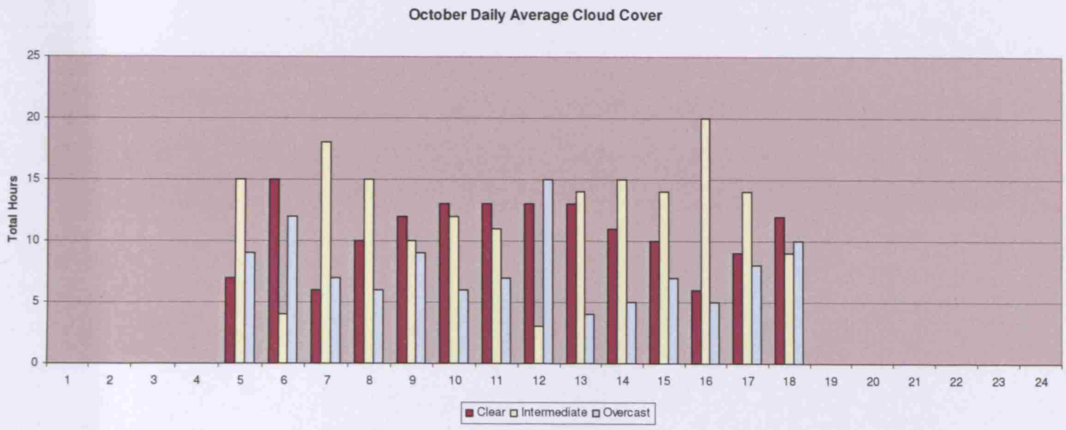
Cloud cover distribution through the day for July



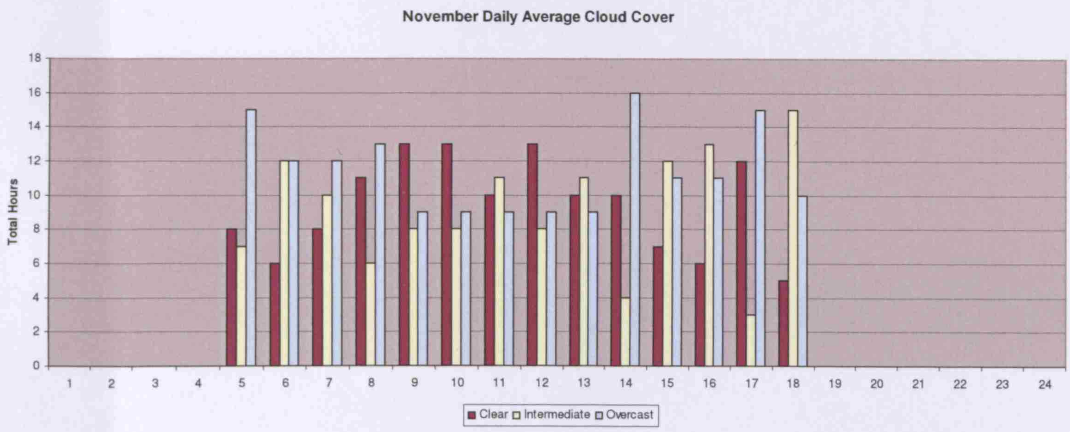
Cloud cover distribution through the day for August



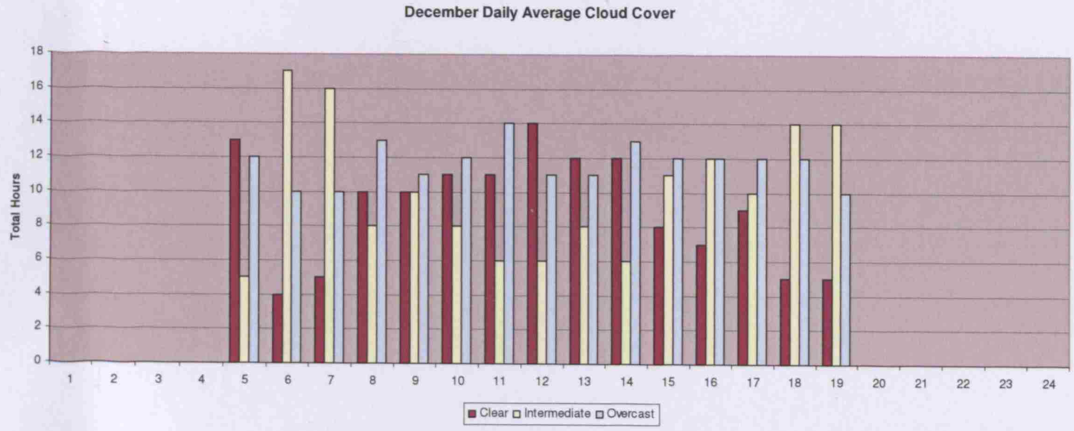
Cloud cover distribution through the day for September



Cloud cover distribution through the day for October



Cloud cover distribution through the day for November



Cloud cover distribution through the day for December