Daylighting for Visual Comfort and Energy Conservation in Offices in Sunny Regions

Evyatar Erell, PhD
Ben-Gurion University of the Negev
erell@bgu.ac.il

Eran Kaftan, PhD
Ben-Gurion University of the Negev

Yaakov Garb, PhD
Ben-Gurion University of the Negev

ABSTRACT

Office buildings in regions with abundant sunlight may still fail to make effective use of daylight: the difficulty in controlling variations in natural illumination, which may be substantial, often results in extensive use of artificial lighting. A solution to this paradox was sought by means of a controlled experiment designed to investigate the effect of several strategies to reduce glare and to achieve visual comfort in a test room configured to represent a typical side-lit office. Subjects performed office tasks such as reading or operating a computer, and completed a detailed questionnaire about their work environment, whose physical parameters were monitored in great detail. The study showed that if the window is exposed to direct sunlight, the use of tinted glass may not be an adequate response. Internal Venetian blinds, if deployed correctly, may prevent glare and provide visual comfort to workers near the window – but they require frequent adjustment and reduce the depth at which daylighting may still be enjoyed. A light shelf with an exterior part to shade the view pane from direct sunlight in summer and an interior part to reflect light to the ceiling resulted in superior daylighting and better visual comfort in all room configurations. It is suggested that since windows in offices fulfil multiple roles (daylighting, natural ventilation and a view outdoors), their functioning could be improved by subdividing them into panes to optimize their provision.

INTRODUCTION

Lighting comprises a significant part of the energy used in office buildings: Estimates range from 35% in Adelaide, which has a mild sunny climate (Blanchard, 2005), to 23% in cooler, overcast London, where heating requirements are greater (Majoros, 1998). Because office buildings are occupied mostly during the daytime, the potential for energy savings through substituting daylighting for electric lights is high. Simulation studies of typical office spaces in Belgium (Bodart and De Herde, 2002) show that approximately 40% of this energy can be saved by automatic dimming of artificial lighting when sufficiently illumination can be achieved by daylighting alone. Demonstration buildings have shown that energy consumption for lighting and HVAC can be reduced by 50% (Voss *et al*., 2005), but savings depend on the proportion of occupants that have access to external windows and on the ratio of window area to floor area (Krarti *et al*., 2005).

The predominant strategy for increasing daylight utilization has been to design extensive glazed

The first and third authors are faculty members of the Dept. for Man in the Desert at the Jacob Blaustein Institutes for Desert Research. The second author was a PhD student at the Dept. and is now an independent consultant and director of Research and EcoDesign.

facades. However, when the sun is out, a person near the window may be exposed to high, asymmetrical radiant loads and very high levels of illumination: mean radiant temperatures of up to 47^{o}C and illumination levels in excess of 30,000 lux were measured indoors near a clear window on a sunny winter day (Erell *et al*., 2004). To counter this, the occupants of such buildings may require curtains or blinds to avoid glare or overheating. Unfortunately, they typically leave their blinds deployed at all times, and employ electric lighting even when external illumination levels are sufficient to provide adequate illumination. In warm sunny locations this behaviour results in a double penalty: First, because in summertime external gains from a glazed area are greater than from an opaque wall; and second, because the use of electric light increases internal gains and increases the load on the A/C system.

Visual discomfort caused by excessive light is referred as ‘glare’, defined by the CIE as the “condition of vision in which there is discomfort or a reduction in the ability to see details or objects, caused by an unsuitable distribution or range of luminance, or extreme contrasts”. Evaluation of glare is sometimes not straightforward, as most traditional indices for visual comfort encounter difficulties either at extreme luminance levels or in the evaluation of large sources of light or sources not mounted close to the ceiling plane, such as vertical windows (Osterhaus, 2005). If the potential sources of glare cover a significant part of the visual field of the observer, the adaptation of the eye to higher luminance reduces the glare sensation and contrast effect. When the glare source is small, however, the observer’s adaptation level, which is determined by the luminance of the background, is virtually independent of the light source.

The Daylight Glare Probability (DGP) is probably the index best-suited for highly luminous environments. It is based on the vertical illuminance at the eye as well as on the luminance of the glare sources, their solid angle and their position index. The DGP, which was calibrated empirically on the basis of controlled experiments at Freiburg and Copenhagen, has values that range from 0 to 1, and is calculated as follows (Wienold and Christoffersen, 2006):

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

where E_v is the vertical illuminance at eye level [lux], L_s is the luminance of the *i*th source contributing to the glare [cd m^{-2}], ω_s is the solid angle subtended by the source and P is the dimensionless Guth position index.

An index incorporating a probability is preferable for most rating schemes, since there is a large variation of responses when comparing visual comfort, especially with respect to glare Osterhaus (2005). Thus, a 100-fold increase in luminance may be required to arrive at the same subjective glare rating between the least sensitive and most sensitive subjects (Osterhaus and Bailey, 1992). Furthermore, responses of individuals are often inconsistent when assessing the same environment on different occasions. This may be due to acclimatization to current daylight levels outdoors, which vary greatly on a daily basis but also between locations. For example, illuminance levels of over 75,000 lux occur on nearly two-thirds of the days in Tel Aviv, but barely on one day in ten in Berlin. The search for a universal index is further complicated by the fact that there are apparently persistent cultural differences in illuminance preferences (Belcher, 1985). Indeed, Veitch and Newsham (1996) suggest that the perception of lighting quality is affected by behavioural factors that are not accounted for in any of the existing indices. Nonetheless, current standards for lighting – artificial or natural – make no allowance for such disparities among countries, or for other sources of individual and contextual variability.

Much of the research on daylighting has been carried out in overcast locations, and the current study seeks to complement this body of knowledge in a highly luminous environment. Its aims are to evaluate several daylight control systems in such locations, and to evaluate the use of the DGP for subjects acclimatized to these kinds of lighting conditions.

METHODOLOGY

A controlled experiment was carried out to investigate occupant preferences with respect to several façade designs for better visual comfort and glare control. The test subjects were asked to perform several tasks representing typical office work, such as reading from paper and typing to a computer, in a room furnished to resemble a normal office. Measurement of light – luminance and illuminance – was carried out concurrently in a second adjacent room where conditions were almost identical. The position of the work station and its orientation with respect to the window were varied according to a predefined schedule. To reduce the possibility of inadvertent bias because of minor differences between the rooms, the roles of the two rooms were alternated. The subjective responses to a questionnaire were analysed and compared to prevailing conditions during the test sessions.

Test rooms

The test rooms were 2.7m by 3.5m wide and 3.05m high, with white walls and ceiling (reflectance 0.75), and a terrazzo floor (reflectance 0.45). An aluminium-framed window 1.34m wide by 1.76m high was located near the middle of the (long) south-facing wall. The windows comprised a 'view pane' consisting of horizontal sliders 114cm in height beginning 95cm above the floor, and a fixed 'daylighting pane' 62 cm high above them. An external roll-down shutter remained open for the duration of the tests. Both test rooms were furnished with identical computer work stations installed on small tables fitted with wheels, to allow easy repositioning by test subjects. Each station included a personal computer with a 19" LCD monitor, keyboard and mouse. Walls were decorated with coloured posters to enhance the visual environment and to reduce glare from uniform white surfaces, simulating a real office.

Daylight control strategies

Three daylight control strategies were tested, singly and in combination:

1. *Tinted glass*: The use of tinted glass is widespread in office buildings in most sunny locations, both to reduce solar gains (so-called ‘solar control’ glazing) and to reduce glare near the windows. The view pane of the window was fitted with either clear double-glazed panes (VT=0.79) or with similar panes equipped with a tinted foil with a total light transmittance of 0.47 (VT47).
2. *Venetian blinds*: Venetian blinds are the most common internal shading device found in offices. The window was equipped with standard white blinds with curved slats (25mm wide, 1.5mm curvature) that covered the entire glazed area. After installation of the light shelf (see below), these blinds covered the view pane only.
3. *Light shelf*: A ‘portable’ light shelf comprising an internal element and an external one was attached to the window at a height of 2.1 meters above the floor (Figure 1a and b). The shelf had a curved section (convex on the interior, concave on the exterior), was 50 cm deep and extended 20cm beyond each side of the window.

Figure 1 Light shelf installed for the experiment, seen from interior (left) and exterior (middle); setup for HDR photography used to establish luminance (right).

Monitoring internal environmental conditions

While subjects were carrying out the test procedure, the following parameters were monitored:

- Indoor air temperature, relative humidity and CO_2 concentration
- Indoor illuminance: 4 horizontal measurements of general room lighting - 10 cm above desk as well as half a meter from wall centres (TES-1332A light meter), each of which received different amounts of light; Illuminance at the task area (vertically next to the computer screen and horizontally on the keyboard); Vertical illuminance at the eye; Total exterior illumination received at the window (on a vertical plane) and the net flux transmitted to the interior, adjacent to the window pane (or 10 cm behind the venetian blinds when these were in place).
- Indoor luminance was evaluated from HDR images taken from the subjects' eye position looking towards the task area and the window (with a Coolpix 5400 camera and FC-E8 fish eye lens, Figure 1c). Images were calibrated using spot measurements (Minolta luminance meter LS-110).
- Outdoor horizontal illuminance (TES-1332A light meter)

Questionnaire

The subjective sensation of glare experienced by the participants in the controlled daylighting experiment was recorded by means of a questionnaire consisting of 4 sections:

a. Personal (demographic) questions
b. Subject assessment of the rooms and quality of the visual environment
c. The subject's explanation of their individual preferences in setting up the subject-defined test environment
d. Questions on subject's perception of indoor climate within the room

Experimental procedure

Experiments in the test rooms at the Sde Boqer campus of Ben-Gurion University (30.8 N 35.1E) took place between October and March at 10:30-15:00. Sessions were conducted only on sunny, cloudless days, characterized as a CIE Standard Clear Sky (Type 12), with a (vertical) illuminance on the window in excess of 50,000 lux. Each subject was asked to carry out a sequence of tasks and to fill in questionnaires to obtain a subjective rating of the visual comfort of the simulated office environment. While the subjects were thus occupied, research staff carried out measurement of the visual environment in the second adjacent test room, which was identically oriented and equipped.

The subjects were requested to follow instructions given in an interactive PowerPoint presentation. This provided the basic structure of the experiment, as follows:

1. After carrying out typing tasks requiring them to copy text from both the screen and from paper, in order to become acquainted with the procedure, subjects were asked to fill in a questionnaire with basic demographic information.
2. The test room was then arranged in the first test configuration, according to a predetermined schedule established to test all possible combinations of desk location relative to the window and of the daylight control strategy. The subjects then performed the first test unit: They watched one of three short videos, to allow them to become acclimatized to the new visual conditions, then performed two typing tasks and finally answered a questionnaire to give their assessment of the visual environment.
3. The test room was then arranged in a second configuration by changing the glazing type. The subjects then performed the second test unit, which was identical to the first one.
4. After completing the second test unit, subjects were asked to arrange the test room so as to maximize comfort. They were allowed to choose either type of glazing, to select any location in the

room for the computer work station, and to manipulate the venetian blinds to any position. Following this, they performed the third test unit.

5. After completing all three test units, the subjects answered one final questionnaire to give their overall assessment of the work environment in general.

RESULTS

A total of 59 subjects completed the entire survey procedure. Subjects were mostly students and faculty at the Blaustein Institutes for Desert Research, between the ages of 17 and 48 (average age 31), equally divided by gender and from diverse ethnic backgrounds. One third of the subjects wore glasses.

Effect of Tinted Glazing

The total number of surveys for clear and tinted glass was the same. Questionnaire findings indicated that installation of tinted glass improved overall satisfaction with the visual environment. However, as the mosaic plot in Figure 2 shows, in spite of much lower levels of illumination in the room, the majority of respondents (as indicated by the width of the two right-most bars) still rated the office as either 'very uncomfortable' or 'somewhat uncomfortable', irrespective of the type of glass (indicated by colour – red for clear and blue for tinted). The main contribution of the tinted glass appears to have been to mitigate the extreme condition somewhat: Only one third of subjects who rated the office very uncomfortable did so when tinted glass was installed – but almost 60% of those who rated the office 'somewhat uncomfortable' did so in spite of the presence of tinted glass.

The Daylight Glare Probability, estimated using digital HDR images of the test office with tinted glass, is significantly lower than for clear glazing (Figure 2, right). However, even though the reduction in the visible light transmission of the glazing is 40 percent, compared to the standard clear glazing used as a reference – the median value of the DGP index was still over 40%, indicating that close to half of the occupants would be likely to suffer from glare in such conditions. In other words: In luminous climates such as Israel, even very substantial reductions in the visible light flux are not, in themselves, sufficient to prevent glare.

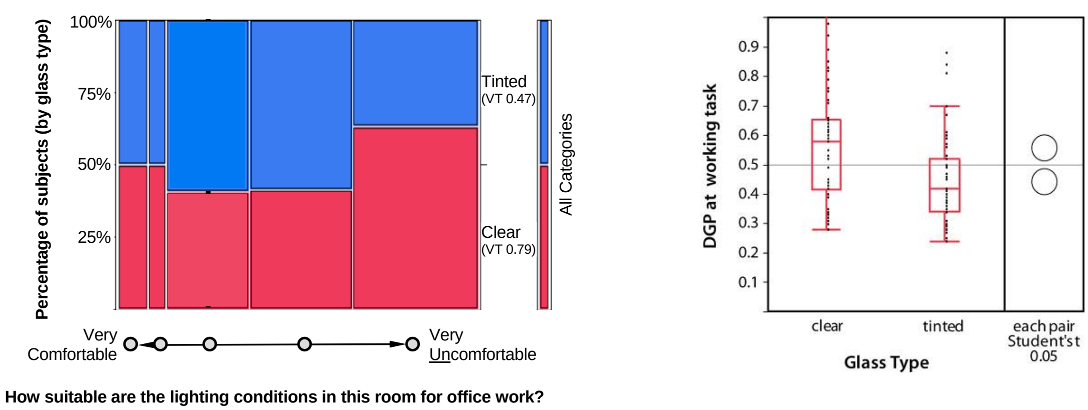

Figure 2 Effect of tinted glass on visual comfort responses of subjects. Left: Mosaic plot of subjective responses from questionnaires. Right: DGP predicted by analysis of luminance from HDR images of subjects' field of view when facing the computer display.

Effect of Venetian Blinds

Subjects were offered the option of deploying Venetian blinds either in conjunction with other light control means such as tinted glazing (with or without a light shelf) or as the only method of controlling exposure to daylight. The degree of exposure to daylight was determined by the subjects, who were allowed to deploy the blinds according to their personal preference, manipulating both the angle of the slats and the proportion of the window shaded (by lowering or raising them). After the position of the blinds was fixed by the subject, the illumination levels in the test room were measured by a technician, who then manipulated the position of the blinds in the reference room to obtain identical illumination levels throughout the room. The subjects were allowed to begin their evaluation of the specific configuration of blinds only after this calibration procedure was completed satisfactorily, and the full set of measurements could be carried out in the reference room.

The responses of the subjects who were allowed to deploy venetian blinds were in very good agreement with the predicted evaluation of the visual environment given by the DGP index. Analysis of the questionnaire indicated that when the venetian blinds were deployed, subjects were in fact almost always satisfied with the resulting visual environment, with only a very small proportion still rating conditions as either ‘somewhat uncomfortable’ or ‘very uncomfortable’ (Figure 3). Although the combination of tinted glass and venetian blinds was slightly more likely to produce ‘very comfortable’ conditions than Venetian blinds alone, the contribution of tinted glass to obtaining merely ‘comfortable’ conditions was negligible. Subjects who gave this evaluation were equally likely to have clear glass as tinted glazing.

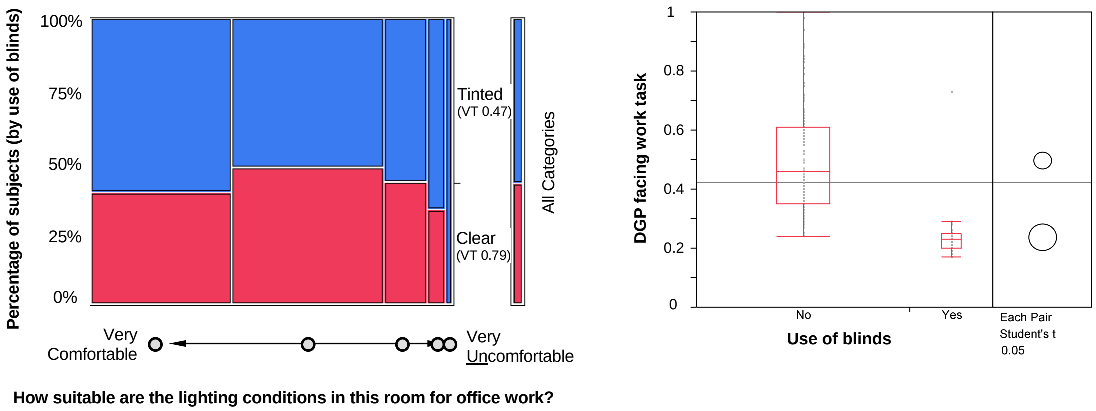

Figure 3 Effect of Venetian blinds in combination with clear or tinted glass on visual comfort responses of subjects. Left: Mosaic plot of subjective responses from questionnaires. Right: DGP predicted by analysis of luminance from HDR images of subjects' field of view when facing the computer display.

Effect of Light Shelf

The role of a light shelf is to redirect sunlight to modify its distribution in the room, and to provide partial shading in hot weather. The experiment evaluated the effect of a light shelf comprised of both an external element and an internal component on the light distribution in the room, with the venetian blinds either deployed or not. The subjects’ evaluation of the resulting illumination was recorded as part of the questionnaire they were asked to fill.

When the Venetian blinds were not deployed the light shelf reduced the light level on the desk significantly. In this mode, its primary role was as a shading device, blocking part of the direct sunlight impinging on the window. As Figure 4 (right) shows, the light shelf reduced median illumination in the room from over 13,000 lux to about 3,500 lux. However, in spite of the reduction in illumination caused by the light shelf, for much of the time light levels were still well above recommendations for visual comfort, both on the desk and on the computer display. Thus, although the light shelf reduced the probability for glare substantially, it by no means eliminated it: the median value of the DGP was 39%, compared to 57% with no light shelf. In sunny conditions when solar elevation is low enough to allow substantial penetration of direct sunlight, additional shading (such as blinds or curtains) may be required for the lower part of the window. When Venetian blinds were deployed, the primary role of the light shelf was to improve light distribution in the room, providing substantially higher levels of illumination in areas not adjacent to the window (Figure 4, left). More importantly, although the light shelf led to median light levels that were twice as high as for window equipped with Venetian blinds only, the probability for glare, as measured by the DGP indicator, remained very low.

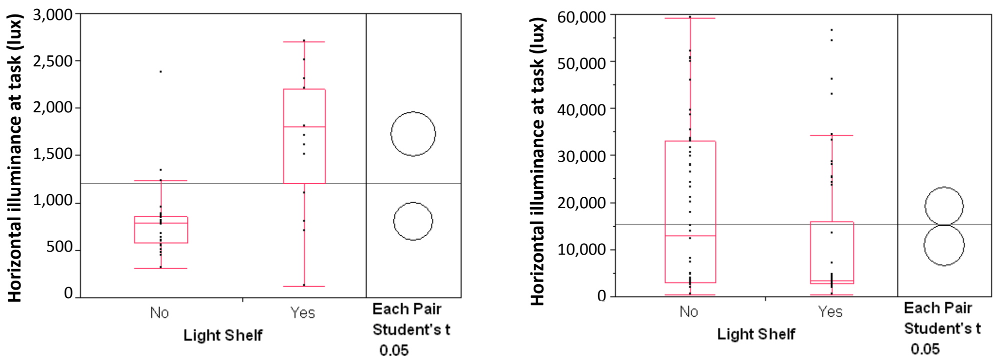

Figure 4 Effect of light shelf on horizontal illuminance of work surface. Left: with Venetian blinds deployed on view pane of window. Right: without blinds.

DISCUSSION AND CONCLUSIONS

The effect of tinted glazing on visual comfort was quite modest. The almost universal use of such glass in office buildings in sunny locations, and its wide application even in overcast ones, should not obscure the fact that even low levels of light transmission do not guarantee comfort.

Venetian blinds are known to be an effective means of controlling penetration of direct sunlight to the office interior, and the ease with which occupants can manipulate their position is a great advantage compared with most other forms of solar control. This suggests that if occupants of small offices take sufficient care in adjusting the position of the blinds, taking into account both the extent of deployment (or proportion of the window left fully exposed) and the angle of the slats – they can enjoy the benefits daylight without being exposed to glare. However, Venetian blinds are not a panacea: maintaining visual comfort with natural light requires frequent adjustment of the blinds in response to changing quantity and quality of external light: variations may be the result of changing weather or cloud cover, but also because the diurnal path of the sun that means a window may be illuminated by direct sunlight for only several hours of each day. The findings of a field survey (Erell and Kaftan, 2011) suggest, however, that such continuous adjustment is rarely carried out in practice. Furthermore, while work stations adjacent to the window may be well-served by Venetian blinds, work areas located further away might require artificial light if the blinds are deployed in response to conditions near the window. This is exacerbated if so-called 'solar control (tinted or reflective) glazing is installed to reduce overheating.

As this study has shown, having a light shelf is beneficial both when the venetian blinds are deployed, and when they are not. In the former case, they reduce illumination levels which might otherwise be excessive, thus reducing glare. In the second instance, they increase illumination levels, especially in parts of the interior not adjacent to the window – without increasing the probability for glare. A light shelf with blinds deployed below it provides high quality daylight: reducing glare in the working area adjacent to the window while enabling higher illuminance levels deeper in the office.

Therefore, a fundamental daylighting solution for buildings in sunny climates may consist of an upper daylight window, a lower view window, a light shelf, and daylighting control systems (such as blinds).

Although it is beyond the scope of the present paper, it may be noted that the experiment also demonstrated that the relation of the working position to the window also has a great bearing on visual comfort. The worst orientation is facing the window, whereas lighting from the side or diagonally results in less glare. However while the desk position may, on its own, mitigate glare to some extent, additional means such as daylighting control systems were still required in sunny conditions.

Daylighting design is frequently concerned with obtaining sufficient light, typically measured by metrics such as illuminance of a horizontal work surface or a daylight factor. These indicators ensure that a minimum level of natural light is obtained, contributing to health and alertness. However, these measures are insufficient when it comes to predicting visual comfort – which is better assessed by means of the Daylight Glare Probability. The calculation of this last metric requires detailed information and appropriate computer software, but demonstrated a very good correlation with subject responses in this experiment.

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REFERENCES

Belcher M. 1985. Cultural aspects of illuminance levels. Lighting Design and Application, 15(2):49-50.

Blanchard, C. 2005. Submission to the Energy Efficiency Inquiry, Australia.

Bodart M. and De Herde A. 2002. Global energy savings in office buildings by the use of daylighting. Energy and Buildings, 34:421-429.

Erell E., Etzion Y., Carlstrom N., Sandberg M., Molina J., Maestre I., Maldonado E., Leal V. and Gutschker O. 2004. SOLVENT: Development of a reversible solar-screen glazing system. Energy and Buildings, 36:468-480.

Erell E., Kaftan E. and Motzafi-Haller W. 2011. Daylighting for visual comfort and energy conservation in offices in sunny locations. Final research report to the Israel Ministry of National Infrastructures. (Partly in Hebrew)

Krarti M., Erickson P. and Hillman T. 2005. A simplified method to estimate energy savings of artificial lighting use from daylighting. Building and Environment, 40:747-754.

Majoros, A. 1998. Daylighting. PLEA International and Queensland University, Brisbane, 76 pp.

Osterhaus W. 2005. Discomfort glare assessment and prevention for daylight applications in office environments. Solar Energy 79:140-158.

Osterhaus W. and Bailey I. 1992. Large area glare sources and their effect on discomfort and visual performance at computer workstations. Proceedings of the IEE Industry Applications Society Annual Meeting, Houston, Texas 4-9 October, pp. 1825-1829, and LBNL Report No. 35037.

Veitch J. and Newsham G. 1996. Determinants of lighting quality II: Research and recommendations. Proceedings of the 104th Annual Convention of the American Psychological Association, Toronto, Canada.

Voss K., Herkel, S., Pfafferott, J., Löhnert, G. and Wagner A. 2005. Energy efficient office buildings with passive cooling – Results and experiences from a research and demonstration programme in Germany. Proceedings of the Conference on Passive and Low Energy Cooling of the Built Environment, Santorini, Greece.

Wienold, J. and Christoffersen, J. 2006. Evaluation methods and development of a new glare prediction model of daylight environments with the use of CCD cameras and RADIANCE, Energy and Buildings 38(7):743-757.