# A Data Collection Method for Long-Term Field Studies of Visual Comfort in Real-World Daylit Office Environments

DENIS FAN, BIRGIT PAINTER, JOHN MARDALJEVIC

Institute of Energy and Sustainable Development, De Montfort University, Leicester, United Kingdom

*ABSTRACT: With the current development towards increased daylighting in buildings and the related progress in daylight evaluation methods, real life monitoring data becomes an urgent need to better support our understanding of the link between daylight and visual comfort. A data collection methodology is presented that links the physical measurements, using luminance maps derived from High Dynamics Range images, with the collection of user perception data at office workstations. The methodology has been developed to facilitate long-term monitoring of visual comfort in real world working environments. The measurement setup represents a compromise, i.e. the measurement position is not as ideal as that in a laboratory environment, but nevertheless provides useful data for situations where the laboratory approach is not viable. It thus opens a wider range of environments for visual comfort studies.*
*Keywords: daylight; comfort; discomfort glare; data collection; HDR imaging techniques*

## INTRODUCTION

A major part of the carbon reduction strategy is to reduce the consumption of electrical energy in non-domestic buildings. Maximising the use of natural lighting is desirable as it can improve the energy efficiency by reducing the artificial lighting requirement. Furthermore, a good distribution of natural lighting may create a more pleasant office environment and improve the productivity and well-being of the occupants [1]. Although daylighting through windows can provide views and changes in light intensity and colour, which have been shown to support occupants' productivity, it can also cause visual discomfort by inducing glare. According to the Lighting Guide [2], glare is defined as a "Condition of vision in which there is discomfort or a reduction in the ability to see details or objects, caused by an unsuitable distribution or range of luminance, or to extreme contrast". The two main types of glare are disability and discomfort glare. Disability glare reduces a subject's ability to perceive the visual information needed for a particular activity. It is usually caused by light scattered within the eye, and is often a problem in office buildings with large glazing areas. Discomfort glare is distracting and uncomfortable, and is mainly caused by high or non-uniform distributions of brightness in the subject's field-of-view. Installing blinds, for example, can help to reduce glare but often results in the loss of daylight benefit as they may remain closed long after the glare condition has disappeared. Several equations and indices have been proposed as means of quantifying glare experienced by occupants in daylit environments. The Daylight Glare Index (DGI) [3] was accepted as a method for predicting glare conditions; the Unified Glare Rating (UGR) [4] and the New Daylight Glare Index ($DGI_N$) [5] were proposed to improve glare formulations for the use in daylight setting. However, most of them were derived from studies using artificial light sources, i.e. are based on conditions which were largely different to those experienced by occupants in real situations. Furthermore, the light sources used in these studies subtended relatively small solid angles from the viewpoint of the subject. The glare indices thus proved to be inadequate and unreliable for discomfort glare when applied to daylit environments [6, 7, 8]. Thus, while there are accepted formulations for the potential glare effect of uniform luminaires on the visual environment, it is recognised that glare from daylight sources is poorly understood. This is largely due to the lack of real life monitoring data, which should consist of physical measurements and qualitative data, so that new metrics can be developed that account for people's perception of the luminous conditions in daylit environments [10]. In order to address this issue, Wienold and Christoffersen [11] conducted a glare study that included fairly comprehensive monitoring of physical conditions and user perception for different window and shading arrangements in a laboratory environment. Based on these measurements, a promising new metric, the Daylight Glare Probability (DGP) has been developed. However, the study was carried out in controlled laboratory environments with subjects relocated and performing standardised tasks that were quite different from their workplace. Furthermore, the evaluation period

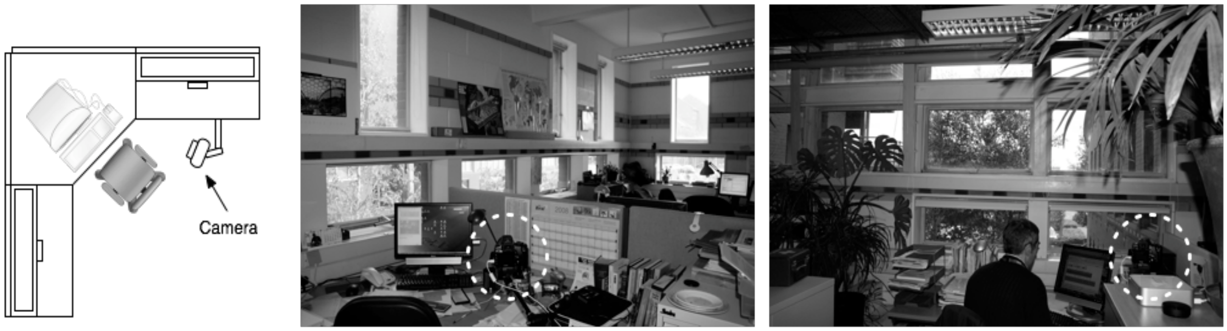



*Figure 1: A floor plan view of our proposed camera position and example pictures of where they are at the subjects' work desk.*

was short and therefore unlikely to capture seasonal variability in daylight conditions.

This paper presents a novel approach that allows long-term data collection of actual instances of daylight glare in a real life working environment. The approach links the quantitative measurement of physical conditions with the collection of qualitative values from the user perception at their work desks. The method is currently applied in a field study carried out at 5 workstations in an open-plan office in the predominantly daylit Queens Building at De Montfort University, Leicester, UK. Data collection in real world spaces has very specific limitations, which are different to those encountered in laboratory environments. The development of the method therefore included choosing compromise options that would allow the collection of useful data while ensuring that the method remained as simple as possible for practical application. Exploratory experiments were conducted to investigate the effect of the study design on measurement accuracy. This paper describes the study setup, outlining both qualitative and quantitative methods, the calibration procedure and an exploratory experiment carried out to assess the accuracy of the luminance measurements. The potential application areas of the method and the effect of the practical limitations on the derived data due to the real-world monitoring location are discussed.

## STUDY DESIGN

Since the monitoring process is being carried out in a real life working environment over a relatively long period, occupant interference must be kept to minimum to ensure that normal working conditions are maintained at all times. This requirement influenced both the design of the method for physical measurements as well as the capture of user perception data, as is outlined below. A further requirement was to automate the data collection method as much as possible in order to (1) ensure that qualitative and quantitative measurements were captured simultaneously and (2) to handle the large amounts of data that would be acquired in a medium to long-term field study.

**Luminance measurements** The luminance distribution at the subjects' workstations is measured using High Dynamic Range (HDR) imaging techniques. A digital camera with a fisheye lens is installed at each workstation, which captures a sequence of images at different exposures. These images are then combined into an HDR image that gives luminance values for each pixel in the scene. The HDR image contains the dynamic range of luminance conditions in a scene similar to what the human eye can see. The approach can accurately capture the wide range of intensity levels found in the field of view, ranging from direct sunlight to shadows. Each HDR image therefore provides a complete record of the magnitude and spatial variation of the luminance in the field-of-view, which represents a significant improvement over the traditionally used spot photometer. HDR imaging techniques have been demonstrated to be accurate with a 10% error margin for a wide range of conditions [12]. The camera was installed in an appropriate location in the subject's work area. Ideally, images of the exact field-of-view of the subject should be used, i.e. images taken from the exact sitting position of the subject, in order to ensure that the camera captures exactly the same visual environment that the subject sees. However, since it is impracticable to take such images without interfering with the subject's work, the camera has to be installed as closely as practicably possible to the subject's usual sitting position. Figure 1 illustrates a floor plan view of our proposed camera position near the subject's work desk, and two example pictures showing how this was realised at two workstations. The camera locations chosen for our field tests were typically within a distance of 30 to 50 centimetres and at an angle of 30 to 40 degrees from the subject's field-of-view position.

**Glare Survey** An on-screen, Java-based, survey was used to capture user feedback regarding the glare experienced when the HDR image was captured. In order to ensure that continuous data collection could be maintained with minimal interference of the subjects' work activities, the survey was designed to be very specific and thus only requires few mouse clicks to complete.

The survey form consists of five components: a pair of 'Yes/No' selection buttons asking if the subject is experiencing any discomfort glare at that moment; a glare scale with slider for marking the level of discomfort experienced; a field-of-view image of the subject's workstation on which they can draw a rectangle to indicate the main glare source; a comments box for additional observations or comments; and a 'Submit' button to exit the survey and send data to local machine.

If the subject indicates, by selecting the 'No' button, that he/she is not experiencing any glare, this is saved as user feedback data and physical measurements are triggered immediately to capture the 'no glare' conditions. If 'Yes' is selected, i.e. subject experiences glare, the remaining components of the survey form become active. The subjects are then asked to report the level of glare they are experiencing on the continuous scale shown in Figure 2, which ranges from 'imperceptible' to 'intolerable', as proposed by Osterhaus et al. [9]. The borderlines between the categories on the glare scale are defined as follows:

- Values below the 'noticeable' range of the scale apply if, having been asked, the user can see that there is some glare in his/her field-of-view, but it does not affect him/her at all.
- The borderline 'just noticeable' refers to lighting conditions which are uncomfortable but could be tolerated for the duration of a working day. If those conditions persisted longer, the user would attempt to remedy the situation.
- The borderline 'just disturbing' marks lighting conditions which the user could tolerate while completing the present task (for approximately 15 to 30 minutes). If those glare conditions persisted longer, however, the user would attempt to alter his/her working environment.
- The borderline 'just intolerable' refers to a luminous environment with extreme glare which the user cannot tolerate and in which he/she would require an immediate change of the lighting conditions in order to continue working.

The subjects are further asked to mark the glare source on the field-of-view image provided on the survey form. Subjects can add any additional information in the comment box at the bottom of the form, e.g. occurrence of unusual conditions, details of additional sources, information regarding the arrangement of shading devices and the use of artificial lighting.

**Data Collection Setup** The data collection framework consists of two main parts: the client and the server application (see Figure 3). The survey software is

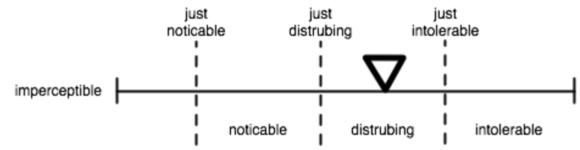
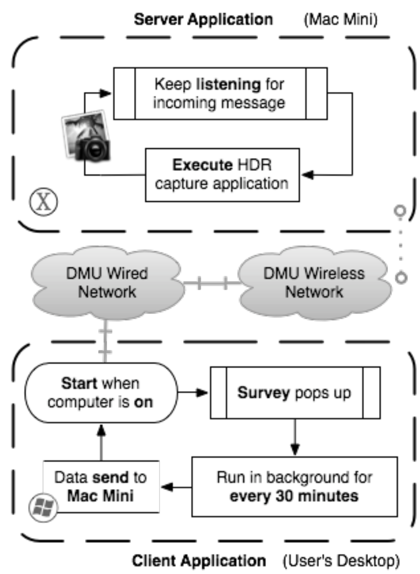



*Figure 2: Scale proposed by Osterhaus et al. [9] describing the degree of discomfort glare perceived by subjects.*

installed on the subjects' desktop (the client application), and run in the background when each machine is switched on. All tasks were scheduled automatically at a regular interval of 30 minutes during weekdays between 9 a.m. till 5 p.m. At the scheduled time a dialog box appears on the subject's computer screen, asking them to either continue immediately to the survey (Yes) or postpone it for 5 minutes (Later). If the subject chooses 'Yes' the survey loads onto the screen, or otherwise it will pop up again after 5 minutes. Alternatively, if glare conditions occur at any other time, the subject can launch the on-screen survey by clicking on a shortcut on their desktop.




After submitting the survey, the subject response data are sent to a wired network and then through a wireless network to a local machine (the server application) that has the digital camera connected to it. Once the local machine has received the survey data, the system activates the capture software to carry out the measurements using the HDR imaging method. At the end of each day during the monitoring period, survey data and HDR images are transferred to the main survey workstation through the wireless network for backup, calibration and analysis.

**Visual Comfort Field Study** Following the initial method development, during which the measurement setup was refined for individual workstations and the survey layout and timing was tested, a medium-term field study commenced in May 2008. Data has been collected for five workstations in a mainly daylit office environment. The workstations were chosen particularly because they have different layouts and thus present different lighting scenarios, ranging from desks with relatively small, distant glare sources to workstations located right next to large glazing areas, as shown in the examples in Figure 1. During the first six months of the study, subjects reported 292 occurrences of glare. Data analysis will focus on extracting luminance values form the HDR images captured at these instances and link them to the user response data. Since the current study is based on a small initial sample, both in terms of the number of daylight scenarios studied as well as the diversity of the subjects in terms of age, gender etc, it is not expected to derive a full comprehensive data set from this initial study. The method will be applied in other work environments and with subjects from a wider range of demographic groups to add to the data set.

## ACCURACY OF THE MEASUREMENT METHOD

**HDR Calibration** Several calibration operations are required as pre-processing steps prior to the use of HDR images in the data analysis [12]. These procedures are summarised in the systematic diagram shown in Figure 4. A set of low dynamic range (LDR) images was taken over an appropriate exposure range to capture the luminance variation within the scene. The camera response function is computationally derived through a self-calibration process from the multiple exposure images [13], and fused into a single HDR image.

In order to improve the accuracy of the HDR method, the HDR image can be calibrated against physical measurements (e.g. from a spot photometer). The calibration factor is determined by dividing the average luminance of a selected region from the HDR image by the spot measurement value of the same region. Applying such factor to HDR images has proved to be vital particularly for high dynamic range scenes such as daylit and sunlit interiors and exterior environments [12].

Camera images generally show a radial falloff of pixel values from the centre of the image. This artefact, prevalent in photography, is known as 'vignetting'. Particularly when using a wide-angle or fisheye lens, a noticeable vignetting effect occurs for pixels far from the optical axis. It is therefore necessary to correct this distortion. We transformed the distortion into a mathematical function and employed an approach, similar to the technique described by Jacobs and Wilson [14]. The ratios of luminance value of the images tilting at different angles were measured, and the vignetting function was estimated according to a forth order polynomial fit. Figure 5 illustrates the equipment setup for estimating the vignetting function. The derived vignetting filter (Figure 5c) was used to correct the vignetting effect by multiplying it across the images.

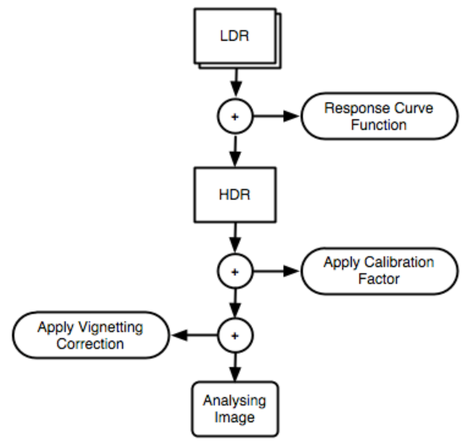



*Figure 4: A systematic diagram showing essential steps for calibrating HDR image.*

**Effect of Camera Position** As outlined above, the digital camera used for HDR luminance measurements cannot be located in the ideal position, i.e. it will not capture the subject's field-of-view exactly. Instead, the camera has to be located as close as possible to the field-of-view position but in a position where it does not interfere unacceptably with the subject's work activities. However, any deviation from the field-of-view position inevitably introduces a certain level of inaccuracy into the measured data, i.e. what the subject sees is different to the scene the camera captures.

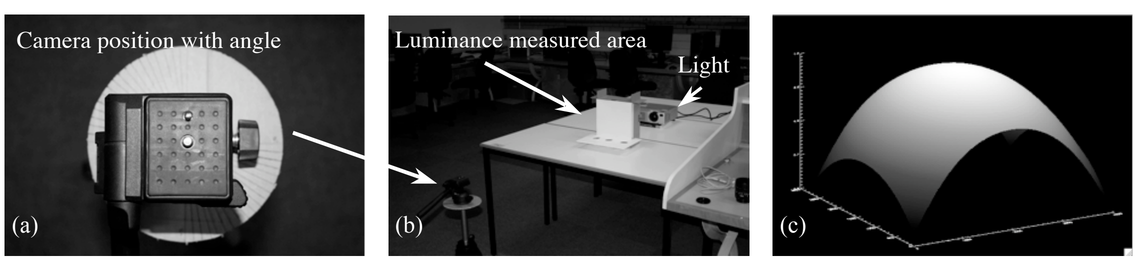



*Figure 5: Equipment setup for estimating the vignetting function (a) and (b), and estimation result (c) for correcting the vignetting effect of the images.*

In order to investigate the effect of deviation from the field-of-view position on HDR measurements, an experiment was carried out in a controlled environment to explore the variation of HDR images taken from different camera positions against the HDR images taken exactly from a subject's field-of-view. Both, deviations in angle and distance from the subject's position were investigated. The experiment was carried out in a basic office room with one window (Figure 6a). The subject's work desk was set 170 cm away from the window and a monitor was installed on it. Two cameras were used to simultaneous capture HDR luminance data. One camera (A) was mounted at the field-of-view position at 120 cm above the floor (see Figure 6b), and was assumed to be the subject's head position. The second camera (B) was positioned further away from the field-of-view position, at varying distances and angles. Both cameras were aimed at the same viewpoint when HDR measurements were taken. For example, Figure 6c illustrates the camera setup when the angle of the camera position (Camera Set B) was modified.

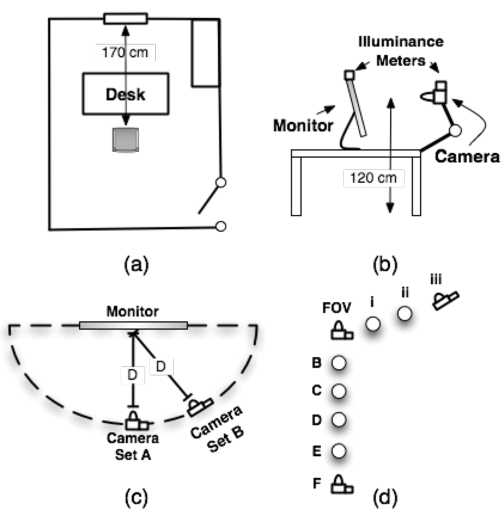



*Figure 6: Experiment setup in controlled office block: (a) floor plan view; (b) side view of subject's work desk; (c) camera pairs setup; and (d) Angles and distance parameters layout.*

As illustrated in Figure 6d, either the distance of camera B in relation to camera A was altered or the angle. This means that when we set the position of camera B by changing its angle against camera A, the distance between both cameras and the monitor remained constant. Similarly, the angle remained fixed when the distance between camera A and camera B was altered. Settings ranged from 23 cm to 118 cm for distance (B-F) and 15˚ to 45˚ for angle difference (i-iii). For each setting HDR images were captured simultaneously with both cameras. The measurements were conducted under overcast sky conditions around midday. Window luminance values during the experiment ranged from approximately 1000 to 3600 cd/m$^2$. Six measurement 'patches' were selected (Figure 7) in the field-of-view scene and luminance values were compared for each image pair, that is the image taken from the field-of-view position (A) and the image taken from the modified camera position (B). Absolute relative errors were calculated for the deviation of the average patch luminance in the image captured with camera B from that in the field-of-view image (A). For example, Figure

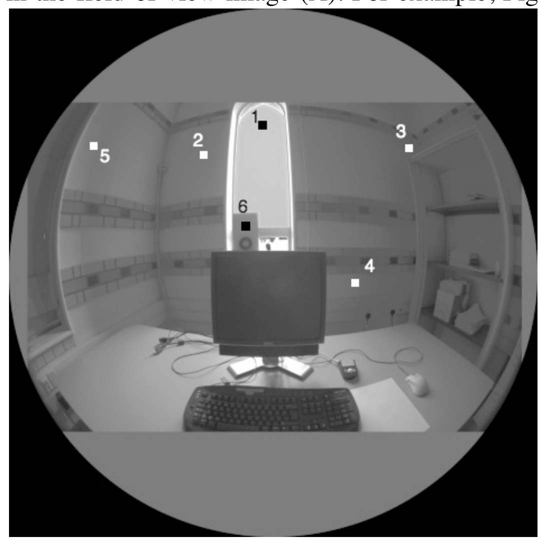



*Figure 7: A field-of-view image showing the scene of the experiment and patch locations for luminance assessment.*

8 shows the effect of the camera position dependent on the deviation of the angle of camera B from the field-of-view position for the six patches. As would be expected, the relative errors increased when the angle of the camera B against the field-of-view position increased. The relative errors were generally low (below 25%) across all the patches. The performance is clearly better for smaller angles but errors increased up to 36% for the measurement patch located right inside the glare source. However, these results indicate that the orientation difference does not introduce considerable errors in terms of the luminance variation of the scene for camera positions that only have small angle deviations from the subject's field-of-view position. When camera B was placed at different distances from the field-of-view position, the results did not show a clear pattern of the effect of the camera position. Average relative errors observed were similar to those for the angle dependency, i.e. generally below 20%. These results are encouraging. They indicate that the errors introduced by measuring close to, but not directly, at the field-of-view position are relatively small for angle deviations that are practical in long-term field studies. For example, suitable (i.e. minimally intrusive) camera positions could be found for the workstations in our study that were typically around 30° from the subjects' field-of-view. However, these exploratory measurements were carried out under overcast sky conditions only. Further experiments under clear sky conditions are required since distance and angle

dependence is likely to have a stronger effect on situations with direct sun. Moreover, the effects of the camera position on measurement errors are strongly scenario dependent. It is therefore envisaged to carry out similar experiments for more complex workstation setups, e.g. including different window sizes and positions plus scenarios with multiple windows.

## DISCUSSION AND CONCLUSION

The use of HDR imaging techniques for physical measurements, together with the capture of user perception data, has enabled us to develop a new data collection method to monitor visual discomfort in real life working environment. This method allows the collection of quantitative and qualitative visual comfort data at relatively high frequency and over longer time periods, which has not been possible using the traditional spot measurement techniques.

In our view, it is essential to keep with the subjects' work activities to a minimum while the monitoring equipment was deployed. Feedbacks from the pilot study have shown that subjects were generally satisfied with minimal interference. It is acknowledged that the limitations in the camera position (i.e. measurement position offset from the subject's field-of-view) have some effect on the accuracy of the measurements. However, this is a problem inherent to all glare studies that measure both qualitative and quantitative data, due to the dependence of glare perception on the location of the glare source. One option is to apply Wienold and Christoffersen's approach [11], who used two virtually identical laboratory rooms, one where the subject is located and one for physical measurements. However, this restricts measurements to a limited range of scenarios. If the aim is to investigate people's glare perception in their normal work environment, i.e. non-controlled desk setup and unstandardised tasks, a method is needed that can be scaled up and deployed in different working environments. Our method uses off-the-shelf technology and a basic network setup, which makes it flexible enough to be set up at new workstations or in other office buildings within a short amount of time. It thus opens a wider range of environments for visual comfort studies.

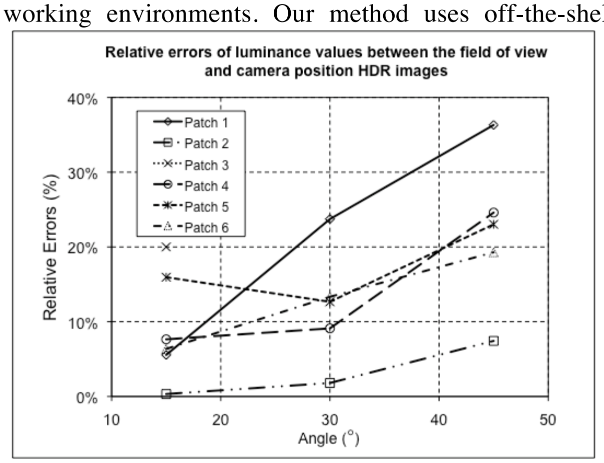



*Figure 8: The effect of the camera position dependent on the deviation of the angle.*

It is envisaged to apply the method introduced here to studies of other working environments, and using subjects from other demographic groups, in order to expand the data set from our initial field study. The aim is to use the data to validate existing glare indices and to potentially develop a new glare metric for visual comfort perception in daylit environments.

## REFERENCES

1. CIBSE, "Energy Efficiency in Buildings," CIBSE Guide F, The Chartered Institution of Building Services Engineers, 2004.
2. SLL, "Lighting Guide 7: Office Lighting," The Society of Light and Lighting, The Chartered Institution of Building Services Engineers, 2002.
3. R. G. Hopkinson, "Glare from daylighting in buildings," *Applied Ergonomics,* vol. 4, 1972.
4. CIE, "Discomfort Glare in the Interior Lighting," *Technical Committe TC-3.13, Division 4, Interior Environment and Lighting Design,* 1992.
5. A. A. Nazzal, "A new daylight glare evaluation method: Introduction of the monitoring protocol and calculation method," *Energy and Buildings,* vol. 33, pp. 257-265, 2001.
6. P. Chauvel, R. Collins, R. Dogniaux, and J. Longmore, "Glare from windows: current views of the problem," *Lighting Research and Technology,* vol. 14, pp. 31-46, 1982.
7. T. Iwata, M. Tokura, M. Shukuya, and K.-i. Kimura, "Experimental study on discomfort glare caused by windows," *International Journal of Architecture,* vol. 439, pp. 19-31, 1992.
8. A. D. Galasiu and J. A. Veitch, "Occupant preferences and satisfaction with the luminous environment and control systems in daylit offices: a literature review," *Energy and Buildings,* vol. 38, pp. 728-742, 2006.
9. W. K. E. Osterhaus and Ian L. Baileyt, "Large area glare sources and their effect on discomfort and visual performance at computer workstations" *Report LBL-35037 UC-350,* Lawrence Berkeley National Laboratory, Berkeley, California, USA, 1992.
10. W. K. E. Osterhaus, "Discomfort glare assessment and prevention for daylight applications in office environments," *Solar Energy,* vol. 79, pp. 140-158, 2005.
11. J. Wienold and J. Christoffersen, "Evaluation methods and development of a new glare prediction model for daylight environments with the use of CCD cameras," *Energy and Buildings,* vol. 38, pp. 743-757, 2006.
12. M. Inanici, "Per-pixel lighting data analysis," Technical Report, Ernest Orlando Lawrence Berkeley National Laboratory, Berkeley, U.S.A. 2005.
13. E. Reinhard, G. Ward, S. Pattanaik, and P. Debevec, "HDR Image Capture," in *High Dynamic Range Imaging: Acquisition, Display, and Image-Based Lighting*: Morgan Kaufmann, 2005.
14. A. Jacobs and M. Wilson, "Determining Lens Vignetting with HDR Techniques," in *Bulgarian National Lighting Conference* Varna, 2007.