İSTANBUL TECHNICAL UNIVERSITY ★ INSTITUTE OF SCIENCE AND TECHNOLOGY

VALIDATION OF THE USE OF HIGH DYNAMIC RANGE IMAGES AND DISPLAYS IN LIGHTING RESEARCH AND LIGHTING DESIGN

PhD Thesis by
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Department : Electrical Engineering

Programme : Electrical Engineering

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İSTANBUL TEKNİK ÜNİVERSİTESİ ★ FEN BİLİMLERİ ENSTİTÜSÜ

YÜKSEK DİNAMİK ÖLÇEKLİ FOTOĞRAFLARIN VE MONİTÖRLERİN AYDINLATMA ARAŞTIRMA PROJELERİ VE AYDINLATMA TASARIMINDA KULLANIMININ ONAYLANMASI

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FOREWORD

Hard to imagine, I have been a student for 25 years and the past 5 ½ years of my life has been spent pursuing the completion of the thesis you are holding. There are many people who have been with me on this long journey to whom I would like to express my warm regards.

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Very special thanks to my husband Alan, for his patience and support in the completion of my dissertation.

This dissertation is dedicated to my parents and my sister…

Ottawa, October 2009

Duygu Çetegen-Morewood

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ABBREVIATIONS

HDR	**:** High Dynamic Range
DO	**:** desk+open
DO-m	**:** desk+open-with neighbour
DT	**:** desk+tilted
DT-m	**:** desk+tilted-with neighbour
DC	**:** desk+closed
DC-m	**:** desk+closed-with neighbour
SPO	**:** seated privacy-open
SPO-m	**:** seated privacy-open-with neighbour
SPT	**:** seated privacy-tilted
SPT-m	**:** seated privacy-tilted-with neighbour
SPC	**:** seated privacy-closed
SPC-m	**:** seated privacy-closed-with neighbour
SP+O	**:** seated privacy+open
SP+O-m	**:** seated privacy+open-with neighbour
SP+T	**:** seated privacy+tilted
SP+T-m	**:** seated privacy+tilted-with neighbour
SP+C	**:** seated privacy+closed
SP+C-m	**:** seated privacy+closed-with neighbour
StPT	**:** standing privacy-tilted
HT	**:** hybrid-tilted
TL	**:** three layers

Note: please find thumbnails for scenes DH – TL in Figure 3.1

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VALIDATION OF THE USE OF HIGH DYNAMIC RANGE IMAGES AND DISPLAYS IN LIGHTING RESEARCH AND LIGHTING DESIGN

SUMMARY

The main goal of this dissertation is to show that a High Dynamic Range (HDR) display can be used in the study of lighting engineering problems, and as a tool in the lighting design process to enhance communications between lighting designers and their clients.

Printed photographs, renderings or images displayed on conventional cathode-ray tube (CRT) or liquid-crystal display (LCD) monitors do not represent the spaces in realistic luminances. Calibrated HDR images contain luminance information from the real space, but current LCD monitors cannot present luminances as high as the luminances encountered in the real world. Therefore these sources do not provide enough information to make accurate judgements of light and shade in the lighting design process. The HDR display used in this study could display luminances up to 4000 cd/m^2 and overcame these problems. This research shows that the HDR method may be used as a surrogate for experiencing a real space to investigate lighting engineering problems both for research and the design process.

The first experiment was designed to investigate the hypothesis that HDR images on an HDR screen would be perceived as more realistic than conventional images displayed on conventional LCD displays. Extensive luminance measurements were conducted using a spot luminance meter and a luminance camera to facilitate accurate reproduction of real space luminances of six scenes (corridor, gym, mezzanine, lobby, open-plan office, staircase) on the HDR display. Thirty-nine participants viewed six scenes in three modes: the real scenes (observing real spaces in the building), single exposure photographs of the scenes shown in conventional mode (screen resolution and luminance of HDR display adjusted to that of a conventional LCD display), and the HDR photographs shown in HDR mode (capable of luminances as high as 4000 cd/m^2 and 2^{16} distinct luminance levels). Half of the participants visited the real spaces first, and the other half saw the digital images first. For each presentation (real and digital

images), participants rated what they saw on four semantic differential scales: dim — bright; non-uniform — uniform; unpleasant — pleasant; glaring — not glaring. Participants then viewed the six digital image pairs again, and recorded whether the HDR or conventional image was more realistic. This experiment demonstrated that HDR images presented on an HDR display are rated as significantly more realistic than conventional computer images.

The second experiment demonstrated the use of HDR images as a research tool. The experiment focused on the relationship between scene characteristics (average luminance, luminance variability and view size) and space appearance judgements. Twenty-one scenes were created, each scene being the view from an interior cubicle across one cubicle to the exterior wall. The scenes varied in terms of the cubicle panels, window blind setting, and presence or absence of a neighbour in the adjacent cubicle. Extensive luminance measurements were conducted. Sets of bracketed images were taken for each of the 21 scenes, and then these images were combined into HDR images using the software Photosphere. The calibrated HDR images were shown on an HDR display at realistic luminances to 43 participants. The participants rated each scene on 8 scales. The average ratings for each image were plotted against the average luminance, luminance variability and relative view size for that image. The second experiment of the dissertation supported the hypothesis that as panel height in an open office gets lower, ratings for satisfaction with lighting increase, and ratings for privacy decrease. As the view size increased, ratings for satisfaction with lighting and amount of view increased. Regarding satisfaction with privacy, Hybrid (one fabric and one glass stack-on on the second panel) performed as well as Standing Privacy (two fabric stack-ons on the second panel), and regarding satisfaction with view and satisfaction with lighting, Hybrid performed better than Standing Privacy.

The results imply that HDR displays may be successfully applied in the lighting design process. Even before a building exists, looking at good rendering of the spaces may be useful in the decision making process. Both experiments show that people can respond to HDR images in the same way as they would respond to the real space, given that the results of both experiments are consistent with what is already known from studies of images (Newsham et al., 2005) and in real spaces (Loe et al., 1994).

YÜKSEK DİNAMİK ÖLÇEKLİ FOTOĞRAFLARIN VE MONİTÖRLERİN AYDINLATMA ARAŞTIRMA PROJELERİ VE AYDINLATMA TASARIMINDA KULLANIMININ ONAYLANMASI

ÖZET

Bu tezin amacı, Yüksek Dinamik Ölçekli (YDÖ) monitörün aydınlatma mühendisliği problemlerinin çözümünde ve aydınlatma tasarım sürecinde tasarımcı ile müşteriler arasındaki iletişimi kuvvetlendirmek amacıyla kullanılabilirliğini göstermektir.

Tezde sunulan ilk deney, YDÖ monitorde görüntülenen YDÖ fotoğrafların, LCD ekranlarda görüntülenen (tek pozlamadan oluşan) geleneksel fotoğraflardan daha gerçekçi olacakları hipotezi üzerine tasarlanmıştır. Noktasal ölçüm yapabilen bir parıltı ölçer ve parıltı kamerası ile detaylı parıltı ölçümleri yapılarak, altı adet gerçek hacmin (koridor, spor salonu, deney laboratuarı, lobi, ofis, merdiven boşluğu) parıltı değerleri, YDÖ ekrana yansıtılmıştır. Otuzdokuz adet denek altı sahnenin görüntülerini üç farklı ortamda değerlendirmişlerdir: gerçek hacim (bina içindeki gerçek hacimleri gözlemleyerek), hacimlerin tek pozlama ile çekilen fotoğraflarının geleneksel yöntemle LCD ekran üzerindeki görüntüsü, ve YDÖ fotoğrafların YDÖ ekran (2^{16} farklı parıltı seviyesiyle parıltı değerleri 4000 cd/m^2 ye dek çıkabilen ekran) üzerindeki görüntüsü. Deneklerin yarısı ilk olarak gerçek hacimleri, diğer yarısı da öncelikli olarak dijital fotoğrafları, her sahneyi dört farklı sıfat çiftini baz alarak değerlendirmişlerdir: loş – aydınlık, tekdüze – değişken, hoş – hoş olmayan, kamaşmaya neden olan – kamaşmaya neden olmayan. Denekler daha sonra altı fotoğraf çiftini tekrar görüp, YDÖ fotoğrafın mı geleneksel fotoğrafın mı gerçeği daha iyi yansıttığına ilişkin görüşlerini belirtmişlerdir. Deney sonuçları YDÖ fotoğraf tekniği ile üretilen fotoğrafların YDÖ ekrandaki görüntülerinin, LCD ekranda görüntülenen geleneksel fotoğraflardan daha gerçekçi algılandığını göstermiştir.

Tezde sunulan ikinci deney, YDÖ fotoğraf tekniğinin bir araştırma projesi kapsamında kullanılmasını içermektedir. Deney, görüntü karakteristikleri ile (ortalama parıltı, parıltı değişkenliği ve manzara büyüklüğü), hacmin görüntüsüne ilişkin değerlendirmeler arasındaki ilişkiyi incelemiştir. Aynı ofis hacmi içerisinde yirmibir adet sahne

oluşturulup, pencereye duvarı yönünde bakan ve bir diğer ofisi gören çalışanın bakış açısına göre fotoğraflanmıştır. Görüntüler paravan yüksekliği, pencere jaluzi açısı ve bir komşu çalışanın olup olmamasına göre çeşitlilik göstermektedir. Detaylı olarak parıltı ölçümleri yapılmıştır. Toplam yirmibir sahne için fotoğraflar çekilmiş, sonrasında bu fotoğraflardan faydalanılarak Photosphere adındaki yazılım aracılığıyla YDÖ fotoğraflar elde edilmiştir. Kalibre edilen YDÖ fotoğraflar gerçeği yansıtan parıltı değerleriyle YDÖ ekranda görüntülenmiş ve 43 adet deneğin değerlendirmesine sunulmuştur. Denekler her görüntüyü, ortalama parıltı, parıltı değişkenliği ve dış manzara büyüklüğüne bağlı olarak, sekiz skalada değerlendirmişlerdir. Bu çalışmanın sonuçları, paravan yüksekliği azaldıkça aydınlatma memnuniyetinin arttığı ve kişisel mahremiyet memnuniyetinin azaldığı hipotezini doğrulamıştır. Manzara büyüklüğüyle doğru orantılı olarak, aydınlatma ve kullanıcıya sağlanan manzara memnuniyeti artmıştır. Kişisel mahremiyet memnuniyetine ilişkin değerlendirmelere göre, kullanıcıya %25 oranında görüntü sağlayan system, aydınlatma memnuniyetinde düşüşe sebep olmadan, kullanıcıya %50 görüntü sağlayan sistemden daha yüksek mahremiyet memnuniyeti sunmuştur.

Çalışmanın sonuçları, YDÖ ekranın aydınlatma araştırma-geliştirme projelerinde ve aydınlatma tasarım sürecinde kullanılabileceğini göstermektedir. Henüz inşa edilmemiş binaların grafik simulasyonlarının, öngörülen gerçek hacim parıltı değerleriyle görüntülenmesi, aydınlatma projesine ilişkin kararların alındığı aşamada faydalı olacaktır. YDÖ fotoğrafların kullanıldığı deney sonuçlarının literatürdeki çalışmaların sonuçları ile tutarlı olması, YDÖ teknolojisinin aydınlatma mühendisliği problemlerinin çözümünde kullanılmasının güvenilirliğini arttırmaktadır.

1. INTRODUCTION AND LITERATURE REVIEW

This chapter gives information on the research problem, motivation and scope of the study. A background is also provided for the lighting design process, images as part of design, importance of occupant behaviour in energy consumption and lighting and High Dynamic Range (HDR) technology.

1.1 Research Problem

The aim of the lighting design is to provide the occupants a secure, productive and pleasing built environment. Light gives both visual and emotional shape to an environment by using bright and dim areas in coordination with the colour rendering of the light sources. A suitable amount of light should be provided, taking cost, energy and maintenance into consideration parallel to the requirements of the function of the space.

When there is a lighting problem, either illuminating a new space or fixing an existing lighting problem, the client consults the lighting designer. Usually the client is a lay person and needs guidance to visualize the ambiance of the space with the proposed lighting installation. Effective communication between the designer and the client is crucial to meet the requirements of the client and to solve the problem.

In addition, there is a problem for researchers needing to present realistic stimuli to participants, either of lighting designs that do not exist yet or of conditions that are not stable over a long enough time for the study to be completed. Just as for the lighting designer, there's a need for researchers to have a validated tool to further their understanding of how people respond to lit environments.

Photographs of lighting installations and design sketches can be used during presentations to demonstrate the ideas to clients and end users. Photographs, however, do not give much information about luminance levels and whether glare was a problem for the occupants for a particular design. The designer may create sketches to illustrate ideas with the intention to demonstrate the contrast (e.g. bright and dim surfaces), however sketches do not provide luminance information. High Dynamic Range (HDR) images would be useful to designers and clients to facilitate communication of the design results and any proposed changes. Tools like the HDR display are needed to give a more realistic impression.

1.2 Motivation and the Scope of the Study

Information in HDR images cannot be fully reproduced visually on current cathode-ray tubes (CRT) or newer liquid-crystal displays (LCDs). A conventional LCD monitor on the market in 2009 can present luminances up to ~ 300 cd/m^2, with 1000 distinct luminance levels. HDR display technology overcomes these limitations. In this device the uniform backlight of a conventional LCD screen is replaced by an array of white light emitting diodes (LEDs), each of which is approximately 5 mm in diameter. The image is backlit by a low-resolution version of the same image formed on the LED array (Figure 1.1). The output of the LED array can reach very high luminances. When these two layers are combined, with correct settings of the parameters of the display, an image is presented with high luminance values and contrast ratios similar to the

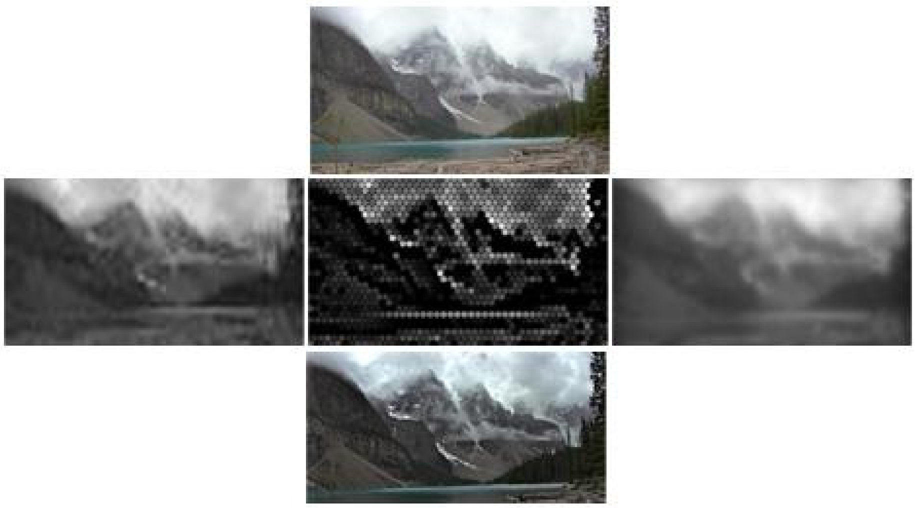


Figure 1.1: Original image, target backlight, deriving LED intensities, backlight simulation and the resulting image (Images with courtesy of UBC).

levels in the real environment. The HDR display that was used in this study can display luminances up to 4000 cd/m^2.

Rendering is the process of generating an image of an architectural space by using computer programs (e.g. Radiance, Cad, AccuRender, Lightscape). Renderings contain geometry, viewpoint, texture, lighting and shading information. One would expect renderings displayed on the HDR monitor to look more real than those on a conventional monitor because they can include a wider range of luminance values and more distinct levels.

The benefits of using this system can be summarized as follows:

- Lighting designers may visualize their design more effectively; as a result the communications between the designer and clients will improve,
- Electrical engineers may use this tool to show their clients what a lighting installation will look like,
- Researchers may benefit from this tool to study psychophysical responses to the lit environment.

The validation of the use of HDR display technology in lighting involved two stages:

1. Perceptions of HDR images were compared to both reality and to conventional images (it was expect that HDR would be more like reality than conventional images).
2. Lighting quality perception was tested using an HDR display in an experiment which included images of an office with some daylight; a window looking out into the campus lawn with trees. The results compare well to the lighting quality literature where real spaces were viewed.

Chapter 1 summarizes the lighting design process, introduces how the HDR method may enhance this process, and reviews the literature in this context. Detailed literature reviews relevant to the two experiments are in chapters 2 and 3, respectively. Chapter 2 describes the experiment comparing the ratings of the visual appearance of real spaces to conventional and HDR images of the same spaces, gives details of the research method and procedure, stimuli and dependent measures; compares the results, and discusses and gives comments on the results (A version of the material in

Chapter 2 is to be published in the journal *ACM Transactions in Applied Perception* [Newsham, Cetegen, Veitch, & Whitehead, in press]). Chapter 3 is dedicated to the experiment investigating the relation of view size and office luminance effects on satisfaction with lighting, explains the reasoning of the method referring to the previous chapter, provides data collection methods and procedure, data analysis plan, results of bracketed effects, full factorial MANOVA results and correlations between image characteristics and ratings, discusses these findings and gives comments on the results (A version of the material in Chapter 3 was presented at the BalkanLight 2008 conference [Cetegen, Veitch, & Newsham, 2008]). Chapter 4 is the overall discussion of the study.

1.3 Lighting Design Process

Lighting design requires making ingenious and functional decisions systematically based on the characteristics of the space and the requirements of the client. The aim of the lighting design is to present the occupants a safe, productive and pleasant built environment. The purpose of the lighting system, cost of setting up and energy requirements of the system and maintenance are the key parameters of a lighting design project (Rea, 2000).

The stages of an ideal lighting design project are (Rea, 1993):

- Programming
- Schematic design
- Design development
- Contract documents
- Bidding and negotiation
- Construction
- Post-occupancy evaluation

1.3.1 Programming

At this initial stage of the project, information is collected regarding occupant and client requirements, constraints, and design objectives including maintenance, flexibility and budget. The function of the space and its architectural style give an overview of the issues. The age of the occupants, the characteristics, length and significance of the tasks to be executed, and period of occupancy during the day and year is valuable information to determine visual and perception needs. Security concerns including personal safety and dangerous conditions (i.e. spinning parts of machines) should be raised at this stage of design. Architectural restrictions and possibilities including ceiling heights, type of ceiling, window and skylight position and orientations should be examined. Construction and safety codes are verified; electrical system requirements regarding circuit capacities, lighting control approaches and appropriate locations are checked. Analysis of daylight availability and night illuminance conditions are studied given the architectural features. Energy code requirements are now a crucial part of the design process. The programming stage is completed after reviewing the budget, which includes initial, maintenance and energy cost.

1.3.2 Schematic Design (Developing the Lighting Concept)

At this stage the link between lighting and specific necessities of the space is considered based on the occupants and function of the space. At this stage, the designer considers how to deliver the necessary light to the various surfaces in the room, delivering the right amount for the various tasks and occupants. Depending on the job, visual task locations are either on the horizontal or vertical plane and they are illuminated with task lighting at a higher luminance than ambient luminance. The importance of colour rendering of the light source is evaluated and how closely the light sources will match daylight is assessed. The location of the controls, occupancy sensors, and energy management system data-loggers will also be decided at this stage. Although the design is not yet refined at this point, images (mostly sketches) are used to communicate the scheme to the client.

1.3.3 Design Development

This is the design conceptualization stage. Ideas developed during the schematic phase are refined and made more precise. Site visits or reviewing photographs of previous lighting solutions are recommended to establish notions. The lighting calculations are completed and the ambiance created in the space is evaluated; for instance, the character of office lighting will be different than the mood in a gourmet restaurant. Photographs, however, do not give much information about luminance levels and whether glare was a problem for the occupants for a particular design. The designer may create sketches to illustrate ideas. Although the idea of these lighting sketches is to demonstrate the contrast (e.g. bright and dim surfaces), they do not provide luminance information either. Photographs of similar installations, journal photographs and design sketches can be used during presentations to demonstrate the ideas to clients and end users.

When working on the design concept, an approach is to see the space as a box with surfaces inside, i.e. desktops, walls, ceiling and floor, waiting to be painted with light. While providing enough task light is necessary, architectural design features may be highlighted to show the character of the space.

After deciding on the lighting model (which surfaces to illuminate), direction of light and distribution of light in the space is considered; photometric data of luminaires and characteristics of light sources are examined, and then light sources and luminaires are chosen. Light may be emitted from a luminaire in a directional beam or in diffused form; from a point source, linear source or area source. The luminaire may be hidden in the ceiling, suspended from the ceiling or mounted on the wall. Although lighting designers and illuminating engineers have the expertise and experience to conceptualize how the the space will look with one luminaire or another in place, clients generally do not. Designers need ways to communicate their design recommendations to their clients, who must make the final choices.

At this stage the goals and restrictions of the project are re-evaluated to meet design objectives. Documentation begins in this design phase. Detailed images of luminaires and mounting details are given. Lighting and energy consumption computations are detailed, exact luminaire locations (including dimensions and space between luminaires) are listed.

Some other design development considerations are: how well the lighting system will coordinate with other building systems; how the lighting system will combine with furniture (i.e., “Do the luminaire locations coordinate with the panel layout in an open-plan office?”); how the lighting system will be maintained (i.e., “How often will the lamps be changed?”, “Are they easy to reach?”) and the availability of the products in relation to project deadlines. At the end of design development, before proceeding with the contract documents, the client is expected to provide feedback and approve the final design. If the communication between the designer and the client is not clear, instead of solving the existing problem, other problems may arise. At this stage of lighting design using HDR technology can be really useful, especially if used with good renderings (Figure 1.2). HDR images would be useful to designers and clients to facilitate communication of the design results, and any proposed changes, more accurately than previous image formats.

Figure 1.2: Renderings of a meeting room and an office.

The lighting designer would benefit from the use of HDR images when explaining the lighting design to clients and asking them to visualize the results. Furthermore, HDR technology would enable the designers themselves to examine the space from different viewpoints. For instance, in order to examine a particular light source in a corner and whether it would cause glare for a relatively short person, HDR technology would provide valuable visual information unavailable using a non-HDR screen.

1.3.4 Contract Documents

At this stage crystal clear documents are prepared for the electrical contractor to make an offer for the project, order the lighting and control systems and set up the lighting system without causing incompatibility issues with the rest of the building systems. Lighting design documents include:

- Lighting requirements listed in the codes and standards, electrical requirements and ballasting;
- Controls procedure and dimming requirements in the standards and codes, control and dimming timetable for the project including circuits and catalog numbers;

- Electrical lighting plan that shows the luminaire types and locations for the entire project;
- Luminaire specifications and catalog numbers; and
- Drawings that include the mounting specifications.

After all contract documents are completed, the project folder is given to the agent responsible for bidding.

1.3.5 Bidding and Negotiation

At this stage, bidding contractors may consult the lighting designer when there are parts that are not clear. The contractors may prefer substitutions to keep costs lower or to decrease delivery time of the products. It is the lighting designer's responsibility to review photometric properties and reliability of substitutions.

1.3.6 Construction

An electrical contractor proceeds with the ordering of the products. It is again the lighting designer's responsibility to control this stage and to verify that contract documents are followed. Product substitutions may be proposed during the construction phase. The lighting designer should review the photometric characteristics and appearance of any replacements. By the end of the construction, the designer works on aiming of luminaires and programs the luminaire control system if presetting is required.

1.3.7 Post-Occupancy Evaluation

After the lighting system is established and the space is occupied, ideally there will be a formal evaluation. This could include using a questionnaire, in which the lighting designer asks the occupants to fill in post-occupancy evaluation (POE) forms, in order to evaluate whether the lighting system met the requirements of the occupants to perform visual tasks and whether the space is comfortable and stimulating. Another part of a POE is for the lighting designer to visit the site to make certain that the installation is installed as designed and planned. Sample photometric measurements may be taken to verify the design. The lighting design project is a success if the POE results are positive, and the budget and energy requirements have also been met (Rea, 1993).

1.4 Validating HDR Technology

In this section a literature review on HDR photography, using HDR technology to obtain luminance maps of images, HDR display and implementations of HDR technology is given.

1.4.1 HDR Photography

Conventional digital cameras cannot capture the full dynamic range (luminance range and contrast ratios) of a scene in the pixels of a single exposure image. Although HDR cameras do exist, these cameras are very expensive. To overcome these drawbacks, multiple exposures from a conventional digital camera can be combined with software to generate an image representing a broad range of luminances (Reinhard et al. 2006; Spheron). There are several techniques to combine the multiple exposures with the help of a specific camera response function (Mann and Picard 1995; Debevec and Malik 1997; Mitsunaga and Nayar 1999). Spot luminance measurements can be made at the time of image capture to better calibrate the pixel luminance values. Inanici (2006) demonstrated that this technique can, if carefully deployed, produce HDR images which record pixel luminances with an average error up to 12% compared to measurements made with a particular luminance meter, over luminances up to 13,000 cd/m^2. Further information on HDR photography will be given in section 2.3.2.2 and 3.3.2.1.

1.4.2 Using HDR Technology to Obtain Luminance Maps of Images

Consumer grade cameras are replacing the luminance calibrated CCD cameras that were used to compose luminance maps of scenes (Moeck and Anaokar, 2006). There are a variety of lenses available for consumer grade cameras, allowing for a resolution of HDR images from consumer grade cameras that is higher than CCD cameras (Anaokar, 2005). Using consumer grade cameras, images captured at a series of exposures are combined to make high dynamic range images, and software is available to convert these images into luminance maps (Ward, 2005). This is a more economical technique to obtain detailed luminance maps than using luminance meters and luminance calibrated cameras (Anaokar, 2005). One of the drawbacks of this technology is vignetting (Inanici, 2005), the light falloff as a function of angular distance from the center of the image, although this can be corrected using software (Rea and Jeffery, 1990). Detailed luminance map of a visual scene cannot be acquired using a spot photometer because the resolution of a digital image cannot be covered with spot luminance measurements. Even if a tripod is deployed, the error of each individual measurement adds up to a high total error. When daylight is present in the space, there is a possibility that sky conditions will change before the completion of data collection. The luminance map of the scenes that the participants are exposed to has an affect on the ratings; therefore, it is important to obtain the luminance map of the participants' view. This matter is given in more detail in section 3.4.5.

Anaokar and Moeck (2005) tested the accuracy of the software Photosphere (Ward, 2005) regarding various Munsell hues, values and chroma under three types of light sources with different spectral power distribution. They also investigated the impact of optical vignetting of the camera and thermal noise to verify the accuracy of luminance measurements, and reported that besides the advantages, there are also some limitations of the method. They reported that Photosphere outputs are reliable for scenes with surfaces of low chroma and saturation, and warmer hues. In scenes with cooler hues (i.e. blue and green) and hues with high chroma, errors can go up to 80%. It was mentioned that most interior buildings and built environments have low chroma and saturation, and the highest errors in such spaces would be 20%. This margin is acceptable since the luminance meter error margin under controlled laboratory conditions is in the range of 2-10% (Ouelette, 1993).

1.4.3 HDR Display

Information in HDR images cannot be reproduced visually on current conventional computer monitors, whether they be the older cathode-ray tubes (CRT) or newer liquid-crystal displays (LCDs). A conventional LCD monitor (circa 2009) can present luminances up to ~ 300 cd/m^2, with 1000 distinct luminance levels. HDR display technology overcomes these limitations (Seetzen et al. 2003; Whitehead et al. 2005). In this device the uniform backlight of a conventional LCD screen is replaced by an array of white light emitting diodes (LEDs), each of which is approximately 5 mm in diameter. The image is shown on the foreground colour LCD screen as in a conventional display, but it is backlit by a low-resolution version of the same image formed on the LED array. The output of the LED array can reach very high luminances. When these two layers are combined, with correct settings of the parameters of the display, an image is presented with high luminance values and contrast ratios similar to the levels in the real environment. The HDR display that was used in this study can display luminances up to 4000 cd/m^2.

1.4.4 Implementation of HDR Technology

HDR technology, which takes the LCD technology a step further by utilizing locally modulated LED backlighting as opposed to using fluorescent tubes, will soon be used in televisions. Using HDR technology, each section of the image is controlled locally, which facilitates higher contrast and provides more details than conventional LCD television monitors. LCD televisions with dimmed backlight LEDS can display black with lower luminance than conventional LCD displays. The company that has the rights to the HDR technology claims that there is potential to save a minimum 20% electrical energy in comparison to using fluorescent backlights for typical movie content. http://www.dolby.com/professional/video/dolby-contrast-overview.html (*last accessed on 16June2009*)

Engineering companies use renderings in product design, manufacturing, building industries, architectural design, 2D and 3D modeling services for various disciplines including lighting design (http://www.schorsch.com, http://www.lightcalc.com/, http://www.luxart.com/). Unless the rendering techniques are investigated, it is not known how realistic they are. Furthermore, presentation technology of renderings is as important as creating the renderings.

1.4.5 Early Tests of HDR Displays

Newsham et al. (2002) used an early version of this HDR display, which could present images with a maximum luminance of 1800 cd/m^2 (using a digital projector as a backlight), to present photographs of non-daylit offices. This pilot study had many limitations, but produced results that suggested that HDR images were viewed in a different way than conventional images, and justified further study. Very recently, other authors have explored how images on an LED-backlit HDR display are perceived compared to other types of presentation. These studies are given in section 2.1.

This dissertation takes these studies further by matching real space luminances to those shown on the HDR display. Adding to existing knowledge, these results show that viewing HDR images on an HDR monitor can result in judgements of space appearance and satisfaction that are similar to judgements of the real space, particularly when there is daylight. Therefore, it is proposed that an HDR display can be used as a tool in the lighting design process.

1.5 General Research Methods Used

The first phase of the dissertation was designed to investigate the hypothesis that HDR images on an HDR screen would be perceived as more realistic than conventional images displayed on conventional LCD displays. Thirty-nine participants viewed six scenes in three modes: the real scenes (observing real spaces in the building), single exposure photographs of the scenes shown in conventional mode (screen resolution and luminance of HDR display adjusted to that of a conventional LCD display), and the HDR photographs shown in HDR mode (capable of luminances as high as 4000 cd/m^2 and 2^{16} distinct luminance levels). Half of the participants visited the real spaces first, and the other half saw the digital images first. For each presentation (real and digital images), participants rated what they saw on four semantic differential scales: dim — bright; non-uniform — uniform; unpleasant — pleasant; glaring — not glaring. Participants then viewed the six digital image pairs again, and recorded whether the HDR or conventional image was more realistic.

The second phase demonstrated the use of HDR images as a research tool. The experiment focused on the relationship between scene characteristics (average luminance, luminance variability and view size) and space appearance judgements. Twenty-one scenes were created, each scene being the view from an interior cubicle across one cubicle to the exterior wall. The scenes varied in terms of the cubicle panels, window blind setting, and presence or absence of a neighbour in the adjacent cubicle. The calibrated HDR images were shown on an HDR display at realistic luminances to 43 participants. The participants rated each scene on 8 scales: too much light-too little light; unpleasant-pleasant; spacious-cramped; tense-calm; exciting-boring; satisfaction with amount of privacy; satisfaction with the amount of view and, satisfaction with the amount of visual comfort.

Psychophysical experiments study the relationship between a stimulus and its effect on a subject's experience or behaviour. Lighting research has a long history of psychophysical and behavioural experimentation; e.g. V (λ), the luminous efficacy function describing the spectral sensitivity of the human visual system was derived through such studies. When designing a controlled psychophysical experiment, the first step is to define a clearly quantifiable and measurable hypothesis. For instance, "Images will appear more realistic when viewed on an HDR display than when viewed on an LDR display".

Then independent and dependent variables should be chosen; independent variables are the variables that are manipulated in order to test the hypothesis, and the dependent variables are those that are measured in the experiment to test the hypothesis. The independent and dependent variables are concrete operations that embody the concepts in the hypothesis. For the first phase of the dissertation independent variables are the scene modes and dependent variables are semantic differential scales: dim — bright; non-uniform — uniform; unpleasant — pleasant; glaring — not glaring. For the second phase, independent variables are the scene characteristics (average luminance, luminance variability and view size) and dependent variables are the space appearance judgements.

The next step is to design an experiment to test the hypothesis. The goal of the experimental design is to ensure that any differences between responses to the target stimuli (independent variable) are attributable to that variable only, and not to confounding variables or to chance.

The aim of experimental design is to eliminate the effect of uncontrolled variables or to make them insignificant, to be able to draw conclusions about how the change in independent variables affects the dependent variables (Durso and Mellgren, 1989). To the extent that this is successful, the experiment has high internal validity. The external validity of the experiment concerns the applicability of the results to settings, times, and people other than those who were studied.

Among the early experimental design choices is how to control for differences between people. In a *within-subjects* study all participants are exposed to the same stimuli, whereas in a *between subjects* study the sample population is divided into groups and each group is exposed to a subset of the stimuli. In the first phase of this dissertation, Experiment 1 had a mixed design: Modality order was between-groups; but everyone saw all the stimuli, so it was repeated measures for the stimuli. In the second phase of the dissertation, repeated-measures (within subjects) design was used and everyone saw all the stimuli. Between-subjects design is a logical necessity for some independent variables (like order of presentation), and is useful in some lighting experiments to hide the independent variables from subjects. In a between-groups design, it is necessary to randomly assign individuals to the experimental conditions (as was done in experiment 1 in the assignment of people to viewing the real spaces or the images first). Provided the groups are large enough, random assignment will ensure that individual differences are equalized between the groups (Durso & Mellgren, 1989).

Repeated measures designs are often used because they control for differences between individuals. Every individual sees every stimulus, so that any differences between responses cannot be caused by differences between individuals. In this dissertation age and sex differences are controlled; therefore, they are not a source of bias in the results. For repeated measures designs, one must control for the effects of the order of presentation; in these experiments this was done by presenting the stimuli in random orders. Another parameter that was controlled in these experiments was the time of day when people viewed the real spaces in Phase 1 (to keep the spaces looking similar to the images). Similar kinds of controls were used to get similar exterior lighting conditions for the different images in Phase 2.

Selection of the population to sample (deciding from whom and how many subjects the data will be collected) influences external validity. Choosing a sample from a work placement agency should better represent the general working population than a self-selected sample of young students from a university population. The sample size will affect both external validity and statistical power. Larger samples permit the detection of smaller effects; but they also can provide a more varied sample of participant ages and characteristics, facilitating broader applications of the results. Based on a literature review of similar experiments, for this study sample sizes around 40 were judged to be adequate to detect statistically significant effects. The demographic data collected from participants is useful to characterize the population to which the results may be applied.

After the data collection stage, statistical techniques are used to analyze how the changes in the independent variables affect the dependent variables and to test whether the effects are significant or not, i.e. whether the changes on the dependent variables are causal effects of independent variables or a result of chance.

Statistical tests are applied to examine whether the hypothesis is supported by the data. Statistical tests are used to enable us to make decisions about whether differences in responses to different stimuli can be attributed to the independent variable(s) that characterize the stimuli, or whether they could equally be the result of chance. The statistical test gives a probability (p value), which means that the probability of the difference is due to chance if in fact there is no effect of the stimuli on the outcome. For instance a p value of 0.05 means that there is a 5% chance that the difference is due to chance, and 95% confidence that there really is a difference between the means. The statistical tests are used to support causal inferences, based on the balance of probabilities. In the experiments of this dissertation, causal inferences were made about differences in responses that had a 5% or lower likelihood of occurring if in fact there were no differences in the responses (Tabachnick and Fidell, 2001, and SPSS, 2006).

The statistical tests in this dissertation were chosen to be appropriate for the type of data and the experimental design:

- Chi-square test to analyze categorical data (the forced-choice items in Phase 1)
- MANOVA (or ANOVA) to analyse ratio-level (continuous) data —by convention, researchers use these techniques with ordinal data like these semantic differential scores, and they are robust to them (Tabachnick & Fidell, 2001).

After examining whether the independent variable is really causing the change in the dependent variable, the effect size of the relation (partial eta-square) was examined to consider whether the effect was large enough to matter — that is, the effect of practical significance.

The research techniques stated in this section were used to validate the use of HDR display technology for lighting research and lighting design. Two controlled psychophysical experiments were designed to examine the change in dependent variables in relation to the manipulation of the independent variables. Internal validity of the experiments was tested by examining the relation of the image characteristics and ratings. A mixed design was used for the first experiment (between-groups design for modality order and repeated measures for the stimuli), and repeated measures was used for the second experiment. Statistical techniques were used to analyze data (e.g. Chi-square and MANOVA). Both statistical and practical significance was considered while interpreting the results. The following chapter gives the first experiment conducted to determine whether HDR display is a valid technology.

2. PHASE 1: COMPARISON OF THE REAL SPACE TO IMAGES PRESENTED ON A CONVENTIONAL AND A HIGH DYNAMIC RANGE DISPLAY

This chapter describes the experiment comparing the ratings of the visual appearance of real spaces to conventional and HDR images of the same spaces, gives details of the research method and procedure, stimuli and dependent measures; compares the results, and discusses and gives comments on the results.

2.1 Literature Review on Use of Images as Stimuli

Using images as a surrogate for experiencing real spaces has been a common practice in architecture for centuries and using images as research tools has been common for decades. The important issue for research has always been to demonstrate that the results obtained using some type of simulation is comparable to what would have been obtained if one could have used a real space, which was often not possible. What has changed recently is that it is easier and cheaper to generate and produce numerous images, and possible to create renderings that have the possibility of being more realistic than was formerly the case.

Friedman et al (2004) investigated the use of HDTV display technology functioning as an artificial window in a windowless office by showing real-time image of a local outdoor scene. An HDTV camera was placed on the façade of a university building facing a fountain quarter on the campus and the image was shown on 50” plasma displays. Data was collected over a 6 week period prior to installing the artificial window system, for 6 weeks with the artificial window system, and over a period of 4 weeks after the removal of the system. Sample size of the subjects reported was very small, therefore the results cannot be generalized. However, the authors emphasized that further assessment is necessary regarding view type preferences and occupants’ interaction with such systems. It was also reported that employees deprived of windows may benefit from artificial window installations.

Radikovic et al (2005) investigated the realism created by artificial windows and mentioned that the representation of real scenes on still images and video lacks the presence of third dimension and motion parallax. When occupants move, the view (and the dimensions) they see does not change as it would have changed from a real window. To overcome this issue, using a head-coupled display with image-based rendering was suggested to simulate the view outside the building. Fourteen students compared the recommended artificial window system to a static display. The authors reported that the subjects found this system provided more realism than static images. The authors claim that a photorealistic artificial window view of nature with motion parallax was achieved in their study; however, they did not report any luminance readings and luminance matching information.

Currently, virtual reality is used in many other sectors. For instance in the automobile industry, virtual tools are used to evaluate ergonomics in the pre-production phase (Dukic et al, 2007). Going back to the field of architecture, graphical models are displayed to study perception of non-existing spaces (Franz et al, 2005). In lighting research, images have been used for subjective evaluations in order to judge visual quality, including discomfort glare and lighting preferences (Mahdavi and Eissa, 2001; Newsham et al., 2005; Tuaycharoen and Tregenza, 2005; Oi, 2005).

Real environments can be simulated in many different ways, and it is important to choose the correct method depending on the purpose of the study and in which terms realism is framed (Bellman and Landauer 2000). In lighting research, visual representations of spaces and scenes, presented in a variety of ways, have been used for evaluation purposes. In addition to one to one model studies, photographs, slides and conventional monitors have also been used to study lighting quality. These studies will be given in following paragraphs.

Danford and Willems (1975) examined the use of slides to measure subjective responses. They emphasized the importance of choosing simulation media that suitably represents the real environment, and developing measurement techniques that give adequate data on the subjective responses. Danford and Willems reported that an experiment should be designed to avoid biased ratings; it was recommended to use a non-complex design (including isolated stimuli that would reduce the complexity of response), to provide subjects similar (if not the same) surrounding facilities and to ensure that all subjects were equally familiar with the experimental spaces. It was noted that the experimenter must use the same vocabulary of introduction for all subject groups in order to avoid biased ratings. The authors also emphasized that using precise and efficient methods and measurement techniques is particularly important for further comparisons of responses to simulated environments.

Danford and Willems (1975) were very critical of the method of using simulations, claiming the measurements do not have precision and efficiency. The authors reported the challenges of using colour photographic slides and collecting the subjective ratings of spaces. In this study, the first group of subjects had a structured guided walk of the law faculty building in real space, the second group saw colour rendered slides of the chosen spots in the building, and the third group did neither have a guided tour of the building nor rated the slides, but completed the questionnaire based on what they would expect a law school building look like. The subjects in these three groups were informed about the function of the building. The fourth group, however, was not notified of the function of the building, and the subjects in this group rated the slides following the same procedure as Group 2.

It was reported that the best method to examine the validity of the simulation was to compare it with the real space. The ratings for real space (ratings from Group 1) and slides (ratings from Group 2) showed high correlation. However, the ratings of Group 1, Group 3 and Group 4 were very close too. Danford and Willems reported that the convergence of the responses of Group 3 (who completed the questionnaire based on their ideas of what a law faculty should look like) and Group 4 (who were not given the function of the building) showed that the results had no practical use. Although Danford and Willems were critical of the use of slides, it should be noted that there are circumstances where subjects' viewing real space is not possible for practical purposes, i.e. when the building does not exist yet, or when the fluctuation of sky luminance has to be controlled in studies including daylight.

Flynn et al (1973) conducted a study to confirm that lighting of a space sends signals to the occupants and these signals cause a persistent impact on occupants. A lighting demonstration room with six lighting scenarios and the specifications of a medium-sized conference room was used to collect data from a total of 96 subjects (in 8 groups, 12 subjects in each group). Before the first phase of the study subjects were not notified that the purpose of the experiment was to study the affect of lighting systems. They were informed, however, before the second phase which was a comparison of pre-selected lighting systems. It was reported that two or more lighting scenarios had statistically significant impact for all rating scales and factor analysis showed that evaluative impression, perceptual clarity and spaciousness had statistically significant results, which indicated that the rating scales had convergent validity. In a follow up study, multidimensional scaling was investigated using the same room, 46 new subjects and 38 comparison scales of similarity or difference. It was reported that there were characteristic differences among participants regarding which dimension was considered with the largest weight.

Hendrick et al. (1977) compared the results of semantic differential scale ratings obtained from two groups of subjects; the first group was exposed to real spaces and the second group observed slides of these spaces. Semantic differential ratings used in this study were grouped in six factors; evaluative (friendly-hostile, pleasant-unpleasant, like-dislike, harmony-discord, sociable-unsociable, relaxed-tense, interesting-monotonous), perceptual clarity (clear-hazy, bright-dim, faces clear-faces obscure, distinct-vague, focused-unfocused, radiant-dull), spaciousness (large-small, long-short, spacious-cramped), perceived horizontality (horizontal-vertical), special complexity and formality (simple-complex, uncluttered-cluttered, rounded-angular, formal-informal, quiet-noisy, serious-gay, public-private, cheerful-somber, usual-unusual, static-dynamic). By comparing the mean ratings of photographic slides to those made by a different group viewing the real spaces, the authors concluded that viewing the slides was a reasonable substitute for viewing the real space, for these types of ratings. In this study, the authors took a number of photographs of the chosen lighting installations, and chose one photo of each scene that best represented lighting of the space according to the researchers' judgement. It was assumed that in future practices the lighting designer would be the person to make this decision. Furthermore, it was also noted that a standardized photographing method should be used in future practices to minimize the real space representation errors.

Mahdavi and Eissa (2002) recorded semantic differential ratings of three non-daylit office spaces presented in two ways in a between-subjects design: viewing the real space, and viewing computer renderings on a conventional display. The following semantic differentials were found to be reliable; bright-dim, uniform-non-uniform, interesting-boring, private-public, dull-shiny, cool-warm. The authors concluded that overall the ratings of the renderings were adequately similar to those of the real spaces.

In later phases of lighting research using image evaluation, several research studies in lighting have used images as their only stimuli to derive information for lighting practice. For example, Oi (2005) studied the differences between generations in evaluating an interior lighting environment by projecting rendered images on a screen with a liquid crystal projector in a dark room. Tuaycharoen and Tregenza (2005) studied the relationship between image content and discomfort glare. In this case, the images were from the viewpoint of a building occupant looking out of a window with both urban and natural views, and a projector was used to present them to participants, potentially at very high luminances. Newsham et al. (2005) used projection to present images of non-daylit office interiors. The participants were given the opportunity to optimize the lit scene to their preference. Although there was no explicit comparison to real scenes, the authors reported good agreement between ratings of the images in this experiment, and those of similar real scenes made by different participants in another experiment.

Although these studies all provide useful information, all can be faulted in that a key physical parameter in visual perception, luminance, was not satisfactorily addressed. Some researchers appear to have given no consideration to the importance of presenting realistic luminances. In some investigations, luminances were matched to those naturally occurring but, because of the limitations of display technology, the authors limited the scenes presented. For example, Newsham et al. (2005) limited luminance to 140 cd/m^2, adequate for scenes of non-daylit offices where no electric light sources are visible. Conventional display technologies have also limited the dynamic range of luminances and contrast ratios that could be presented: Tuaycharoen and Tregenza (2005) did reproduce realistic luminances for potentially glary daylit situations, but this involved bulky digital projectors. These projectors delivered luminances up to 150,000 cd/m^2, but at the low dynamic range (1:150 luminance levels) of conventional equipment.

Akyuz et al (2007) used an HDR display with a resolution of 1920 by 1080 pixels and a peak luminance of 3000 cd/m^2, which was illuminated with 1380 LEDs, to explore whether Low Dynamic Range (LDR) image content can be practically displayed on High Dynamic Range displays. Ten images representing a variety of indoor and outdoor environments captured at nighttime and daytime were ranked by 22 participants between 20 and 40 years old. Each image was displayed in six modes; HDR image displayed on HDR mode, three tone mapping techniques for HDR images that were displayed on conventional display, and LDR images of objective-best and subjective-best exposures. Objective best image had equal number of under and over exposed pixels, and subjective-best exposure was chosen by 20 participants in a pilot study.

Akyuz et al (2007) found that HDR displays surpassed LDR displays. In this study, however, HDR images displayed on the HDR display did not represent the real space luminances, as the pixels with luminances higher than 3000 cd/m^2 were trimmed. Therefore, it should be noted that best ranked HDR images displayed on the HDR monitor did not represent the real scene accurately. The authors also reported that when tone mapped HDR images (that went through a process of dynamic range reduction) were displayed on conventional monitors, they were not rated better than the best single LDR image displayed on conventional monitor and LDR images boosted linearly to fit the HDR display can even outperform the impression of an HDR image.

Yoshida et al. (2006) presented participants with HDR images (with peak luminance of 3000 cd/m^2) and the corresponding real scenes simultaneously; participants were asked to use brightness, contrast, and colour saturation controls to match the HDR image to the real scene. After making these adjustments, participants rated the accuracy of reproduction. Several trials were conducted in which the luminance range of the HDR display was restricted in various ways, to simulate displays with different properties, including a conventional LCD screen. Three scenes were used; one of an office desk under two different electric lighting conditions, and the third was a view to the outdoors under naturally occurring daylight. Results showed that the preferred combination of control settings was significantly affected by scene. HDR images did demonstrate significantly better perceived reproduction than conventional images.

The studies cited in this section used slides and images displayed on monitors as tools to measure lighting quality; however none of these studies addressed adequate luminance mapping to real space luminances, which is a key physical parameter in visual perception. This dissertation contributes to the lighting quality literature by studying daylight in built-in environments, controlling fluctuation of natural lighting and by displaying realistic real space luminances using the HDR photography technique on an HDR monitor.

2.2 Hypothesis

The following hypothesis was tested in the first phase of this dissertation:

> **H1:** The visual appearance of HDR images of office building interiors will be judged as more realistic than that of conventional images.

This study complements those of Akyüz et al. (2007) and Yoshida et al. (2006), in using a broader range of outcome variables than the former, and a broader range of images than the latter. In Akyuz et al.'s study, participants ranked the images based on their preferences; and the outcomes of the study were reported based on these rankings only. The reasons behind participants' preferences were not investigated. In the experiment given in this chapter, participants completed a semantic differential ratings of four factors for each of the six scenes and in addition to these completed the realism ratings. Yoshida et al. (2006) used only three scenes; an office desk under two different electric lighting conditions, and an outdoor view including daylight. Further, whereas both of these studies compared HDR to conventional images, only the latter compared HDR directly to reality; the current study will compare HDR to both conventional images and reality. Support for the hypothesis will demonstrate that the use of HDR imagery may go beyond simply producing more appealing images. If the results show that viewing HDR images is perceptually similar to viewing the equivalent real space, then HDR imaging may find application as a tool in the architectural decision-making process, in vision and lighting quality research, and in applied perception research more generally.

2.3 Methods and Procedures

In this section information regarding the participants, stimuli, dependent variables and procedure is given.

2.3.1 Participants

Thirty-nine participants (19 women and 20 men, ages 18-55 years) were recruited from a temporary staffing agency. Participation was voluntary and the reward for participation was the staffing agency's normal hourly rate for a clerical job. All participants had English as their first language and self-reported normal or corrected-to-normal vision. Colour capacity, blind spots, floaters or other vision impairments were not tested. The experiment consisted of two phases and there was an experimenter assigned for each phase. One experimenter assisted the participants in the room where images were displayed on the HDR display and the other assisted the participants in the real spaces. Each participant took part in each phase alone, while the other participant was partaking in the other phase or waiting for his/her turn. Two participants were recruited each day, although attendance was not perfect and nine participants took part alone.

2.3.2 Stimuli

In this section the choice of real spaces, and collection and display of conventional images and HDR images is given in detail.

2.3.2.1 Real Spaces

Six spaces were chosen in a research facility building located in Ottawa, Canada (Figure 2.1). These spaces were chosen to be representative of the spaces found in a typical office building, and to contain illumination from a variety of electric and daylight sources. Figures A1-A6 in Appendix A show images of the spaces.

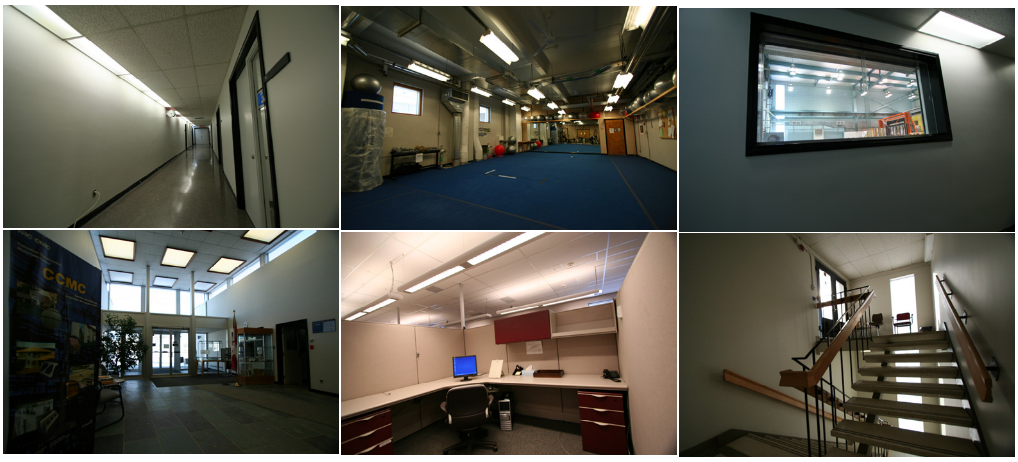


Figure 2.1: Thumbnails of the images used in the experiment, from left to right; corridor, gym, mezzanine, lobby, open-plan office, and staircase.

2.3.2.2 Conventional and HDR Images

The participants saw two images of the chosen spaces, one in conventional and the other in HDR mode. All images in this phase were taken with a Canon EOS Digital Rebel XT camera mounted on a tripod at seated head height and fitted with a wide-angle eye lens (Canon EFS10-22mm). The angle of view was 74° vertical and 97° horizontal; image capture size was 1728 x 1152 pixels.

The conventional images were taken with the aperture priority exposure program, with a sensitivity of ISO-100. These images were saved in JPEG format. The conventional images were displayed on the HDR display but in a conventional mode, and display brightness and gamma adjustments were set individually so that luminance on the display did not exceed 200 cd/m^2, typical of prevailing conventional LCD displays. The overall appearance was reasonable for a single conventional image, as judged by the experimenter; no standardized tone mapping was employed. We chose to do this, rather than use a conventional display for the conventional images, so that all images were the same size, any colour differences between displays would be eliminated, and to exclude any other external cues that might bias the subjects' ratings; a similar choice, for similar reasons, was made by Akyüz et al. (2007) and Yoshida et al. (2006).

To make HDR images, sets of images were captured in each space from the same location as the conventional images. The camera was connected to a computer and all image capture settings were controlled using remote shooting software. The camera was set to full manual mode and no auto-exposure features were used to ensure that the only difference between the multiple images was the exposure time; the aperture size was set to f/4. Images with exposure times from 4 to 1/4000s were taken sequentially.

To ensure the best correspondence between image luminance and real luminance, separate camera response functions were developed for spaces illuminated with daylight, and those without daylight. The number of images to combine for each HDR image was determined individually for each space, depending on the luminance variations of each scene (Debevec and Malik 1997). A brightness histogram of each image was examined to ensure that the darkest images used had no RGB values greater than 200 and the lightest images had no RGB values less than 20, as recommended by Reinhard et al. (2006, p.146). The individual exposures were combined into HDR images using the software Photosphere (Ward, 2005). Over all images, the exposure times used in the final HDR images covered the range 2 to 1/500 seconds; the range for each individual image is shown in Appendix A. Faster shutter speeds were not included because these generated Photosphere files with maximum luminances that may have been realistic, but were well beyond those that the HDR display could present, and this led to very poor luminance reproduction overall.

On the day the images were taken, luminance measurements at a number of points in the image were taken using a Gigahertz Optic LDM-9810 luminance meter. A single calibration point was chosen in each scene, for which we later would compare the HDR image luminance calculated by Photosphere to the real scene luminance. The calibration factor, the ratio of the real space luminance to the Photosphere luminance, was then applied to all pixel luminance values in the image. Then these images were displayed on the HDR display, and the display brightness and gamma adjustments were set to create the best overall match across all measurement points between the on-screen luminance and the luminance in the real scene, while also preserving reasonable colour reproduction, as judged by the experimenter.

A comparison of the spot luminances measured in each real space at the time the images were taken, and the luminances of the HDR and conventional images as presented on-screen, is shown in Appendix A Figures A1-A6. Measuring points were on uniform surfaces and were chosen based on a grid, covering the wide luminance range of each scene. These comparisons show clearly that in terms of luminance the HDR images very obviously come closer to the real space than the conventional images. Nevertheless, there are still differences between the real and HDR luminances, which are sometimes substantial in percentage terms. However, it is important to note that these differences might be more attributable to unavoidable measurement error in the comparisons than to differences in the luminance field itself, as detailed below:

- In spaces with daylight, luminance measurements were made both before and after taking the photographs at multiple exposures, and the average of these two measurements was used for comparisons. Although the attempt was to conduct this process with stable exterior luminance conditions, luminance values did change over the typical 20-minute period of these measurements.
- Repeatability in aiming the luminance meter was not perfect, as is typical in field measurements of luminance.
- The Gigahertz luminance meter yielded the mean luminance over the area of a 1° circle. When comparing to the luminances in the HDR image created by the Photosphere software, Photosphere calculated luminances over a rectangular area only, which may lead to calibration error.
- When measuring the luminance on the HDR display the 20' measurement circle of the luminance meter covered a larger representative area of the image than the 1° circle did in the real space, which could generate large comparison errors in regions of the image with large luminance variation over small areas (e.g. luminaire surfaces).
- While matching the luminance on the HDR display to real space luminance measurements, the experimenter had to compromise. If the gamma and brightness levels were adjusted to match the high luminance values, the error for points with low luminance was excessively high, and vice versa. A final choice was made based on average luminance errors, and the appearance of luminance gradients and colour, as judged by the experimenter.
- The size of an individual LED was relatively large compared to some of the features in the images, which could cause luminance "bleeding". For example, if an LED was activated to a high level to provide a realistic luminance on a small, bright feature, this then also backlit a neighbouring darker feature. To first order

this effect is counteracted in the image rendering software controlling the LCD panel, but this correction cannot be perfect due to the limited dynamic range of the LCD. This could cause local luminances to be in error, although perceptually such luminance gradients were not so apparent.

One must also be cognizant that for low luminances, small absolute differences can generate large percentage differences. For instance, for point 17 in the gym (see Appendix A, Figure A2), the real space and HDR readings were 7 cd/m^2 and 10.3 cd/m^2 respectively, which gave a difference of 39%. The absolute difference of 3.3 cd/m^2 falls within the margin of error for many calibrated luminance instruments.

2.3.3 Dependent Measures

During the procedure described below, participants rated real scenes and images on semantic differential (adjective pair) scales. The scales rated were: dim-bright, nonuniform-uniform, unpleasant-pleasant, glaring-not glaring. These were derived from a larger set of 27 scales commonly used in lighting research (e.g. Hendrick et al. 1977), and which have often been successfully abridged (e.g. Mahdavi and Eissa 2002; Newsham et al. 2005). These are also similar to the rating scales used by Seetzen et al. (2006) when investigating perceived image quality on HDR displays of various properties. Prior to beginning their ratings, participants were given the dictionary definitions of these adjectives. The ratings were made on the pages of a booklet (one page per evaluation). Each scale showed the adjectives at either end of a 100 mm line. Participants placed a pencil mark on the line to indicate the strength of their opinion, and the distance along the line in mm formed the score on a scale of 0-100.

In a final set of ratings, pairs of images of the same space were displayed and the participants' task was simply to indicate which one of the images was more realistic.

2.3.4 Procedure

On the day of the experiment, participants were directed to the space where image evaluation would occur. They were given information about the experiment, and then asked to sign a consent form.

According to random assignment, one participant evaluated the real spaces first, followed by the images, and the other evaluated the images first, followed by the real spaces. When participants evaluated the six real spaces they were viewed in a pre-determined random order. All spaces were checked before the participants visited them to ensure that the objects in the space were the same as when the images were taken. The participants sat in chairs that were located at the viewpoints from which the images had been taken, and were informed which direction to look towards, this direction being the centre of the corresponding image. The participants were asked to take the whole scene into consideration when making their judgements of the visual appearance of spaces. The participants were given 30 seconds to become accustomed to the scene and then were prompted to complete the rating scales. Meanwhile the experimenter took a luminance measurement for the calibration point of the space. When they finished, they proceeded to the next space.

Image evaluation took place at a desk in an open-plan office laboratory; Figure 2.2 shows this space. The experimenter ran the experiment from the other side of the partition behind the computer screen. Each participant saw all 12 images (six HDR and six conventional images) of the spaces in a random order. Conventional and HDR images of the same spaces were not shown sequentially. When rating an image, the participants sat in a chair facing the HDR display; the lighting in the laboratory provided a luminance on the furniture panel behind the display of around 100 cd/m^2. Before the first image, and between the images, a blank white image (luminance 126 cd/m^2, chosen to be similar to the average luminance of all images) was displayed for 30 seconds. When an image appeared on the screen, the participants had 30 seconds to become accustomed to the scene, then the participants were invited to complete the rating scales for that scene. When the participants finished the ratings, they informed the experimenter so that they could move on to the next blank screen and image. The participants were asked to keep their attention on the screen when it was blank.

Figure 2.2 : Laboratory space for image evaluations.

After these two sets of ratings, each participant returned to the office laboratory for the final set of ratings. In this case, the six pairs of images, HDR and conventional, of the same space were displayed sequentially; which image of the pair was shown first was determined randomly. The participants' task was simply to indicate which one of the image pair was more realistic. Again, the screen was blank for 30 seconds before the first image was displayed. Then each image of the pair was displayed for 15 seconds, after which the judgment was made. While one participant completed this task, the other waited outside the laboratory space.

After this phase, participants were asked to provide any other comments they had on the experiment. The whole procedure took about 75 minutes.

2.4 Results

2.4.1 Analysis Strategy

For the semantic differential ratings, the general experimental design was 3 (presentation type: real, HDR image, conventional image) x 6 (scenes) within-subjects, with four outcome variables. An additional between-subjects variable, presentation order (images or real scenes rated first) was also considered. Therefore, a series of multivariate analyses of variance (MANOVAs) have been conducted. Each analysis looked at specific contrasts on the presentation type variables, specified *a priori*: HDR vs. real; and, HDR vs. conventional. Full support for the hypothesis would be demonstrated by no significant differences in the former contrast, and significant differences in the latter, with the mean values of ratings of the HDR images falling closer to the ratings of the real spaces than the ratings of the conventional images.

For ratings of realism in the direct comparison of HDR and conventional images, univariate chi-squared tests for each of the six scenes have been used.

Correlations of the ratings of the HDR images with photometric descriptors have also been examined. Analysis of variance (ANOVA) was used for this analysis, with the semantic differential ratings as independent outcomes, and various luminance-based measures as predictors.

2.4.2 Data Cleaning

Data preparation and screening was conducted using the procedures recommended by Kline (1998). According to Kline, absolute skewness values greater than 3 and absolute kurtosis values greater than 8 indicate univariate normality problems. Only one outcome for one presentation/scene combination had a kurtosis greater than 8. Univariate outliers were identified by examining frequency distributions of standardised scores, and scores greater than 3 standard deviations from the mean were excluded from analysis. This process reduced the final sample size for analysis to 33.

2.4.3 Semantic Differential Ratings

The results of the initial fully-factorial MANOVA are shown in Table 2.1, and Figure 2.3 shows the graph of mean ratings. Table 2.1 is divided into three sub-sections, covering the main effects of presentation type and scene, and their interaction, respectively. The first row in each sub-section shows the statistics for the overall effect over all outcomes and levels of the independent variable(s); $\eta^2_{partial}$ is the proportion of variance in the outcome(s) explained by the effect. Each sub-section is further divided, showing the effect on each individual outcome measure. Finally, under each outcome in the presentation type sub-section, we show the effect of the specific presentation type contrasts. For example, in the first sub-section we see that the presentation type has a significant effect on the outcome variables overall. Specifically, there are significant effects for the dim-bright, non-uniform-uniform, and unpleasant-pleasant outcomes. Focusing on the dim-bright outcome, there are significant differences between the HDR and real presentations, and between the HDR and conventional presentations, and so on.

Table 2.1: Results of the initial fully-factorial MANOVA, empty cells indicate non-significant tests.

Effect	Outcome / Contrast	Statistical test	$\eta^2_{partial}$
Presentation		Wilks' λ= .295, $F_{8,118}$= 12.42***	.46
	dim-bright	$F_{2,62}$= 61.21***	.66
	HDR vs. real	$F_{1,31}$= 29.55***	.49
	HDR vs. conv.	$F_{1,31}$= 53.20***	.63
	non-uniform-uniform	$F_{2,62}$= 11.67***	.27
	HDR vs. real		
	HDR vs. conv.	$F_{1,31}$= 14.42***	.32
	unpleasant-pleasant	$F_{2,62}$= 22.78***	.42
	HDR vs. real		
	HDR vs. conv.	$F_{1,31}$= 36.88***	.54
	glaring-not glaring		
	HDR vs. real	$F_{1,31}$= 6.37*	.17
	HDR vs. conv.		
Scene		Wilks' λ= .216, $F_{20,505}$= 14.85***	.32
	dim-bright	$F_{5,155}$= 45.34***	.59
	non-uniform-uniform	$F_{5,155}$= 5.40***	.15
	unpleasant-pleasant	$F_{5,155}$= 9.77***	.24
	glaring-not glaring	$F_{5,155}$= 26.48***	.46
Presentation x Scene		Wilks' λ= .435, $F_{40,1166}$= 7.15***	.18
	dim-bright	$F_{10,310}$= 21.84***	.41
	non-uniform-uniform	$F_{10,310}$= 4.95***	.14
	unpleasant-pleasant	$F_{10,310}$= 7.38***	.19
	glaring-not glaring	$F_{10,310}$= 7.22***	.19

* = $p \leq 0.05$, ** = $p \leq 0.01$, *** = $p \leq 0.001$

This initial analysis provided general support for the hypotheses.

HDR image ratings were closer to those of the real space than the conventional image ratings. However, there was a significant presentation type x scene interaction, suggesting that the effect of presentation type varied according to the scene content. Further, an exploratory three-way MANOVA with presentation order as an additional between-subjects variable indicated a significant effect of presentation type x presentation order (Wilks' λ= .766, $F_{8,114}$= 2.03, p=0.03, $\eta^2_{partial}$=.13). These issues are addressed in subsequent analyses.

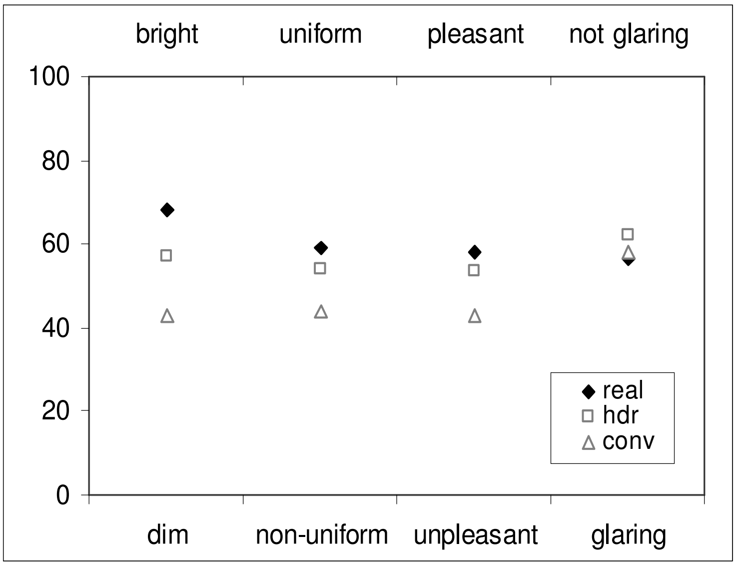
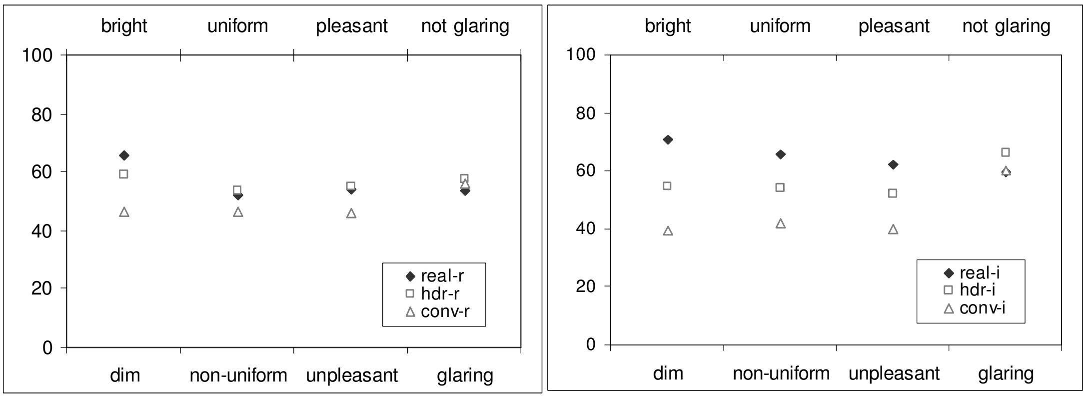


Figure 2.3: Mean ratings on the four semantic differential scales, by presentation type (Note: For clarity, error bars are not shown on these graphs, but standard deviations were typically half the mean values).

Fully-factorial MANOVAs were repeated with the sample split into two equal groups according to presentation order. The graphs of mean ratings are shown in Figure 2.4. It is clear from Figure 2.4 that the differences between ratings of the different presentation types was substantially suppressed for those who saw the real spaces first. One can easily imagine that seeing the real space first might create different expectations regarding the appearance of the subsequent images, and vice versa. However, it is important to recognize that in the practical application of HDR images and displays for design decision-making, observers would be evaluating images prior to the existence of the real space. Similarly, in research applications, observers would be viewing the HDR images as a surrogate for viewing a real space that they would not experience directly. Therefore, in further analysis of these results we chose to focus on the sub-sample of ratings from people who rated the images prior to seeing the real spaces as being more relevant to the application of the HDR technology.



(a) (b)

Figure 2.4: Mean ratings on the four semantic differential scales, by presentation type. (a) shows data for those who saw and rated the real spaces before the images (N=16); (b) shows data for those who saw and rated the images before the real spaces (N=16).

For this sub-sample, the MANOVA analysis for each of the six scenes were repeated separately, that allowed us to interpret the presentation type x scene interaction (which was also significant for this sub-sample). Results are shown in Tables 2.2(a)-(f) and Figures 2.5(a)-(f).

Table 2.2(a): Results of the MANOVA analysis, for the sub-sample who saw and rated the images first, and for Scene 1 (corridor); empty cells indicate non-significant tests.

Effect	Outcome / Contrast	Statistical test	$\eta^2_{partial}$
Presentation		Wilks' λ= .347, $F_{8,58}$= 5.05***	.41
	dim-bright		
	HDR vs. real		
	HDR vs. conv.		
	non-uniform-uniform	$F_{2,32}$= 14.37***	.47
	HDR vs. real	$F_{1,16}$= 23.67***	.60
	HDR vs. conv.		
	unpleasant-pleasant	$F_{2,32}$= 5.85**	.27
	HDR vs. real		
	HDR vs. conv.		
	glaring-not glaring	$F_{2,32}$= 3.67*	.19
	HDR vs. real		
	HDR vs. conv.	$F_{1,16}$= 9.98**	.38

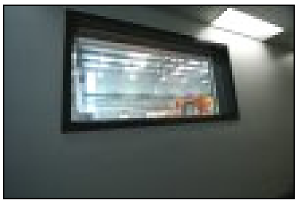
* = p≤0.05, ** = p≤0.01, *** = p≤0.001

Table 2.2(b): Results of the MANOVA analysis, for the sub-sample who saw and rated the images first, and for Scene 2 (gym); empty cells indicate non-significant tests.

Effect	Outcome / Contrast	Statistical test	$\eta^2_{partial}$
Presentation		Wilks' λ= .260, $F_{8,58}$= 6.96***	.49
	dim-bright	$F_{2,32}$= 28.13***	.64
	HDR vs. real	$F_{1,16}$= 30.57***	.66
	HDR vs. conv.		
	non-uniform-uniform	$F_{2,32}$= 9.96***	.38
	HDR vs. real		
	HDR vs. conv.	$F_{1,16}$= 10.40**	.39
	unpleasant-pleasant	$F_{2,32}$= 24.03***	.60
	HDR vs. real	$F_{1,16}$= 20.54***	.56
	HDR vs. conv.		
	glaring-not glaring		
	HDR vs. real	$F_{1,16}$= 4.54*	.22
	HDR vs. conv.		

* = p≤0.05, ** = p≤0.01, *** = p≤0.001

Table 2.2(c): Results of the MANOVA analysis, for the sub-sample who saw and rated the images first, and for Scene 3 (mezzanine); empty cells indicate non-significant tests.

Effect	Outcome / Contrast	Statistical test	$\eta^2_{partial}$
Presentation		Wilks' λ= .340, $F_{8,58}$= 5.19***	.42
	dim-bright	$F_{2,32}$= 14.85***	.48
	HDR vs. real	$F_{1,16}$= 19.30***	.55
	HDR vs. conv.		
	non-uniform-uniform	$F_{2,32}$= 3.64*	.19
	HDR vs. real		
	HDR vs. conv.		
	unpleasant-pleasant	$F_{2,32}$= 5.86**	.27
	HDR vs. real		
	HDR vs. conv.		
	glaring-not glaring	$F_{2,32}$= 7.19**	.31
	HDR vs. real	$F_{1,16}$= 5.06*	.24
	HDR vs. conv.	$F_{1,16}$= 12.66**	.44

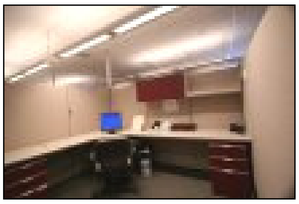
* = p≤0.05, ** = p≤0.01, *** = p≤0.001

Table 2.2(d): Results of the MANOVA analysis, for the sub-sample who saw and rated the images first, and for Scene 4 (lobby); empty cells indicate non-significant tests.

Effect	Outcome / Contrast	Statistical test	$\eta^2_{partial}$
Presentation		Wilks' λ= .119, $F_{8,58}$= 13.78***	.66
	dim-bright	$F_{2,32}$= 50.30***	.76
	HDR vs. real		
	HDR vs. conv.	$F_{1,16}$= 56.07***	.78
	non-uniform-uniform	$F_{2,32}$= 18.36***	.53
	HDR vs. real		
	HDR vs. conv.	$F_{1,16}$= 24.16***	.60
	unpleasant-pleasant	$F_{2,32}$= 13.04***	.45
	HDR vs. real		
	HDR vs. conv.	$F_{1,16}$= 16.90***	.51
	glaring-not glaring	$F_{2,32}$= 4.86*	.23
	HDR vs. real		
	HDR vs. conv.		

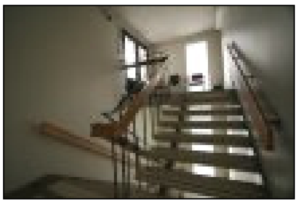
* = p≤0.05, ** = p≤0.01, *** = p≤0.001

Table 2.2(e): Results of the MANOVA analysis, for the sub-sample who saw and rated the images first, and for Scene 5 (open-plan office); empty cells indicate non-significant tests.

Effect	**Outcome / Contrast**	**Statistical test**	$\eta^2_{partial}$
Presentation		Wilks' λ= .300, $F_{8,54}$= 5.57***	.45
	dim-bright	$F_{2,30}$= 14.77***	.50
	HDR vs. real	$F_{1,15}$= 23.93***	.62
	HDR vs. conv.		
	non-uniform-uniform	$F_{2,30}$= 5.25*	.26
	HDR vs. real	$F_{1,15}$= 6.91*	.32
	HDR vs. conv.		
	unpleasant-pleasant	$F_{2,30}$= 4.97*	.25
	HDR vs. real	$F_{1,15}$= 10.64**	.42
	HDR vs. conv.		
	glaring-not glaring	$F_{2,30}$= 7.89**	.35
	HDR vs. real		
	HDR vs. conv.	$F_{1,15}$= 9.65**	.39

* = p≤0.05, ** = p≤0.01, *** = p≤0.001

Table 2.2(f): Results of the MANOVA analysis, for the sub-sample who saw and rated the images first, and for Scene 6 (staircase); empty cells indicate non-significant tests.

Effect	Outcome / Contrast	Statistical test	$\eta^2_{partial}$
Presentation		Wilks' λ= .113, $F_{8,58}$= 14.34***	.66
	dim-bright	$F_{2,32}$= 112.4***	.88
	HDR vs. real	$F_{1,16}$= 5.44*	.25
	HDR vs. conv.	$F_{1,16}$= 157.7***	.91
	non-uniform-uniform	$F_{2,32}$= 11.76***	.42
	HDR vs. real		
	HDR vs. conv.	$F_{1,16}$= 19.96***	.56
	unpleasant-pleasant	$F_{2,32}$= 15.12***	.49
	HDR vs. real	$F_{1,16}$= 5.37*	.25
	HDR vs. conv.	$F_{1,16}$= 28.20***	.64
	glaring-not glaring	$F_{2,32}$= 5.70**	.26
	HDR vs. real		
	HDR vs. conv.	$F_{1,16}$= 7.97*	.33

* = $p \leq 0.05$, ** = $p \leq 0.01$, *** = $p \leq 0.001$

This analysis clearly shows that the hypothesis is strongly supported for two of the six scenes, the lobby and the staircase, but finds little support in the data from the other four scenes.

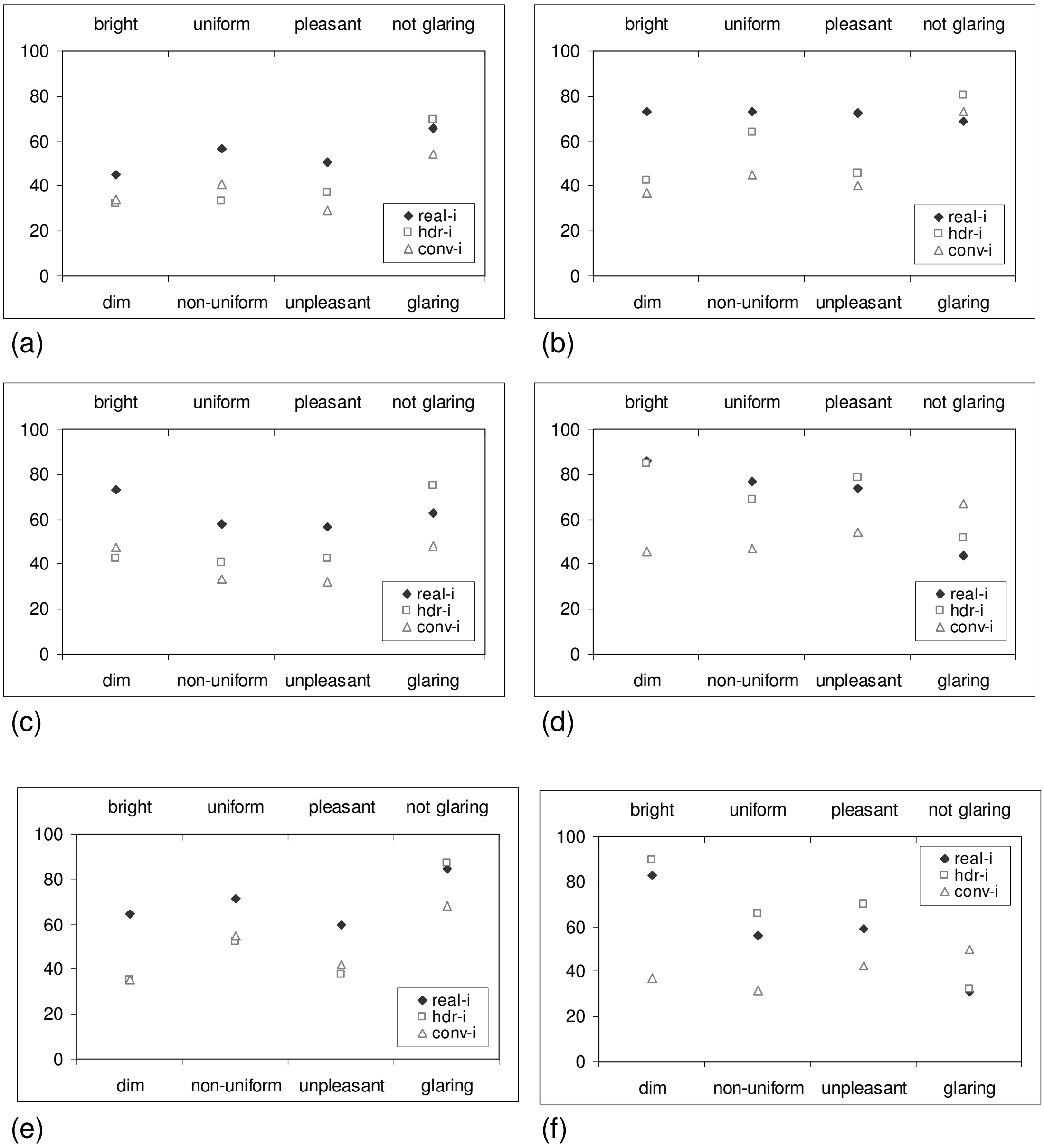


Figure 2.5: Mean ratings on the four semantic differential scales, by presentation type, and for each scene. Graphs show data for those who saw and rated the images before the real spaces. Scenes: (a) corridor; (b) gym; (c) mezzanine; (d) lobby; (e) open-plan office; (f) staircase.

2.4.4 Realism Ratings

The result of the chi-squared analysis is shown in Table 2.3. At this point in the experiment, all participants had seen both the real scenes and the images, therefore all participants are included in this analysis. The HDR image was rated as significantly more realistic in four of the six scenes, whereas the difference was not significant for the other two scenes.

Table 2.3: Results of the chi-squared analysis on realism ratings, by scene.

Scene	***More realistic?***		χ^2
	HDR	conventional	
Corridor	21	12	2.46
Gym	21	12	2.46
Mezzanine	28	5	16.03***
Lobby	31	2	25.49***
Open-plan office	24	9	6.82**
Staircase	26	7	10.94***

* = p≤0.05, ** = p≤0.01, *** = p≤0.001

2.4.5 Relating Photometric Descriptors to Semantic Differential Ratings

The correlation between the ratings of the HDR images and photometric descriptors were examined. The primary motivation was a validity check on the method: did the ratings correspond to photometric properties in the expected manner? The analysis may also provide direction to future, more specific investigations into physical correlates for lighting quality ratings. Given the considerations above, the focus has been on data from participants who saw the images before the real spaces. Within-subjects analysis of variance (ANOVA) has been conducted in which the ratings of brightness, uniformity, pleasantness and glare were dependent variables, and luminance-based photometric values from each of the six HDR images were the independent variables. In these analyses the independent variables were scaled according to the differences in the photometric value.

The photometric descriptors for each of the four dependent variables were selected based on previous research (Newsham et al. 2005), and these are defined in Table 2.4. For brightness and glare, overall luminance and elevated luminance were tested. For uniformity, luminance variability was tested. For pleasantness, overall luminance and variability were tested. Table 2.4 shows the photometric descriptors for each image, derived from pictures of the screen using a calibrated Prometric video photometer; video photometer iso-plots of each image are shown in Appendix B, Figures B1-B6. Table 2.5 shows the results of the analyses, with examples shown graphically in Figure 2.6.

Table 2.4: Luminance-based photometric values from each of the six HDR images.

Predictor	Description	Concept	Corridor	Gym	Mezzanine	Lobby	Open-Plan Office	Staircase
LUM	Mean luminance (cd/m²)	Overall luminance	46.2	39.2	59.3	202.2	41.6	458.3
MAXLUM	Maximum luminance (cd/m²)	Elevated luminance	1040	1691	1513	2311	1094	3224
PIX>1000	Pixels in Prometric image (total 98431) >1000 cd/m²	Elevated luminance	19	246	637	4850	26	5787
SD/LUM	Standard deviation of luminances, normalized by mean luminance	Variability	1.60	2.62	2.22	1.77	1.43	0.96
75P:25P/LUM	Ratio of luminances of 75th to 25th percentile pixels normalized by mean luminance	Variability	0.045	0.067	0.064	0.027	0.091	0.005

Table 2.5: Results of the analysis on physical correlates to semantic differential ratings for the HDR images, for the sub-sample who saw and rated the images first. Polynomial contrasts are shown, empty cells indicate non-significant contrasts.

Rating	Predictor	Polynomial Component									
		Linear		Quadratic		Cubic		Quartic		Quintic	
		F-test	$\eta^2_{part.}$	*F*-test	$\eta^2_{part.}$	*F*-test	$\eta^2_{part.}$	*F*-test	$\eta^2_{part.}$	*F*-test	$\eta^2_{part.}$
dim-bright	LOG_{10}(LUM)	385***	.96			4.69*	.23				
	LOG_{10}(MAXLUM)	388***	.96			15.8***	.50	5.54*	.26		
	PIX>1000	430***	.96								
nonuni-uni	SD/LUM			7.45*	.32			8.65**	.35	22.6***	.59
	75P:25P/LUM	6.17*	.28	6.46*	.29			27.2***	.63	4.55*	.22
unple-ple	LOG_{10}(LUM)	17.4***	.52	9.18**	.36	7.66*	.32				
	SD/LUM	6.52*	.29			6.24*	.28	16.7***	.51	9.02**	.36
	75P:25P/LUM	16.1***	.50			5.80*	.27	11.0**	.41		
gla-notgla	LOG_{10}(LUM)	38.1***	.70							7.91*	.33
	LOG_{10}(MAXLUM)	36.5***	.70	24.2***	.60					8.60**	.35
	PIX>1000	34.9***	.69							8.83**	.36

* = p≤0.05, ** = p≤0.01, *** = p≤0.001

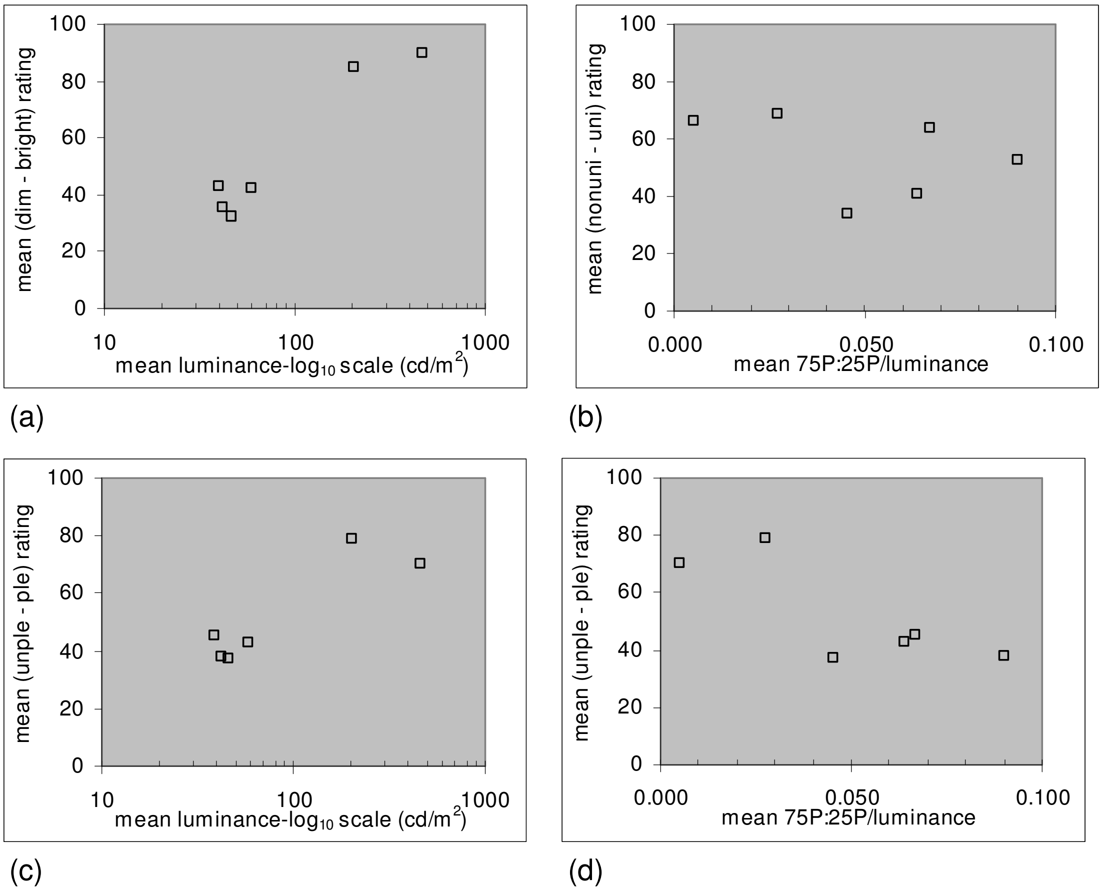


Figure 2.6: Example scatterplots of the relationships between mean ratings and photometric descriptors, for the HDR images. Graphs show data for those who saw and rated the images before the real spaces.

2.5 Discussion

It was predicted that the visual appearance of HDR images of office building interiors would be judged as more realistic than that of conventional images, and that there would be no differences between ratings of real scenes and HDR images, but differences between HDR and conventional images. The analyses of the semantic differential ratings for the three presentation types suggest that this hypothesis is supported for certain scenes only. Only the results for the lobby and staircase scenes followed the expected pattern. The lobby and the staircase were also among the four scenes for which the HDR image was rated as significantly more realistic in side-by-side image comparisons, after the real spaces had been experienced. These two spaces had substantially higher luminance than the other spaces (Appendix A and Table 2.4), and were the only two spaces with extensive window areas and daylight. In other words, the HDR images showed a significant reality improvement over conventional images for scenes with relatively large, high-luminance areas in which the conventional images could not reproduce the real scene luminance, the very situation for which the HDR device was designed. For scenes with only small areas of high luminance there was no apparent benefit for the HDR display. The mezzanine and open-plan office images were viewed as more realistic on the HDR display in the side-by-side comparison with the conventional display, but there were no obvious advantages in the semantic differential ratings. One explanation is that the HDR cannot faithfully reproduce small, high-luminance areas due to the size of the individual sources in the LED array. Future advances in HDR technology might mitigate this limitation. Akyüz et al. (2007) also found that some types of conventional images were rated as high or more highly than HDR images, for some scenes. However, one of the scenes for which this was true did appear to have (luminances were not reported) a large area of high luminance. Akyüz et al. (2007) also commented that some conventional images might be viewed more favourably simply because conventional images are currently more familiar to participants.

The results obtained with the present hardware show that, although HDR images were not always better than conventional images, when compared to reality, they were generally no worse. This is an important point when considering the use of images in the design process. Decisions made on the basis of images prior to the existence of a real space could be the same as those that would have been made had it been possible to view the design alternatives in reality. In this context, if the image presentation device is a conventional computer display, then HDR images will be at least as good, and in many important situations better, for the kind of visual judgements made in this study.

The findings related to ratings of brightness and uniformity give confidence in the overall validity of the ratings. As expected, ratings of brightness on the HDR images were strongly related to measures of overall luminance and elevated luminance. For example, there was a very strong linear effect of LOG_{10}(LUM), LOG_{10}(MAXLUM), and PIX>1000, with some smaller, higher-order effects. This mirrored the findings of Newsham et al. (2005) and is logically to be expected. We tried the same predictors for ratings of glare, and again found strong linear effects along with smaller, higher-order effects.

Ratings of uniformity were related to physical measures of luminance variability. However, these relationships were complex and involved multiple polynomial effects of similar size. Newsham et al. (2005) found a significant linear effect for a measure similar to SD/LUM, whereas the linear effect in this study was not for

SD/LUM, but for the related 75P:25P/LUM. In both studies, the linear component suggested that ratings of uniformity increase as luminance variability decreases, as would be expected. It is worth noting from Figure 2.4 the surprising trend for the real spaces to be rated as more uniform than the images. Whereas the analysis with HDR images does suggest that perceived uniformity does relate to variability in luminance as expected, this might not be the case across presentations. Newsham et al. (2005), with projected conventional images, in addition to uniform-non-uniform, tried using two other scales that were expected to be synonyms (varied – unvaried; simple – complex), but ratings were very different. This observation raises legitimate questions about how participants interpret the semantic scales related to uniformity.

Of more interest to the lighting quality research community are ratings of pleasantness, which were related to mean luminance and luminance variability. Higher luminance was generally related to higher pleasantness, similar to Akyüz et al. (2007), Seetzen et al. (2006), and Newsham et al. (2005). However, both Newsham et al. and Seetzen et al. also found a negative quadratic component for contrast ratios below 7500, suggesting that if luminance was too high pleasantness might suffer, an effect we did not see in the present study. The negative quadratic effect in Newsham et al. and Seetzen et al. might have been a reaction to glare, which was not separately rated in their studies. The range of luminances used in Newsham et al. (2005) was 0-140 cd/m^2, far below that used in the present study, but Seetzen et al., covered luminances of >6000 cd/m^2. Interestingly, the negative quadratic effect in Seetzen et al. was absent for a contrast ratio of 10000.

Newsham et al. (2005) found that attraction increased as variability increased, whereas the present study found that pleasantness decreased as variability increased. There may be a confound here, in that in this study the scenes with highest luminance (also a predictor of pleasantness), tended to be the most photometrically uniform. Such explorations are at an early stage, and invite more dedicated work.

3. PHASE 2: VIEW SIZE AND OFFICE LUMINANCE EFFECTS EVALUATION ON SATISFACTION WITH ROOM APPEARANCE AND PERCEIVED PRIVACY USING HDR TECHNOLOGY

This chapter presents the experiment investigating the relation of view size and office luminance effects on satisfaction with lighting, explains the reasoning of the methodology referring to the previous chapter, gives the data collection methods and procedure, data analysis plan, results of bracketed effects, full factorial MANOVA results and correlations between image characteristics and ratings, discusses the findings and gives comments on the results.

3.4 Literature Review on Windows and Blinds

This section includes literature review on window preferences, blinds in workspaces and use of images as stimuli as an alternative to real spaces. Providing a view to occupants is important as it affects occupant satisfaction and ultimately is a factor affecting organizational productivity. Delivering a view involves windows and shading systems. Occupants have preferences for both of these systems, and how occupants interact with these systems affect building energy performance. Therefore, it would be beneficial to have a technique for realistically evaluating windows, shading systems and view before a building is built. HDR technology is a potential tool for such analysis.

This study was conducted as a follow-up to the one presented in Chapter 2 to demonstrate the utility of the HDR display as a lighting design guidance tool. The research problem was chosen such that the capacities of the display would be used and that would help to guide lighting and interior design decisions. Based on the results of phase 1, a research problem that included daylight was indicated. The examination of different panel configurations can give practical information to interior designers about office layouts which balance the desires for view and privacy, and was the chosen daylighting problem for this phase.

3.4.4 Studies on Windows in the Workplace

In contemporary open-plan offices in North America, many occupants do not have direct access to a window. The potential for these occupants to enjoy the beneficial effects of windows is reduced. Windows provide a view to the outside, which provides information on the weather and time of the day, relief from claustrophobia, monotony or boredom, a change of eye focus, and spatial awareness of the surrounding area. There is also a general preference for daylight over electric light. Window access reduces stress and has restorative effects on the occupants (Leather et al. 1998, Farley and Veitch, 2001).

Studies of conditions in open-plan offices have also found that employees were more satisfied with lighting when access to windows/daylight was available in the occupant's workstation (Veitch et al, 2005, Newsham et al, 2009). A link between satisfaction with lighting and overall environmental satisfaction, and between overall environmental satisfaction and job satisfaction, was also shown in these studies (Veitch et al., 2007).

The design of office furniture and window shading devices can affect window access (view and daylight availability) for occupants not seated next to a window. The second part of this thesis studied these effects.

3.4.4.4 Window Preferences at the Workplace

This section presents previous studies investigating window preferences and proximity to windows, as well as collecting subjective response data using real spaces and scale models.

Keighley (1973a and 1973b) used a 1/12 scale model to investigate the most favoured shape and location of windows that cover a constant size of 20% of an external wall. Thirty subjects selected the best window geometry after seeing each of the eight views. The results showed that preferences were mediated by mean skyline height. The preferred window height was slightly but consistently lower for ground floor views than for upper floor views. Overall, the optimum window for the distant views was 1.1 m high and 3.4 m wide, with a sill about 0.8 m and head 1.9 m above the floor. However, when a nearby building obstructed the whole view, the results did not demonstrate one best shape and location of window. When subjects were asked which view they favour the most, the distant views with no obstacles in between the window and the view were chosen, whereas fully blocked views by nearby buildings were least preferred.

Butler and Biner (1989) tested whether window preferences differ depending on the function of spaces, whether small windows or no windows are favoured in some spaces, and what the motivational reasons are for subjects' preferences. Fifty-nine undergraduate students completed a questionnaire in a single assembly in a large lecture hall. Fourteen spaces common to students (including a computer work room, library, office and residential spaces) were selected. The list for the type of windows included size, transparency, on how many walls windows were preferred, and the option of no windows. The authors found that larger windows were preferred for family room, dorm room and library, small windows were preferred in houses for garage and bathroom, and no windows were preferred for lecture hall, public bathroom and computer workroom. The motivations affecting the subjects' ratings regarding size of office windows were; to see the view outside to follow transitory conditions, to see other people, to change the mood, to get exposure to sunlight, and to be able to perform their specific tasks. Furthermore, the authors reported that the amount of windows desired in a space could be foreseen when the personal preferences of occupants were known.

Butler and Steuerwald (1991) studied the effects of view and room size on window size preferences. They used a 1/12 scale model of 140 cm x 57 cm x 25 cm and the model had adjustable walls and windows. A 100 watt incandescent lamp lit the model from above. Subjects observed the model at the center front using a chin rest from a height of 13 cm above the floor of the model. Butler and Steuerwald found that window preferences were affected by room size and type of room, and type of view also had an effect on window size preferences. Natural scenes that included sky, horizon and foreground were preferred over built environments. More beautiful scenes were associated with larger preferred windows.

Boubekri and Haghighat (1993) examined whether proximity to windows affected workers' satisfaction with lighting and their overall workplace satisfaction by conducting a survey study on the eighth and ninth floors of an eleven-storey building with the participation of 102 workers. Approximately half of the workers had offices adjacent to bay windows and the remaining half were in the core area of the building, with no accessible windows. They reported that satisfaction with lighting and view was high for the workers who were adjacent to windows, whereas workers without access to windows were not satisfied with lighting and view. Workers without access to windows ranked lighting and view to be very important. On the contrary, those who had windows did not rank them very important. Boubekri and Haghighat reported that satisfaction with workplace environment is positively correlated with having access to a window.

The studies cited above give the window size and location preferences of occupants and the influence of having access to view on occupant satisfaction. The second phase of this dissertation will focus on the effect of view size on occupants and the lighting quality analysis by using HDR images, to validate whether the results obtained using the HDR technology will correlate with the existing literature.

3.4.4.5 Optimum Window Size – Balance of Solar Thermal Load and Daylight Penetration

Lighting design of an office should be done consciously to provide adequate lighting depending on the function of the space and to save energy. A combination of energy efficient lamps, luminaires and associated equipment is necessary to save energy. Lighting systems should be optimized by using control systems and by maximizing the integration of daylight to the electric lighting.

Ghisi and Tinker (2005) collected energy consumption data between March 1999 – April 2000 from a three-storey building on Leeds University campus, UK; and presented a methodology to assess the optimum window area that provides potential for energy savings through integration of daylight to the artificial lighting system and minimization of thermal energy load. Ghisi and Tinker simulated the energy consumption of each room with different sizes of windows by using VisualDOE. The simulation results were then validated by the collected data. Daylighting contribution and thermal energy analysis of windows were investigated for ten room sizes facing four orientations in Leeds, UK and Florianopolis, Brazil. It was reported that as the size of the room got larger and the width became narrower, the optimum window size increased. Rooms that had greater width than their depth had high daylight levels, but did not have the lowest energy consumption. Thermal load and daylight harvesting capacity of rooms with different sizes of window area and room ratios were presented, however no reference was made to window coverings (i.e. blinds) or partition heights.

3.4.5 Blinds

Rea (1984) collected data from a 16 story building with clear window glazing and horizontal blinds and studied the effect of window orientation, time of day, weather, and interaction of these three variables in relation to occupants' blind adjusting behaviours. Images of 555 windows facing east, south or west were taken on two days (a cloudy day in April and on a clear day in May) three times a day, in the morning, at noon and in the afternoon. A total of 3330 window images were examined.

Blind occlusion, that represented relative area of the blinds covering the window, was calculated from the photos of the façade. However, this measure was determined only by examining the vertical length of the blinds covering the windows and the blind tilting angle was not investigated. A scale of 0-10 was used; 0 indicated that the blinds were folded up and did not cover any area of the window, 10 indicated that blinds covered the whole length of window. One finding of this study was that during the day, even when there was a dramatic change regarding the sunlight penetration to the office, occupants made few adjustments to blinds or no changes at all.

Reinhart and Voss (2003) collected data from ten offices (with six female and eight male occupants) at a three-storey building facing SSW in Weilheim, Germany. The building had no air-conditioners but an external light-shelf and venetian blinds. The blinds were operated both manually and automatically, and the settings were recorded by an external video camera. The electric lighting and external venetian blinds were connected to a European Installation Bus (EIB) system. Two indirect luminaires consisting of 2 x 58W light sources were manually switched on and off. The light sources were dimmed during the day via a control sensor located on the ceiling and the maximum illuminance reached on the work plane was 400 lx. User occupancy, indoor temperature, direct and diffuse irradiance, and façade illuminance data were collected. Reinhart and Voss tested whether an electrical lighting system and controlled blinds are adjusted in relation to each other or if they are controlled independently.

Reinhart and Voss (2003) reported that people generally switch on the lights when they come to the office and switch them off when they are leaving at the end of the working day. Before leaving the office temporarily during the day, the probability of switching off lights depends on the length of absence. The longer the office will be unoccupied, the more likely that the lights will be switched off before the occupant leaves. The probability of switching on the lights also depends on the work plane illuminance when the occupants enter the space. The lower the illuminance (<200lx), the more likely that the lights will be switched on.

The occupants were more likely to accept when the exterior blinds were automatically opened than when closed. The occupants did not react to automatically closed blinds under the following two conditions:

- The illuminance at the façade reached a high of 50 000 lx,
- The illuminance at the workplace was higher than 10 000 lx due to direct sunlight.

Regarding switching patterns of the individuals in relation to the illuminance at the workplane, although there were differences between individuals, groups of individuals followed the same pattern.

Blinds are consciously adjusted in a certain position considering the advantages and disadvantages over a long period of time (Rea, 1984); and occupants tend not to adjust the blinds manually depending on the solar elevation and time of the day, which is perfectly reasonable from the practical point of view. The reasons for adjusting the blinds are:

- To block direct sunlight,
- To prevent overheating (Rea, 1984; Reinhart and Voss, 2003),
- To reduce glare on computer screens (Reinhart and Voss, 2003).

3.4.5.4 Predicting and preventing visual discomfort from window glare

Fisekis et al (2003) collected data during ten months from two identical rooms located on the roof a two-storey house in the UK and evaluated the Daylight Glare Index (DGI) in relation to various calculations of background luminance and the Unified Glare Rating (UGR) from the CIE. Luminance and subjective evaluations data were collected from two types of views under overcast, intermediate and clear sky conditions. In total 5 glare prediction models were evaluated; DGI model with background luminance (L_b) in the denominator, DGI model modified with average luminance over the hemisphere of view (L_a), DGI model modified with $L_a^{0.85}$, $8\log(L_a)$, UGR modified with L_a, and an experimental UGR. In addition, UGR data was compared to DGI values. A positive correlation was found between the predicted DGI values and the data collected from the subjects. UGR values showed correlation when L_a was substituted for L_b, and modified DGI with $L_a^{0.85}$ indicated the best fit.

Tuaycharoen and Tregenza (2007) studied discomfort glare from windows in relation to view. The authors conducted two experiments in May and June 2005, in a twenty-storey building in Sheffield, UK. The first experiment examined ratings in real spaces. Identical unfurnished rooms with dimensions of 4 m x 3 m x 3 m were chosen from different levels of the building facing different orientations, and having different views. Subjects sat 2 m away from the window and rated aspects of urban and natural scenes. Seventy-two subjects compared discomfort glare of a bright window covered by a diffusing material, first with a window that had a view of little interest and then with a window that had an interesting view.

In the second experiment, participants viewed high-dynamic-range images (Tuaycharoen and Tregenza, 2007). Ninety-six subjects compared glare from views that contained natural scenes and man-made objects, and views with combination of foreground, middle distance, far distance and sky, with views of middle distance only. Luminous distribution of the views were obtained from high dynamic range images, a photocell with a conical mask was used to measure mean luminance of the view and illuminance at each subject's eye position was measured by an illuminance meter on a vertical plane. The Hopkinson Cornell Daylight Glare Index was calculated from the angular and luminous measurements taken when the subjects were completing the questionnaire. The authors reported that subjects' had more tolerance of discomfort glare for views that contained interesting information and concluded that discomfort glare cannot be forecasted only from physical variables of source luminance, source size, background illuminance and position index alone.

3.5 Hypotheses

Examining lighting research questions that require subjective analyzes of spaces involving daylight are cumbersome. This is due to the difficulties associated with controlling exterior conditions (i.e. sun elevation angle, sky conditions) over the long periods of time required to collect data from subjects and which are necessary to yield interpretable results. HDR technology is proposed to overcome these difficulties. Phase 1 has demonstrated that HDR images are viewed as more realistic than conventional displays, for scenes containing substantial window (high luminance) areas. HDR images prepared in advance are proposed to be used as stimuli. These images with controlled parameters may be shown to each participant over the subjective data collection period. Following this approach, HDR images were used as stimuli in Phase 2. Furthermore, HDR images modeling non-existing buildings that represent the final outcome of the electrical lights and daylight penetrating through windows may be used at the design stage to enhance communication between the lighting designer and their clients.

Satisfaction with office space is an indirect contributor to organizational performance while open-plan offices are the norm in North America; therefore, parameters affecting satisfaction in open-plan offices were chosen for investigation in this experiment. These parameters desired by occupants are; view of a window, privacy from neighbouring cubicles, daylight in the office space and control of glare from windows or electric light sources. Previous research showed that once people closed the blinds early in the day they were unlikely to open them again. Understanding how the blind setting chosen by the occupant close to the window affects the occupant in the interior cubicle will provide useful information, as blind adjustments also affect the view provided to the occupants away from the windows. Moreover, the decision making process for panel configuration is an optimization of desire for view and privacy, and these factors were studied in this experiment.

In this experiment HDR images of an open-plan office were used. Privacy was studied by varying the presence of a neighbour in the view. Employees need personal privacy to focus on tasks that require high attention. Therefore, offices should be designed to satisfy this need. High panels that provide complete privacy block the view to the outside and prevent daylight entering the space, which causes dissatisfaction. The aim of this study was to find the panel height and panel material combination that provides the benefits of both privacy and view. The hypotheses of the study were:

H1: As panel height gets lower, ratings for satisfaction with lighting and spaciousness increase, and ratings for privacy decrease,

H2: Presence of a neighbour in the images will affect subjects' ratings for privacy,

H3: As the view size increases, ratings for satisfaction with lighting and amount of view increase,

H4: Regarding satisfaction with lighting and satisfaction with view, Hybrid will perform better than Standing Privacy; and regarding satisfaction with privacy, Hybrid will perform as well as Standing Privacy.

The following were the measures of the study:

- Satisfaction with lighting measures: amount of light and visual comfort,
- Room appearance measures: pleasantness, spaciousness, tenseness, excitement,
- Privacy judgements,
- Amount of view judgements.

The results may contribute to office furniture design, and rating schemes for green buildings.

3.6 Methods and Procedures

This section gives information on participants, stimuli, dependent measures and experimental procedure.

3.6.4 Participants

Forty-three participants (25 women and 18 men, ages 18-65 years) who were employees at the National Research Council (NRC), Ottawa, Canada volunteered to participate in this experiment. Table 3.1 shows the demographic data of the participants. Office type, number of employees in the workspace and presence of a window next to desk relates to where the subjects normally work. Employees who might have participated in previous lighting experiments were excluded. Recruitment was arranged via internal e-mail to NRC employees on the Montreal Road, Ottawa campus. For this study the recruitment criteria were as follows:

- Between the ages of 18 and 65 years (covering the age range typical of the general office population);
- Have normal or corrected-to-normal vision (i.e., glasses or contact lenses were worn if needed);
- Have no physical disabilities that would prevent access to the experimental facility.

Depending on the participant's availability, one to four participants participated per day from November 5 - November 26, 2007.

The number of participants was chosen to be approximately 40. This was determined by a review of previous studies in which images were used as stimuli and in which interpretable effects were observed. Hendrick et al.(1977) employed 185 participants, groups of 30-40 students observed images at a time; Eissa and Mahdavi (2001) employed 50 participants, Newsham et al. (2005) employed 40 participants; Tuaycharoen and Tregenza (2005) employed 24 participants, and Newsham et al. (2002) employed 54 participants using an early version of the HDR display prototype. In the first phase 39 participants were employed using the HDR display, which was also used for this phase, and interpretable data were obtained. This information suggested a target of 40 participants for this study would yield interpretable results.

Table 3.1: Demographics of the participants.

	18-29	30-39	40-49	50-59	> 60
Age of participants	2	9	18	12	2
	no correction lenses	multi-focal lenses	others		
Lens	14	13	16		
	administrative	technical	professional	others	
Job type	12	10	18	3	
	private office	open office with partitioned cubicles	others		
Office type	17	22	4		
	only me	me and two or more others	others		
Number of employees in the workspace	20	19	4		
	I have	I don't have			
Window next to desk	31	12			

3.6.5 Stimuli

Images of an open-plan office were taken from the viewpoint of an employee sitting in the second row of cubicles from the window. Figure 3.1 shows thumbnails of the images rated by the participants. The view varied depending on the height of the panel between the cubicle rows, the position of the venetian blinds in the window, and the presence or absence of a person in the neighbouring cubicle (the one by the window). The view in this thesis had a natural scene (suburban campus with trees) with combination of foreground, middle distance and sky; and according to Tuaycharoen and Tregenza's classification, falls in the category of interesting scenes.

The electric lighting in the space consisted of 1' x 4' recessed flat-lensed troffers, each with 2- 32WT8, 4100 K, 80 CRI fluorescent lamps on non-dimming electronic ballasts.

This experiment involved a 3 X 3 X 2 (Panel X Blind X Neighbour) factorial design, plus three additional stimuli (described below). In the factorial design, there were three panel heights; no visible panel (desk+), one level high panel (seated privacy) and two level high panel (seated privacy+). The barrier between the cubicles in the Desk+ panel condition was 81 cm high, seated privacy was 122 cm high and standing privacy was 163 cm high (measured from the floor).

The panel immediately above desk level was made of fabric of a light brown colour. Where a second panel was used, it was located above the first panel and made of glass covered by a film of dots (with 82% light transmittance). This panel permitted daylight to pass, yet provided more privacy than plain glass.

The workstation was near an external window which was covered with blinds in one of three positions: closed, tilted (partially closed) or open (slats horizontal).

The final factor was whether a neighbour was visible in the next cubicle, or not. The neighbour was always seen from the side, facing to the left of the image. For the images with desk+ panels, the neighbour was seated as though working on a computer. For the images with seated privacy and seated privacy+, the neighbour stood, facing in the same direction as when he was seated. The same young male assistant served as the neighbour in all cases.

In addition to 18 images that were part of the full factorial experiment design, three cases were added (all without a neighbour):

- standing privacy (two levels of fabric panels),
- hybrid (two panels with one glass and one fabric stack-on on the second level) and
- three levels of fabric panels.Figure 3.2 shows the experimental design diagram.

3.6.5.4 HDR Photography

High Dynamic Range (HDR) images representing each of the 21 configurations were prepared prior to data collection from subjects. The image shooting was completed on two afternoons, on August 27th and 28th, 2007 between 2:15 p.m. and 6:00 p.m. Furthermore, to limit the fluctuations in luminance from images with and without a neighbour, images with a neighbour were captured right after capturing images without a neighbour and all measurements for each panel and blind setting were completed within 20 minutes. Appendix C shows image luminance iso plots of the images as displayed to participants on HDR display.

In the process of making HDR images, extensive luminance measurements were taken. Figure 3.3 shows the measuring points for the scene desk+open (desk+ panel height and open blinds).

Initial luminance measurements in the real space were taken based on a grid. The results showed that readings symmetrical to the mid vertical line of the images were consistent with the readings taken on the mid vertical line in real space. Because measurements for each scene had to be completed within a short period of time to minimize the confounding effects of daylight variability, final readings were taken only on the points in the middle. Point 5 was located to the right of the image for practical reasons. It was convenient to find that point with the luminance meter. A mark on the window frame made it easier to locate, whereas the frame on the left was not visible due to the furniture mid line. Measurements were taken on three points on the ceiling. In order to capture the luminance data on the left and right of the images, two representative points (point 9 and 10) were added. The chosen measuring points were also representative of the variety of luminance levels in each scene.

Photos were taken between 2:15 p.m. and 6:00 p.m. because the luminance readings earlier in the day exceeded the luminance level that we could display on the HDR display. Ideally in such a study, all images would have been taken at the same time to eliminate the fluctuations of sky luminance, but in practice that was not possible. The fluctuation of sky luminance affected the real space and HDR image luminance matching particularly for points on the windows. Table 3.2 shows sky luminance readings taken from the same measuring point on September 2nd, 2007. To reduce differences due to the changes in sky luminance, taking of images and luminance readings were completed within 20 minutes for each scene.

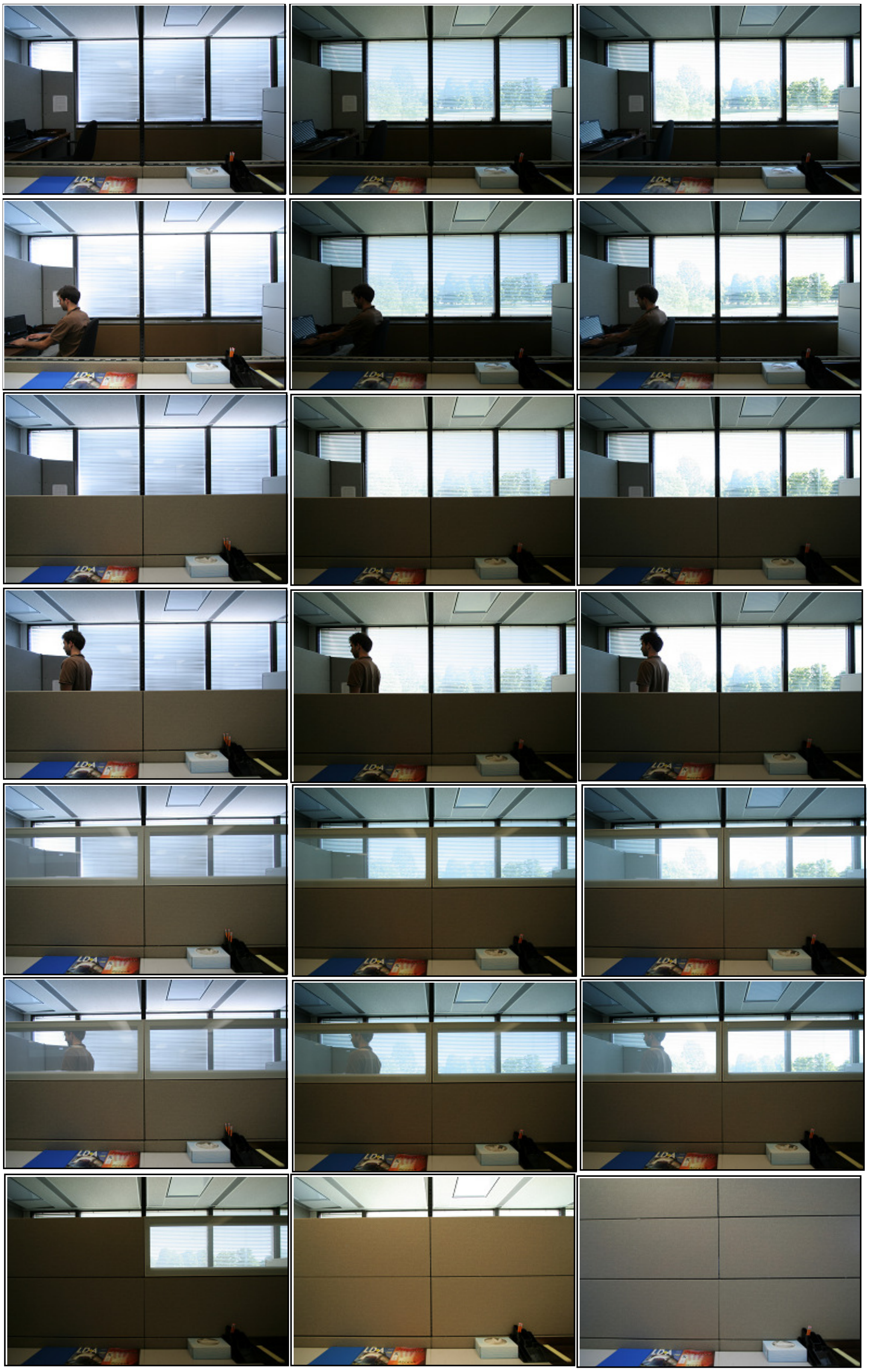


Figure 3.1: Images rated by the participants: on columns blinds are closed, tilted and open respectively; on rows panel heights are desk+, seated privacy and seated privacy+ respectively; three additional images on last row are hybrid, standing privacy and three layers. Images with neighbour follow the images without neighbour.

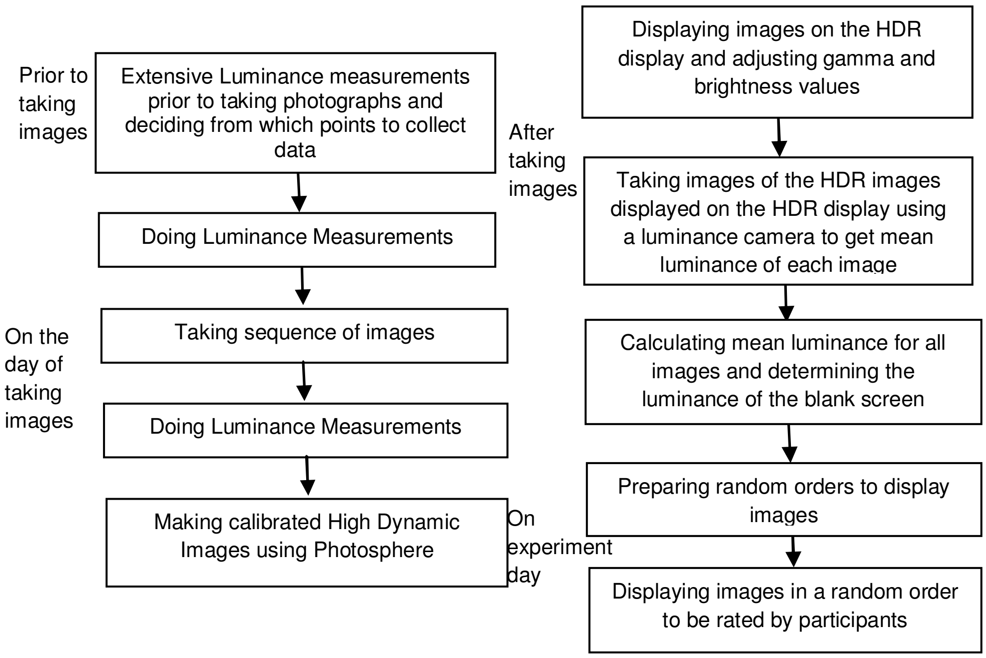


Figure 3.2: Diagram of the experimental design.

Figure 3.3: Measuring points for the scene desk+open (desk+ panel height and open blinds).

Table 3.2: L_{sky} measurements of September 2nd, 2007.

time	14:45	15:00	15:15	15:30	15:45	16:00	16:15	16:30
L_{sky}(cd/m^2)	5530	5003	4760	4439	4180	3998	4000	3960

time	16:45	17:00	17:15	17:30	17:45	18:00	18:15
L_{sky}(cd/m^2)	3890	3530	3376	3238	2720	2470	2272

As in the first phase, all images in this phase were captured with a Canon EOS Digital Rebel XT camera mounted on a tripod at seated head height and fitted with a wide-angle lens (Canon EFS10-22mm). The angle of view was 74^o vertical and 97^o horizontal; image capture size was 1728 x 1152 pixels. The camera was connected to a computer and images were captured using remote shooting software. All bracketed images were taken from the same location. The camera was used in the manual mode and exposure of images was changed only by varying the shutter speed (exposure time). Images were taken using shutter speeds of 2 to 1/500s (2s-1s-1/2s-1/4s…1/500s) by halving the shutter speed as the exposure becomes shorter. The aperture size was set to f/4, ISO was set to 100.

Sets of bracketed images taken of a given scene at the selected exposure settings were combined into HDR images using the software Photosphere (Ward, 2005). As in the first phase, the brightness histogram of each image was examined so that the darkest images used had no RGB values greater than 200 and the lightest images had no RGB values less than 20, as recommended by Reinhard et al. (2006, p.146). One calibration point was selected in each scene. For that point, luminance of the real space was divided by luminance obtained from the software Photosphere and this ratio was set as calibration factor. The calibration factor was then related to all pixel luminance values in the image.

3.6.5.5 HDR Image Display

The final HDR images were displayed on the HDR display, and the display brightness and gamma were fine-tuned to generate the best overall match across all measurement points. The aim was to match onscreen luminance with the luminance in the real scene. The HDR display used in this experiment has the capability of displaying luminance up to 4000 cd/m^2. For more information about the HDR display, please refer to Chapter 3. A comparison of spot luminance readings in the real space setting and on the HDR display is shown in Appendix D for all 21 scenes. Appendix E shows the images with measuring points.

A Prometrics luminance camera was used to capture images of the HDR scenes displayed on the HDR display. These images were then used to obtain the luminance distribution of the images. Appendix C shows L iso plots of the images. Appendix F shows average luminance of each scene and average luminance of selected areas on these scenes. Average luminance of various surfaces has been calculated in addition to spot luminance measurements to examine the luminance distribution of the scenes.

In the laboratory, where participants rated the images, luminance around the HDR display was adjusted to the same level on all experiment days. Extensive luminance readings were taken before the experiments started and these measurements were repeated after the first half of the data collection from participants, to ensure that all participants were exposed to same luminance conditions in the laboratory. Figure 3.4 shows the measurement points around the HDR display and Table 3.3 shows the luminance readings corresponding to these points.

Figure 3.4: Measurement points around the HDR display.

Table 3.3: L readings around the HDR display.

Point	L(cd/m^2)
1	61.5
2	28
3	25
4	25
5	25
6	21
7	37
8	34
9	32
10	28
11	28
12	18
13	31

3.6.6 Dependent Measures

Each participant rated each of the 21 HDR images on eight scales. Five were presented as semantic differential pairs: too much light-too little light, unpleasant-pleasant, spacious-cramped, tense-calm, exciting-boring. There were three satisfaction scales: satisfaction with the amount of privacy, satisfaction with the amount of view and satisfaction with the amount of visual comfort. All three satisfaction ratings were scored on 7-point scales. Appendices G and H show the questionnaires in English and in French respectively.

For analysis of the data, amount of light, spaciousness, excitement and excitement were reverse-scored. Thus, for all variables, ratings are from less to more. For instance, a value of 1 for amount of light means a rating of 'too little light' and a value of 7 means 'too much light'.

Prior to starting their ratings, participants were given the dictionary definitions of the adjectives that were used in the questionnaire. The definitions, given in Appendix I and J respectively for English and French versions, were put on a separate document holder on the desk next to the display and were accessible during the entire experiment.

3.6.7 Procedure

On the day of the evaluations, participants were met in the lobby and guided to an open-plan office that was used as a laboratory for this study. Figure 3.5 shows this space.

Figure 3.5: Laboratory space used to inform participants and for evaluations of images.

Participation took place in either English or French (the official languages of Canada, where the experiment took place), according to the participant's choice. For English speaking participants, one experimenter ran the experiment from the cubicle behind the HDR display. For French speaking participants, a French-speaking colleague gave the instructions in French and the experimenter ran the tasks at the computer.

Each participant was informed about the experiment at the meeting table seen on the left in Figure 3.5, and asked to sign a consent form. Then the experimenter explained the details of the experiment. At that level it was important not to give any information that would bias the participants' ratings. Brief instructions were given on how to proceed through the experiment. Participants were then led to the open-plan office where the image evaluation took place.

Each participant observed all 21 HDR images displayed in one of six predetermined random orders. It was ensured that two images with the same partition height and blind position (with or without neighbour present) did not come one after the other. During the development of these random sequences, in one instance there were four cases with the same partition height in a row. This was avoided by swapping the first and last scenes with others.

For adaptation purposes, before the first image and in between each image a blank white image was displayed for 30 seconds. The luminance of the blank image was chosen based on the average luminance of all images and was 121 cd/m^2. The participants were asked to keep their attention on the screen when it was blank.

When an image appeared on the screen, the participants had 30 seconds to become accustomed to the scene. Then the experimenter invited the participants to complete the rating scales for that scene. When the participants finished the ratings, they informed the experimenter so that the experimenter could move on to the next blank screen and then to the following image. The ratings questionnaires were presented in paper booklets on a clipboard, and answered in pen.

The whole procedure took about an hour. The participants were then asked to fill in a questionnaire to provide demographic information about themselves. The questionnaire consisted of information on sex, age, type of corrective lenses they wore on the day of the experiment, their job type, type of office space, how many people occupied their office room, how long they had had that office, and whether they had access to a window in their current office. The demographics questionnaire is shown in Appendices K and L; in English and in French.

3.7 Results

In this section, bracketed effects, MANOVA factorial analysis, and correlations between image characteristics and ratings (including effects of average luminance, luminance variability and view size) are given.

3.7.4 Data Analysis Plan

Initially, planned comparisons were conducted to test effects involving the three extra images, which bracketed the possible effects by representing extremes in conditions. Then multivariate tests of the full factorial design were examined to isolate the effects of panel height, blinds position, and the presence of a neighbour. In the last part of the analysis, trends in relation to the photometric properties of images were examined. Full support for the hypotheses would be shown by an increase in satisfaction with lighting, as the panel height decreases and the amount of view increases.

3.7.5 Data Checking

Although participants had been randomly assigned to one of six randomly-created orders of presentation, there remained the possibility that the order of presentation could have biased their responses. For instance, there might have been something different about a particular order, or something different about participants assigned to that order.

The order effects were checked by first running the multivariate analysis of variance (MANOVA) for Panel x Blind x Neighbour (the basic repeated-measures experimental design), then saving the residuals. This removed the variance associated with the repeated-measures variables. The residuals were examined using a mixed model, Panel x Blind x Neighbour x Order, where order was introduced as a between-groups variable. In the multivariate test, Panel x Order ($F(80,110)=1.65$, $p<0.01$, $\eta^2_{partial}=0.53$) and Panel x Blind x Order ($F(160,35)=2.31$, $p<0.01$, $\eta^2_{partial}=0.91$) were statistically significant.

After obtaining these results, original ratings data were used to calculate average ratings for each case (giving one score for each image averaged over all the ratings for that image). The average ratings for the images were averaged across the order groups. Figure 3.6 shows that ratings for order 4 differed from the other five groups. Luminance sequences of images in each order were plotted, but order 4 did not seem any different than other orders; that is, the pattern of average luminances from one image to the next for each set of images did not differ. Demographics of the participants in each group were checked but it was not clear how order 4 differed from the others. Although we were uncertain of the reason for the difference, we judged that the results from order 4 could bias the results. Therefore data collected from 7 participants, who had been randomly assigned to order 4, were discarded.

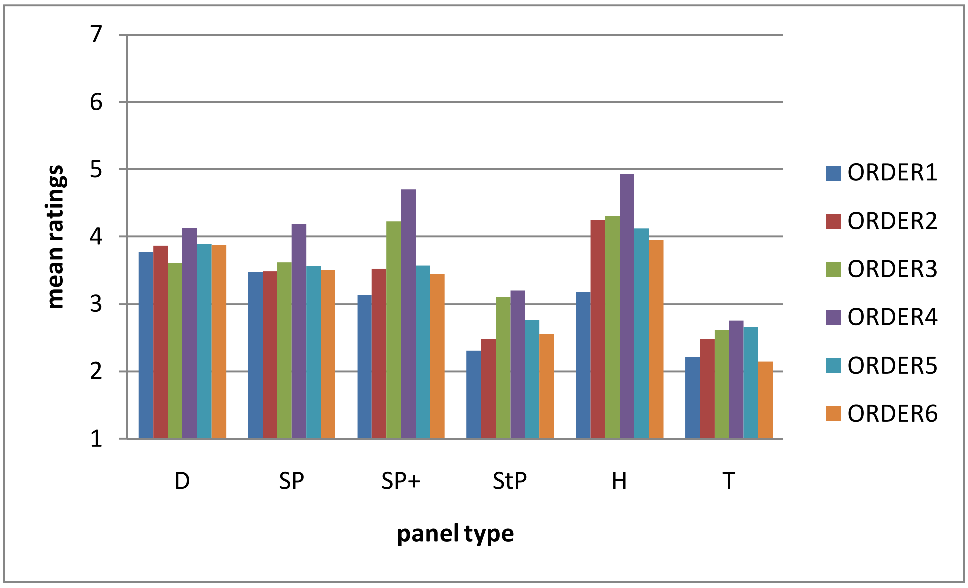


Figure 3.6: Average ratings for cases grouped by panel type (desk+, seated privacy, seated privacy+, standing privacy, hybrid and three layers) and order (predetermined random sequences of images).

3.7.6 Bracketed Effects

Planned comparisons are given in this section.

3.7.6.4 Planned Comparisons

The planned comparisons were between (1) *desk+open* (DO) versus *three layers* (TL), (2) *hybrid-tilted* (HT) versus *seated privacy+tilted* (SP+T) and (3) *hybrid-tilted* versus *standing privacy* (StP). The first comparison was between the most open and the most closed scenes in relation to view. The second and third comparisons examined the differences due to panel material on the second panel level. Each analysis looked at the contrasts regarding all the dependent measures: too much light-too little light, unpleasant-pleasant, spacious-cramped, tense-calm, exciting-boring, satisfaction with amount of privacy, satisfaction with the amount of view and satisfaction with the amount of visual comfort.

The General Linear Model (GLM) was used to run one-way repeated measures analysis of variance for the multivariate construct, to investigate the contrast between the independent variables desk+open (panel height: desk+, blinds: open; DO) and three layers of panels (TL). Table 3.4 shows the multivariate and univariate test results associated with desk+open and three layers of panels.

Table 3.4: Univariate statistics for DO versus TL.

DO versus TL	*Wilks' lambda = 0.046, F*(8,28)=73.36**, η^2*partial* =0.95	
	Univariate Statistics *df*=1, 35	
	F	η^2*partial*
amount of light	77.69**	0.69
pleasantness	155.9**	0.82
spaciousness	73.66**	0.68
tenseness	36.13**	0.51
excitement	123.56**	0.78
privacy	52.5**	0.60
amount of view	494.68**	0.93
visual comfort	8.71*	0.20

*=p≤0.01, **=p≤0.001

Figure 3.7 shows the ratings contrasted in this test between the most open view, and the most closed one. Means and standard deviations are reported in Appendix M. As expected, desk+ was rated to have more light than three layers. Desk+ was also rated as more pleasant, spacious, calm (not tense) and exciting than three layers. Ratings for 'satisfaction with amount of view' and 'satisfaction with visual comfort' were higher for desk+open than three layers. On the other hand, as one would expect, satisfaction with privacy was much higher for three layers than desk+open. Except for visual comfort, all of the effect sizes are statistically very large.

Figure 3.8 presents statistically significant results for planned comparisons of Hybrid (HT) versus Standing Privacy (StPT), and Hybrid versus Seated Privacy+ (SP+T). Means and standard deviations are reported in Appendix M. Table 3.5 and 3.6 show the multivariate and univariate test results associated with Hybrid and Standing Privacy, and Hybrid and Seated Privacy+ respectively. Blinds were at tilted position for these three cases.

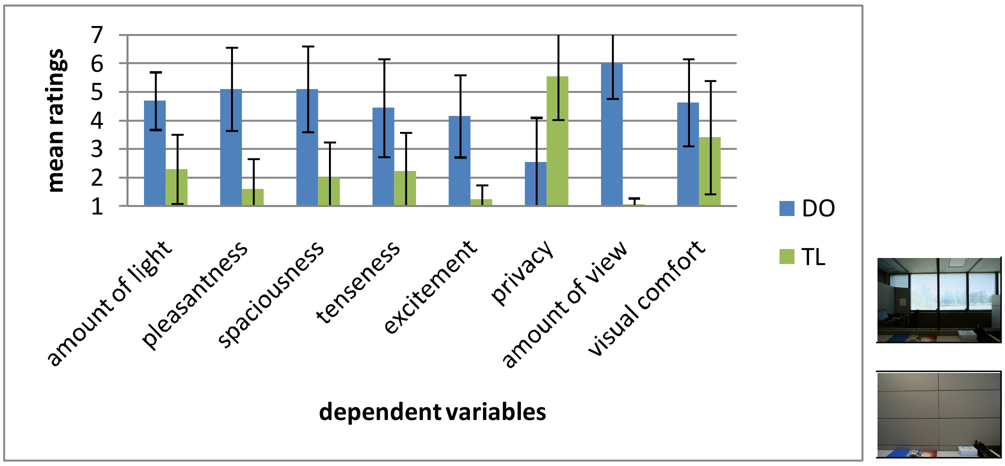


Figure 3.7: Planned comparison between Desk+blinds open(DO) versus three layers of panels (TL) (with standard deviation bars on the chart).

Table 3.5: Multivariate and univariate statistics for HT versus StPT.

HT versus StPT	*Wilks' lambda = 0.241, F*(8,28)=10.99**, η^2*partial* =0.76	
	Univariate Statistics *df*=1, 35	
	F	η^2*partial*
amount of light	24.25**	0.40
pleasantness	57.32**	0.62
spaciousness	40.16**	0.53
tenseness	28.02**	0.45
excitement	62.01**	0.64
privacy		
amount of view	53.43**	0.60
visual comfort	11.03*	0.24

*=p≤0.01, **=p≤0.001

In comparison to Standing Privacy (StPT), Hybrid was rated to have more light, to be more pleasant, spacious, calm and less boring. Satisfaction with the amount of view and visual comfort was higher for Hybrid than Standing Privacy. While providing all these benefits, with respect to satisfaction with privacy there is no statistically significant difference between Hybrid and Standing Privacy.

Table 3.6: Multivariate and univariate statistics for HT versus SP+T.

HT versus SP+T	*Wilks' lambda = 0.497, F*(8,28)=3.54*, η^2*partial* =0.50	
	Univariate Statistics *df*=1, 35	
	F	η2partial
amount of light	10.03*	0.22
pleasantness		
spaciousness		
tenseness		
excitement		
privacy	6.09**	0.15
amount of view		
visual comfort		

*=p≤0.01, **=p≤0.001

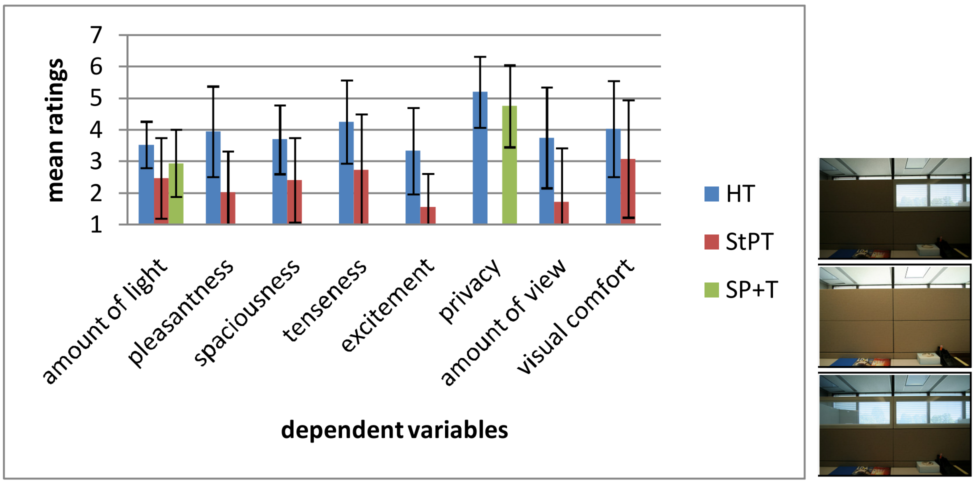


Figure 3.8: Planned comparisons of Hybrid (HT) versus Seated Privacy+ (SP+T) and Hybrid (HT) versus Standing Privacy (StPT) (with standard deviation bars on the chart).

In the comparison between Hybrid (HT) and Seated Privacy+ (SP+T), there was no statistically significant difference with respect to pleasantness, spaciousness, calmness, excitement, satisfaction with the amount of view and visual comfort. Ratings regarding satisfaction with privacy indicated that Hybrid provided more privacy than Seated Privacy+.

Ratings showed that Hybrid had more light than Seated Privacy+. Hybrid had one glass and one fabric stack-on on the second layer, and Seated Privacy+ had two glass stack-ons on the second layer, therefore this finding was rather confusing.

The files with physical measurements of the spaces revealed that the photographs for Seated Privacy+ were taken one day after taking the photographs for Hybrid and Standing Privacy. Average Luminance for these three images were:

HT = 88 cd/m^2,

StPT = 48 cd/m^2,

SP+T = 62 cd/m^2.

The ratings for "amount of light" showed that the participants had detected the luminance difference of 26 cd/m^2 successfully. Besides practical difficulties of the technique, ratings of the first question (on y axis, 1 = too little light, 7 = too much light) indicated that participants were very sensitive to luminance differences of the HDR images displayed on HDR display.

3.7.7 Factorial MANOVA Analysis

The full factorial general experimental design for the semantic differential ratings was 3 (panel heights: desk+, seated privacy or seated privacy+) x 3 (blinds: closed, tilted or open) x 2 (with and without neighbour) within-subjects, with eight outcome variables. There were no statistically significant three-way interactions.

Panel X Blind, Panel X Neighbour and Blind X Neighbour interactions with single-degree-of-freedom comparisons were explored, followed by main effects of the three variables. For Panel, the single-degree-of-freedom planned comparisons were between Desk+ and seated privacy (DvsSP) and between seated privacy and seated privacy+ (SPvsSP+). For Blind, the single-degree-of-freedom contrasts were the polynomial trends for linear and quadratic effects. Mean ratings of Panel X Blind X Neighbour are given in Appendix N.

3.7.7.4 Panel X Blind Interactions

Univariate tests of Panel X Blind interactions were conducted. Table 3.7 shows the multivariate statistics for Panel_DvsSP X Blind-Linear, Panel_DvsSP X Blind-Quadratic, Panel_SPvsSP+ X Blind-Linear, Panel_SPvsSP+ X Blind-Quadratic.

Table 3.7: Panel X Blind Multivariate Statistics.

	df=8, 28	
	F	$\eta^2 partial$
P_D vs SP X B-L	4.65**	0.57
P_D vs SP X B-Q		
P_SPvsSP+_B_L	13.58**	0.79
P_SPvsSP+_B_Q	6.92**	0.66

*=p≤0.01, **=p≤0.001

Both Panel_SPvsSP+ X Blind-L and Panel_SPvsSP+ X Blind-Q are statistically significant. The effect size of Panel_SPvsSP+ X Blind-L is larger, and it has the largest number of significant effects; therefore, these results were interpreted first. The results indicate that the effect of panel height (seated privacy versus seated privacy+) was different depending on the degree of blind openness (closed or open). The univariate statistics for Panel_SPvsSP+ X Blind-L are given in Table 3.8. There were statistically significant differences for seven of the eight dependent variables.

Table 3.8: Univariate statistics for Panel X Blind.

	df=1, 35					
	DvsSP_Blind_L		SPvsSP+Blind_L		SPvsSP+Blind_Q	
	F	$\eta^2_{partial}$	F	$\eta^2_{partial}$	F	$\eta^2_{partial}$
amount of light			45.16**	0.56	29.16**	0.45
pleasantness	8.44*	0.19	14.52**	0.29	17.19**	0.33
spaciousness			13.01**	0.27	8.09*	0.19
tenseness			8.34*	0.19	7.5*	0.18
excitement	12.66**	0.27	12.7**	0.27	26.83**	0.43
privacy						
amount of view	24.45**	0.41	16.27**	0.32	23.83**	0.4
visual comfort			13.32**	0.27		

* = p≤0.01, ** p≤0.001

Post hoc tests showed that when blinds were open, the mean rating for amount of light was higher for seated privacy panel height than seated privacy+. Nevertheless, when the blinds were closed, mean ratings for the amount of light for seated privacy+ was higher than seated privacy (Figure 3.9). Light reflected from the glass on the second panel level maybe the reason for this finding.

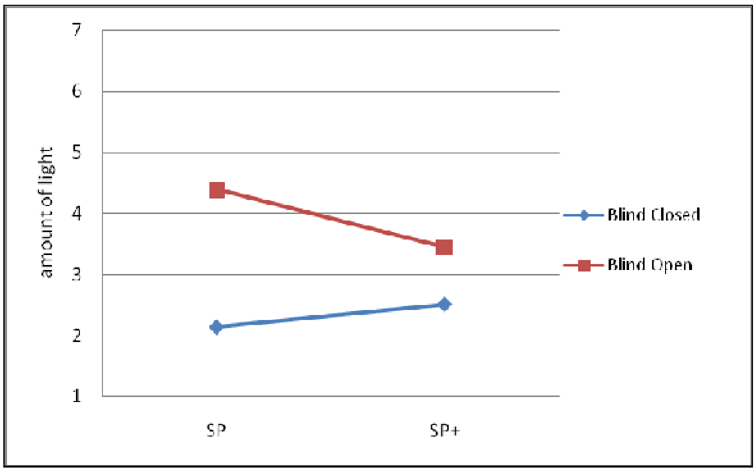


Figure 3.9: Ratings for amount of light for images with Seated Privacy and Seated Privacy+ Panel height, under closed and horizontal blind conditions, 1 stands for too little light and 7 stands for too much light.

The univariate effects of pleasantness, spaciousness, excitement, amount of view and visual comfort follow the same trend. The blind position affects the subjects' ratings for seated privacy panel height, and makes little or no difference to ratings for seated privacy+. The related charts are given in Appendix O. The univariate statistics for Panel_SPvsSP+ X Blind-Q are given in Table 3.8. There were statistically significant differences for six of the eight dependent variables.

Post hoc tests (Appendix P) showed that when blinds were closed, ratings for Seated Privacy+ on the amount of light, spaciousness, calmness, excitement and amount of view were higher than ratings for Seated Privacy. Ratings for Seated Privacy did not differ or differed very little when blinds were tilted or open. As expected, when blinds were open, both SP and SP+ had higher ratings for the amount of light and amount of view, than when blinds were closed. Images with Seated Privacy panel height had higher ratings than images with Seated Privacy+, when blinds were open or tilted. Figure 3.10 shows the univariate ratings for pleasantness.

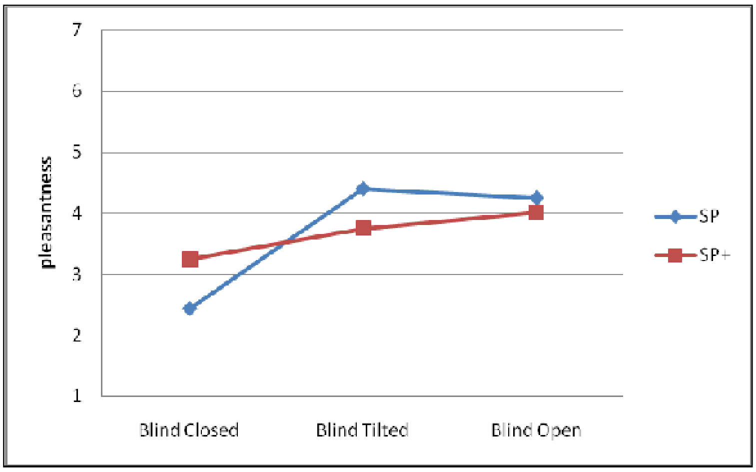


Figure 3.10: Ratings for pleasantness for images with Seated Privacy and Seated Privacy+ Panel height, under closed, tilted and horizontal blind conditions, 1 stands for unpleasant and 7 stands for pleasant.

Univariate results for amount of light, spaciousness, calmness, excitement and amount of view follow a similar pattern and these results are given in Appendix P.

The relations of panel height desk+ versus seated privacy, and blind position were also examined. Table 3.8 shows the univariate statistics for Panel-DvsSP_Blind_L.

The univariate test regarding the amount of view showed that blind position affected the subjects' ratings. Scenes with open blinds had higher ratings than scenes with closed blinds (Figure 3.11).

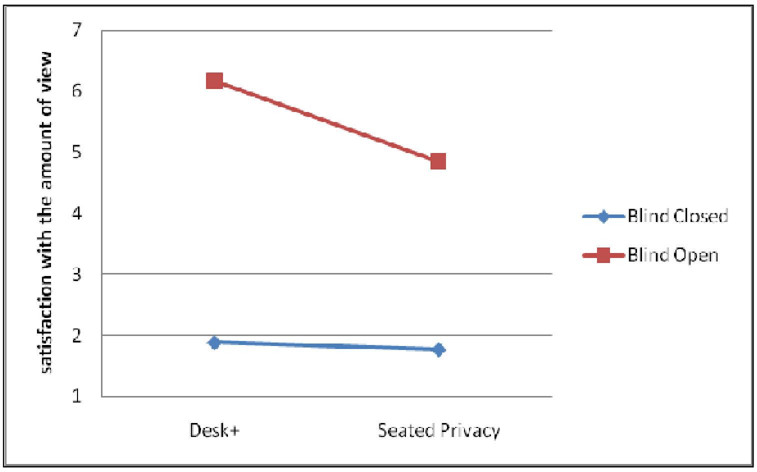


Figure 3.11: Ratings for satisfaction with the amount of view for images with Desk+ and Seated Privacy panel height, under closed and horizontal blind conditions, 1 stands for very unsatisfied and 7 stands for very satisfied.

3.7.7.5 Panel X Neighbour Interactions

The presence of a neighbour did not affect the subjects' ratings for images with seated privacy and seated privacy+ panel heights (Table 3.9). However, the visually present neighbour affected the subjects' ratings as the panel height changed from Desk+ to Seated Privacy.

Table 3.9: Panel X Neighbour Multivariate Statistics.

	df=8, 28	
	F	η^2*partial*
Panel-DvsSP X Neighbour	4.24*	0.55
Panel-SPvsSP+ X Neighbour		

*=p≤0.01, **=p≤0.001

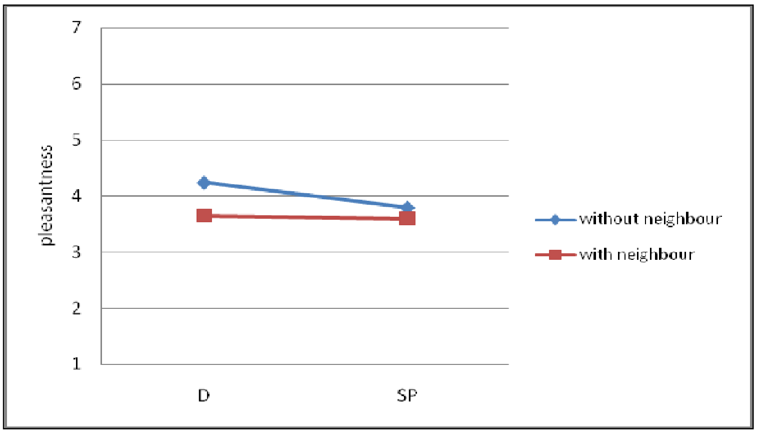


Figure 3.12: Ratings for pleasantness for images with Desk+ and Seated Privacy Panel height, with and without neighbour, 1 stands for unpleasant and 7 stands for pleasant.

Examination of the univariate tests showed that Panel (Desk+ versus Seated Privacy) X Neighbour interaction affected the participants' ratings only in terms of pleasantness with a relatively small effect size, $F(1,52)=5.53$, $p<0.05$, $\eta^2_{partial}=0.14$. Figure 3.12 shows the interaction graph. The desk-high-panel workstation was less pleasant with a neighbour present than absent; there was no difference for the seated privacy workstation. Univariate test results for none of the other dependent variables were statistically significant.

3.7.7.6 Blind X Neighbour Interactions

The relations of Blind and Neighbour were examined. Table 3.10 shows the multivariate statistics.

Table 3.10: Blind X Neighbour Multivariate Statistics.

	df=8, 28	
	F	η^2*partial*
Blind-L X Neighbour	2.47**	0.41
Blind-Q X Neighbour		

*=p≤0.01, **=p≤0.001

Univariate tests showed that images without Neighbour had higher ratings than images with Neighbour when the blinds were open but not when they were closed (Table 3.11). Figure 3.13 shows that when the blinds were closed, ratings regarding pleasantness, spaciousness, tenseness and excitement, for images with and without Neighbour in the next cubicle, were very close to each other. Regarding pleasantness, when the blinds were open, the Neighbour affected the subjects' ratings with an effect size slightly higher than the other dependent variables' effect sizes.

Table 3.11: Univariate statistics for Blind-L X Neighbour.

	df=1, 35	
	F	η^2*partial*
amount of light		
pleasantness	13.15**	0.27
spaciousness	5.5**	0.14
tenseness	6.09**	0.15
excitement	8.72*	0.20
privacy		
amount of view		
visual comfort		

*=p≤0.01, **=p≤0.001

Examination of the univariate tests also showed that although the effect sizes were small, there was a similar trend for unpleasant-pleasant, cramped-spacious, tense-calm and boring-exciting differential scales (Figure 3.13).

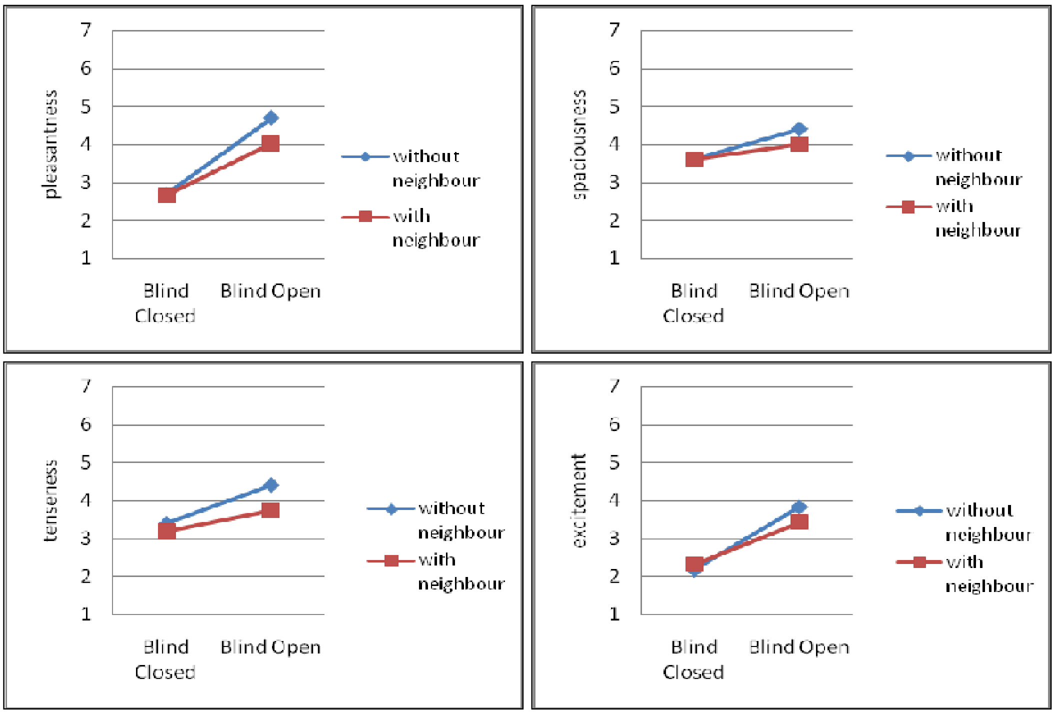


Figure 3.13: Ratings for pleasantness, spaciousness, tenseness and excitement for images with closed and open blind, and with and without neighbour; regarding pleasantness, 1 stands for unpleasant 7 stands for pleasant; regarding spaciousness, 1 stands for cramped and 7 stands for spacious; regarding tenseness, 1 stands for tense and 7 stands for calm; regarding excitement, 1 stands for boring and 7 stands for exciting.

3.7.7.7 Main effects

The main effects of panel configuration, blind settings and neighbours will be given.

Panel

The main effect of panel height was also examined. Both Panel-DvsSP (no panel; scene Desk+, versus one level of fabric panel; scene Seated Privacy) and Panel-SPvsSP+ (one level of fabric panel; scene Seated Privacy, versus one level of fabric and one level of glass panel on top of each other; scene Seated Privacy+) affected the subjects' ratings. Table 3.12 shows the panel main effect and univariate statistics for Panel-DvsSP and Panel-SPvsSP+. Table 3.13 shows the mean and standard error of ratings.

Table 3.12: Panel main effect and univariate statistics.

	Wilks' lambda	F (df=8, 28)	η2partial
DvsSP	*0.174*	16.56***	0.83
Panel- SPvsSP+	*0.192*	14.76***	0.81

	DvsSP (df=1, 35)		SPvsSP+ (df=1, 35)	
	F	$\eta^2_{partial}$	F	$\eta^2_{partial}$
amount of light			32.56***	0.48
pleasantness	6.08*	0.15		
spaciousness	34.64***	0.5		
tenseness				
excitement	15.69***	0.31		
privacy	52.29***	0.6	52.92***	0.6
amount of view	48.07***	0.58	7.73**	0.18
visual comfort	4.35*	0.11		

* = p≤0.05, ** = p≤0.01, *** p≤0.001

Table 3.13: Main effect Panel mean and standard errors.

	Desk+		Seated Privacy		Seated Privacy+	
	mean	SE	mean	SE	mean	SE
amount of light	3.70	0.12	3.56	0.12	3.02	0.12
pleasantness	3.95	0.17	3.69	0.16	3.67	0.18
spaciousness	4.65	0.22	3.69	0.16	3.61	0.17
tenseness	3.80	0.20	3.65	0.15	3.92	0.18
excitement	3.44	0.17	3.02	0.16	2.92	0.17
privacy	2.24	0.18	3.12	0.17	4.31	0.18
amount of view	4.51	0.12	3.67	0.14	3.37	0.18
visual comfort	4.15	0.16	3.84	0.15	3.83	0.17

The univariate too little light - too much light test for Panel-SPvsSP+ showed that adding the second level glass stack-on slightly decreased the ratings of amount of light (Figure 3.14).

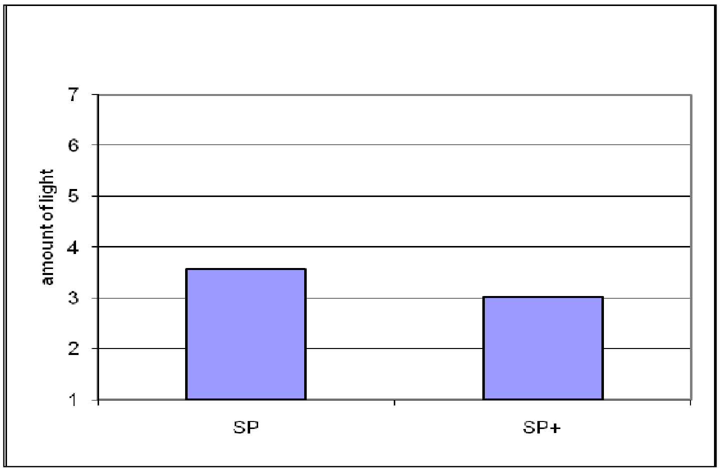
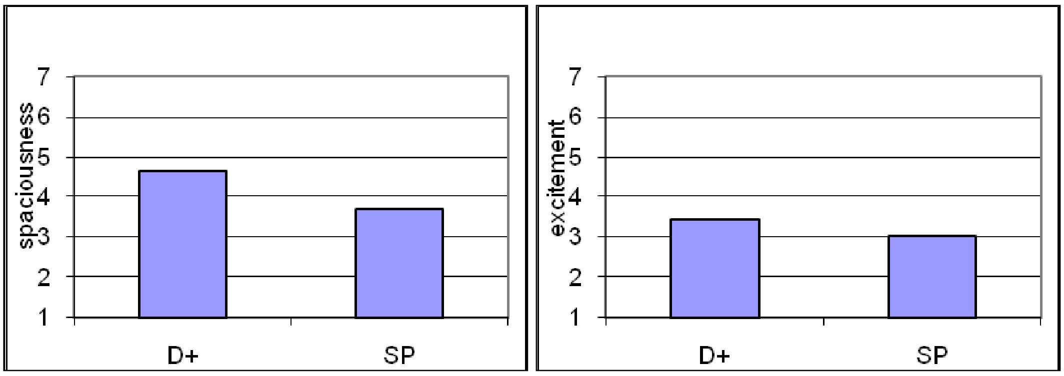


Figure 3.14: Ratings for amount of light for images with Seated Privacy and Seated Privacy+ panel height, 1 stands for too little light and 7 stands for too much light.

The panel height affected the subjects' ratings regarding satisfaction with privacy. Figure 3.15 shows that ratings for satisfaction with privacy increased as the panel height increased. The univariate tests showed that images with Seated Privacy panel height had higher ratings than images with Desk+. Images with Seated Privacy panel height were rated as somewhat unsatisfying, whereas images with Seated Privacy+ panel height had the highest ratings that slightly exceeded the mid-point of the scale.

Figure 3.15: Ratings for satisfaction with the amount of privacy; Desk+ versus Seated Privacy, and Seated Privacy versus Seated Privacy+, 1 stands for very unsatisfied and 7 stands for very satisfied.

The univariate tests showed that scenes with Desk+ panel height were rated as more spacious than scenes with Seated Privacy panel height. Images with Desk+ were also rated as slightly more exciting than images with Seated Privacy panel height (Figure 3.16).



(a) **(b)**

Figure 3.16: Ratings for (a) spaciousness and (b) excitement for images with Desk+ and Seated Privacy panel height; regarding (a) spaciousness 1 stands for cramped and 7 stands for spacious; regarding excitement (b), 1 stands for boring and 7 stands for exciting.

The univariate satisfaction with the amount of view tests showed that satisfaction with view was higher for Desk+ than Seated Privacy. Ratings for Desk+ exceeded the scale mid-point regarding satisfaction with the amount of view, whereas ratings for seated privacy were below the mid-point level (Figure 3.17).

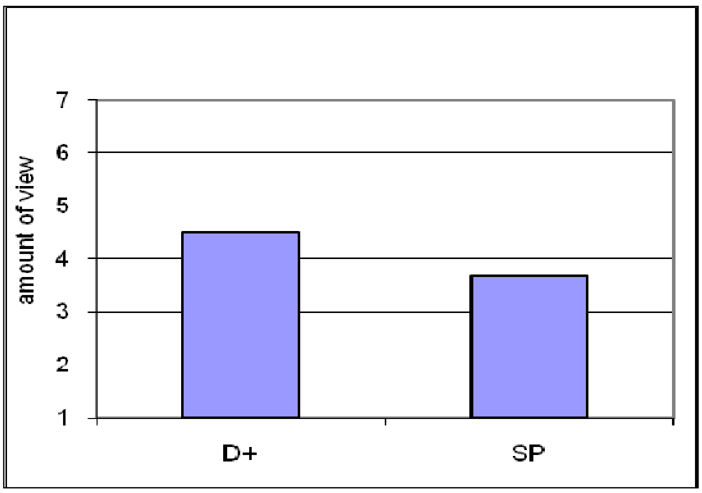


Figure 3.17: Ratings for satisfaction with the amount of view for Desk+ versus Seated Privacy, 1 stands for very unsatisfied and 7 stands for very satisfied.

Blind

Subjects' ratings were affected by blind position (Table 3.14). Scenes with open blinds had higher ratings, in comparison to the scenes with closed blinds. Both Blind-Linear and Blind-Quadratic were statistically significant. Table 3.14 shows the blind main effect and univariate statistics. Table 3.15 shows the mean and standard error of ratings. The univariate test regarding the amount of light showed that scenes with open blinds were rated slightly higher than neutral amount of light, whereas scenes with closed blinds were rated to have an unsatisfying amount of light. Ratings regarding pleasantness followed the same trend as the amount of light ratings. They were only slightly higher (Figure 3.18).

Table 3.14: Blind main effect and univariate statistics.

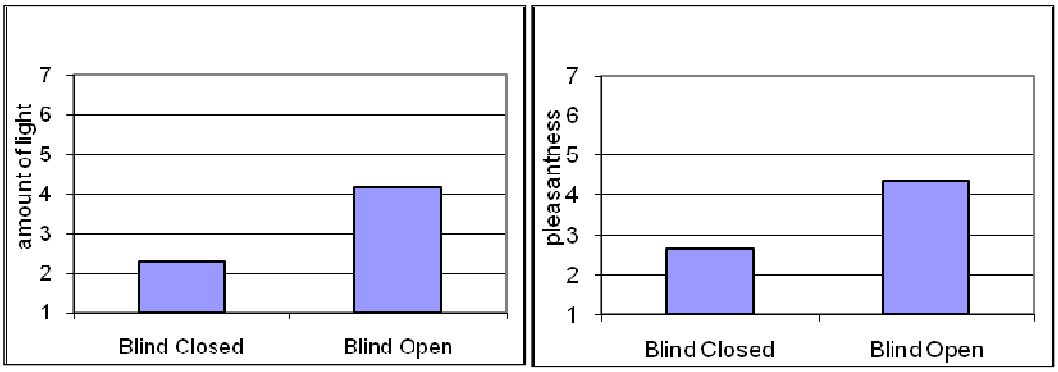
	df=8, 28		
	Wilks' lambda	*F*	*η2partial*
Blind-Quadratic	*0.162*	18.08***	0.84
Blind-Linear	0.086	37.24***	0.91

	df = 1, 35			
	Blind-Quadratic		Blind-Linear	
	F	$\eta^2_{partial}$	*F*	$\eta^2_{partial}$
amount of light	39.52***	0.53	122.3***	0.78
pleasantness	61.12***	0.64	116.6***	0.77
spaciousness	10.79**	0.24	20.1***	0.36
tenseness	7.48**	0.18	17.9***	0.34
excitement	29.04***	0.45	102.78***	0.75
privacy			5.52*	0.14
amount of view	124.34***	0.78	219.1***	0.86
visual comfort	10.14**	0.22	20.61***	0.37

* = p≤0.05, ** = p≤0.01, *** p≤0.001

Table 3.15: Main effect Blind mean and standard errors.

	Blind Closed		Blind Tilted		Blind Open	
	mean	SE	mean	SE	mean	SE
amount of light	2.31	0.13	3.80	0.12	4.17	0.14
pleasantness	2.66	0.15	4.29	0.17	4.36	0.17
spaciousness	3.59	0.17	4.14	0.16	4.21	0.16
tenseness	3.28	0.19	4.01	0.16	4.07	0.16
excitement	2.25	0.13	3.50	0.19	3.63	0.18
privacy	3.08	0.16	3.25	0.16	3.34	0.17
amount of view	1.83	0.15	4.69	0.17	5.04	0.17
visual comfort	3.28	0.20	4.26	0.16	4.27	0.16

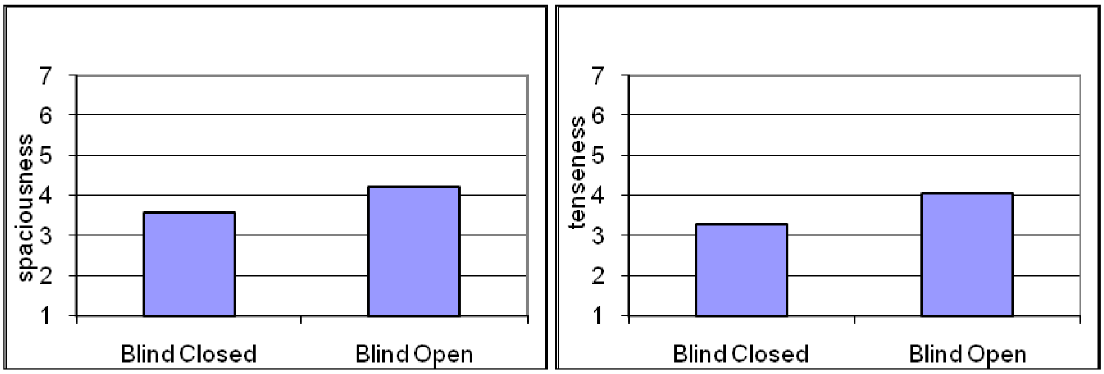


(a) **(b)**

Figure 3.18: Ratings for amount of light (a) and pleasantness (b), for all images with closed and open blind; regarding amount of light (a), 1 stands for too little light and 7 stands for too much light; regarding pleasantness (b), 1 stands for unpleasant, 7 stands for pleasant.

Ratings on spaciousness showed that images with closed blinds were rated as less spacious than images with open blinds (Figure 3.19a).

Regarding calmness, images with open blinds were rated as calmer than images with closed blinds. Figure 3.19b shows that ratings for images with closed blinds were somewhat negative, whereas ratings for images with open blinds were slightly above the mid-point level.

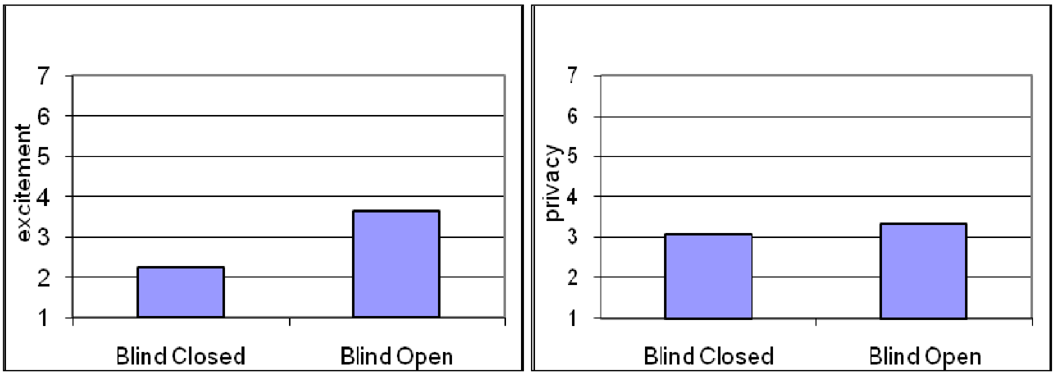


(a) **(b)**

Figure 3.19: Ratings for spaciousness (a) and tenseness (b), for all images with closed and open blind; regarding spaciousness (a), 1 stands for cramped and 7 stands for spacious; regarding tenseness (b), 1 stands for tense, 7 stands for calm.

Regarding excitement, the univariate boring-exciting test showed that scenes with closed blinds were rated as boring, whereas scenes with open blinds were rated between somewhat boring and neutral on the scale (Figure 3.20a).

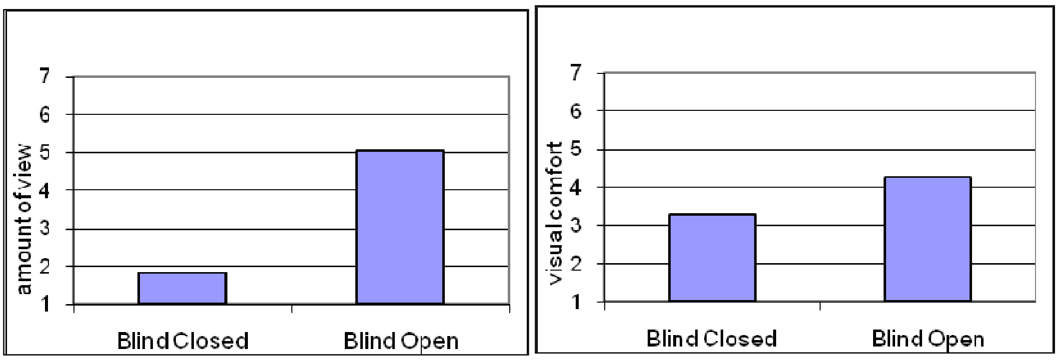
Examination of the univariate tests regarding privacy showed that blind position affected the subjects' ratings only slightly with a relatively small effect size. Figure 3.20b shows that ratings regarding satisfaction with privacy were somewhat less private for scenes with closed blinds, whereas scenes with open blinds were rated slightly higher. As might be expected, blinds had minimal effect on privacy ratings.



(a) **(b)**

Figure 3.20: Ratings for excitement (a) and satisfaction with privacy (b), for all images with closed and open blind; regarding excitement (a), 1 stands for boring and 7 stands for exciting; regarding satisfaction with privacy (b), 1 stands for very unsatisfied, 7 stands for very satisfied.

The Blind position affected the subjects' ratings regarding satisfaction with the amount of view. Scenes with open blinds had higher ratings than scenes with closed blinds (Figure 3.21a).

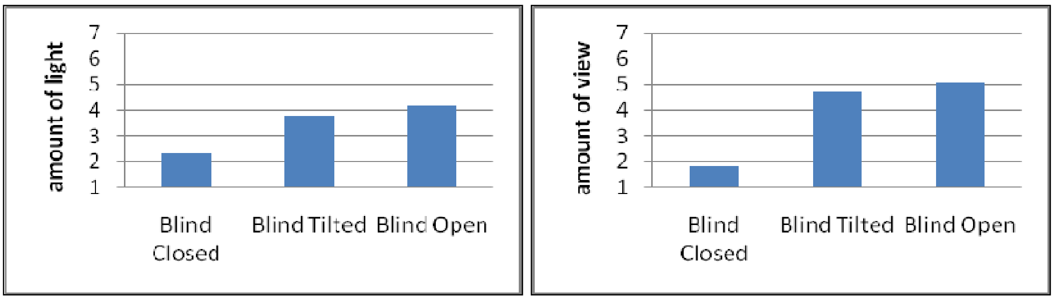


(a) **(b)**

Figure 3.21: Ratings for satisfaction with the amount of view (a) and visual comfort (b), for all images with closed and open Blind; 1 stands for very unsatisfied, 7 stands for very satisfied.

The position of Blinds also affected the subjects' ratings regarding satisfaction with visual comfort. The univariate tests regarding satisfaction with visual comfort showed that scenes with open blinds were rated slightly above the scale mid-point, whereas scenes with closed blinds were rated somewhat less comfortable (Figure 3.21b).

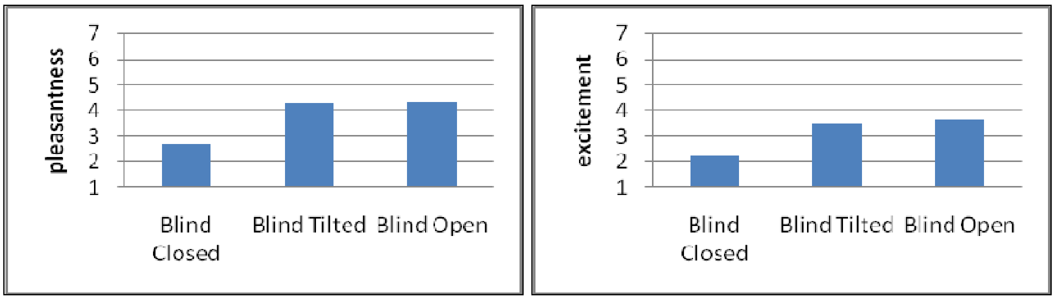
Table 3.14 shows the univariate statistics for the Blind-Quadratic tests. Blind occlusion did not affect subjects' ratings on privacy. As expected, regarding the amount of light and amount of view, ratings for open blinds were slightly higher than ratings for tilted blinds (Figure 3.22). Ratings on pleasantness and excitement were higher for tilted and open blinds than ratings for closed blinds. However, ratings for open blinds were only slightly larger than ratings for tilted blinds (Figure 3.23).



(a) **(b)**

Figure 3.22: Ratings for the amount of light (a) and amount of view (b), for all images with closed, tilted and open Blinds; for (a) 1 stands for too little light and 7 stands for too much light, for (b) 1 stands for very unsatisfied and 7 stands for very satisfied.

Open and tilted blinds had the same ratings regarding visual comfort (Figure 3.24). This finding suggests that open blinds do not add much to the benefits provided by tilted blinds.



(a) **(b)**

Figure 3.23: Ratings for pleasantness (a) and excitement (b), for all images with closed, tilted and open Blinds; for (a) 1 stands for unpleasant and 7 stands for pleasant, for (b) 1 stands for boring and 7 stands for exciting.

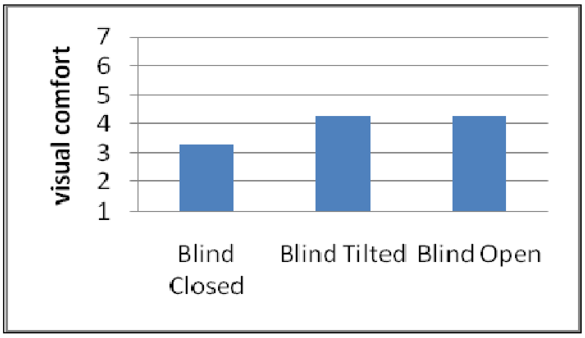
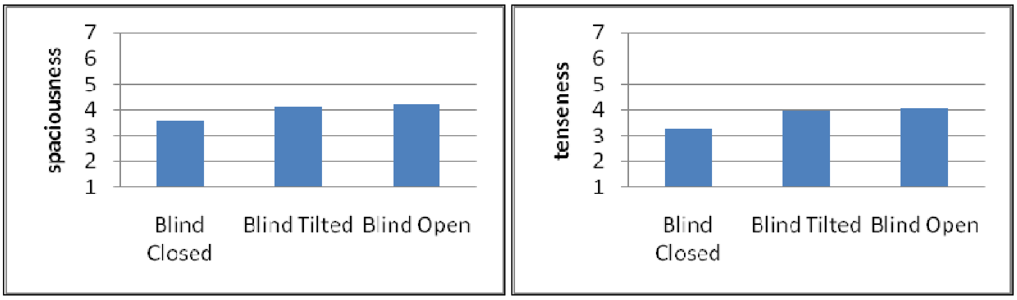


Figure 3.24 : Ratings for the amount of visual comfort for all images with closed, tilted and open Blinds; 1 stands for very unsatisfied, 7 stands for very satisfied.

Ratings for spaciousness and tenseness were very close for tilted and open blinds with small effect sizes (Figure 3.25).



(a) **(b)**

Figure 3.25 : Ratings for spaciousness (a) and tenseness (b), for all images with closed, tilted and open Blinds; for (a) 1 stands for cramped and 7 stands for spacious, for (b) 1 stands for tense and 7 stands for calm.

Neighbour

The results for the main effect of Neighbour showed that a visually present neighbour in the next cubicle affected the subjects' ratings. Scenes without a neighbour had slightly higher ratings than scenes with a neighbour. In the multivariate test of significance, $F(8,28)=3.15$, $p=0.01$, $\eta^2_{partial}=0.47$. Table 3.16 shows the univariate test results for the main effect of Neighbour.

Table 3.16: Main effect statistics for Neighbour.

	df=1, 35	
	F	η^2*partial*
amount of light		
pleasantness	13.02**	0.27
spaciousness	5.87***	0.14
tenseness	14.97**	0.30
excitement	5.69***	0.14
privacy	19.86**	0.36
amount of view		
visual comfort	4.27***	0.11

*=p≤0.01, **=p≤0.001, ***=p≤0.05

All the univariate tests for Neighbour had the same trend. The images without a neighbour had higher ratings than the images with a neighbour. Table 3.17 shows the mean and standard error of ratings.

Table 3.17: Main effect Neighbour mean and standard deviations.

	with neighbour		without neighbour	
	mean	SE	mean	SE
amount of light				
pleasantness	3.60	0.16	3.94	0.15
spaciousness	3.89	0.16	4.07	0.16
tenseness	3.55	0.15	4.03	0.16
excitement	3.04	0.16	3.21	0.15
privacy	2.92	0.15	3.53	0.18
amount of view				
visual comfort	3.86	0.13	4.02	0.14

Ratings on pleasantness showed that the scenes without a neighbour were rated as less unpleasant than the same scenes with a neighbour. Regarding the scale of calmness, where higher values indicate greater calm, images without a neighbour were rated as neutral, whereas images with a neighbour were rated between somewhat tense and neutral on the scale. The neighbour in the next cubicle affected the subjects' ratings regarding privacy. Images without a neighbour were rated as providing more privacy, than the images with a neighbour.

3.7.8 Correlations Between Image Characteristics and Ratings

Selected combinations of image characteristics and mean ratings were plotted and the trends they revealed were examined. Effects of average luminance, luminance variability and view size on average ratings of images were investigated. In this section, the following plots will be presented: L_{ave} in relation to mean ratings for the amount of light, pleasantness, satisfaction with the amount of view and satisfaction with visual comfort; $\log(L_{max}/L_{min})$ in relation to ratings for unpleasant-pleasant, cramped-spacious, tense-calm, boring-exciting and satisfaction with the visual comfort; and the relative view size in relation to the amount of light, pleasantness, satisfaction with the amount of view and satisfaction with visual comfort. Support for the hypotheses would be shown by an increase in mean ratings, as the amount of view, average luminance, and $\log(L_{max}/L_{min})$ of the scenes increase (Cetegen, Veitch, & Newsham, 2008). Photometric descriptors for each image, derived from photographs of the screen using a calibrated Prometric video photometer are given in Table 3.18.

Table 3.18: Luminance-based photometric values for the images.

		L_{ave}*	MAXLUM**	Pix>1000***	SD/L_{ave}†	75P:25P/L_{ave}‡
DO	desk+open	348	2608	6297	1.68	0.030
DT	desk+tilted	175	1274	123	1.28	0.077
DC	desk+closed	55	371	0	0.94	0.093
SPO	seated priv-open	208	1338	3475	1.57	0.036
SPT	seated priv-tilted	180	1041	15	1.29	0.055
SPC	seated priv-closed	58	464	0	1.09	0.111
SP+O	seated priv+open	81	669	0	1.67	0.052
SP+T	seated priv+tilted	63	444	0	1.26	0.080
SP+C	seated priv+closed	45	332	0	0.95	0.122
StPT	standing priv-tilted	49	448	0	1.38	0.053
HT	hybrid-tilted	89	686	0	1.39	0.064
TL	three layers	24	82	0	0.44	0.072

note: * mean luminance (cd/m^2)

** maximum luminance (cd/m^2)

*** number of pixels in prometric image >1000cd/m^2

† standard deviation of luminances, normalized by mean luminance

‡ Ratio of luminances of 75th to 25th percentile pixels normalized by mean luminance

3.7.8.4 Effects of Average Luminance

The correlation between average luminance of the images and average ratings of the corresponding images was investigated (Table 3.19). It should be noted that average image luminance and view size are not independent. Figure 3.26 shows the ratings for pleasantness plotted against the average luminance in logarithmic scale to facilitate comparison of results from Phase 1. Figure 3.27 shows the results for plots against the average image luminance, L_{ave}. As expected, mean ratings for the amount of light increase as the average luminance for the scenes increases. However, the best-fitting curves are not linear. All graphs in Figure 3.27 show that the increase in ratings is faster for scenes with luminances of 24 to 90cd/m^2. There is a more slow increase between luminances 175-348 cd/m^2. The effect is clearest and strongest for ratings of pleasantness and satisfaction with the amount of view, and smallest for the satisfaction with visual comfort.

Table 3.19: Average luminance multivariate and within-subjects contrasts statistics.

	df=11,25			*df*=1,35			
	Multivariate			Linear		Quadratic	
	Wilks' lambda	*F*	η^2*partial*	*F*	$\eta^2_{partial}$	*F*	$\eta^2_{partial}$
amount of light	0.184	10.06***	0.82	133.85***	0.79	47.65***	0.58
pleasantness	0.117	17.11***	0.88	124.77***	0.78	56.07***	0.62
amount of view	0.038	57.89***	0.96	267.80***	0.88	66.76***	0.66
visual comfort	0.448	2.80*	0.55	15.39***	0.30	7.57**	0.18

* = p≤0.05, ** = p≤0.01, *** p≤0.001

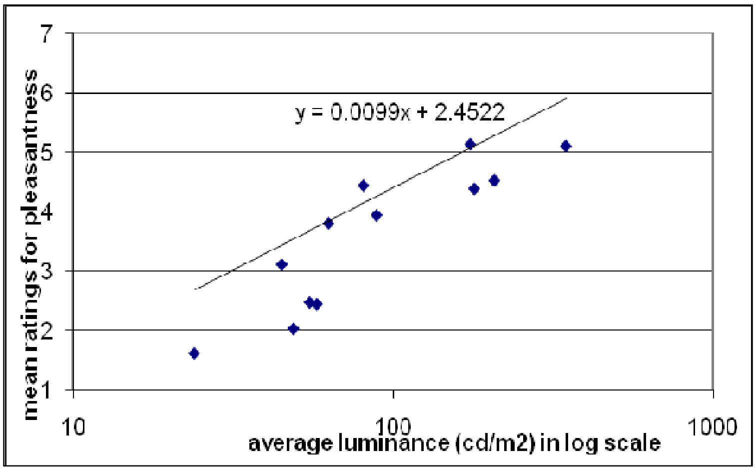


Figure 3.26: Mean ratings for the seven-scale questionnaire for semantic differential unpleasant-pleasant.

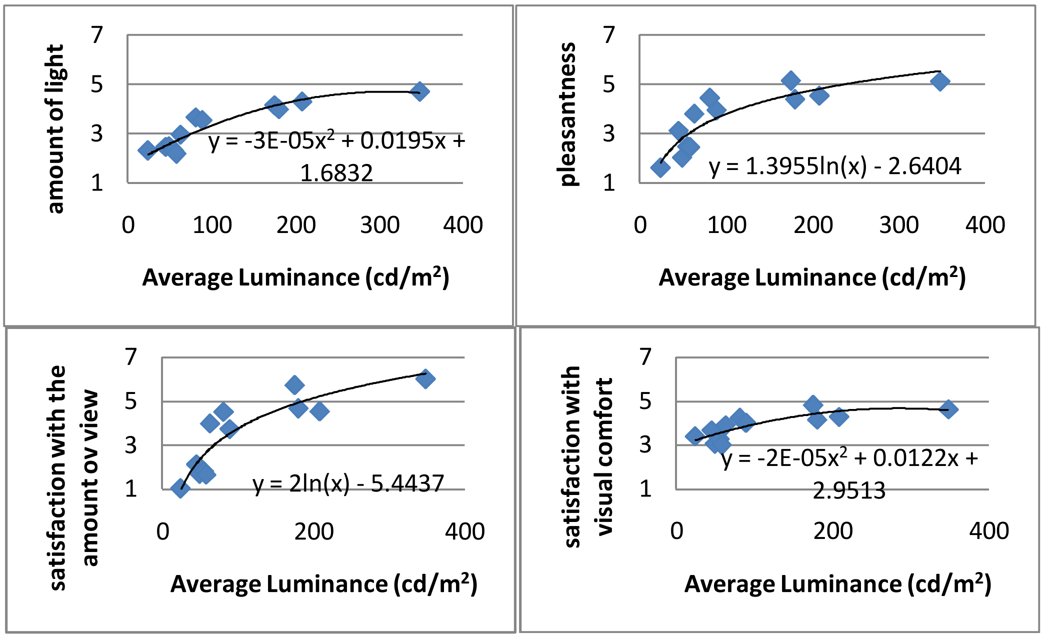


Figure 3.27: Mean ratings for the seven-scale questionnaire for semantic differentials too little light-too much light, unpleasant-pleasant, satisfaction with the amount of view and satisfaction with visual comfort, 1 stands for very unsatisfied and 7 stands for very satisfied.

3.7.8.5 Effects of Luminance Variability

Table 3.20 shows the statistics of luminance variability multivariate and within-subjects contrasts. The plots for $\log(L_{max}/L_{min})$ showed the expected positive slopes (Figure 3.28 and 3.29). Of the five dependent measures, only one (tense-calm) showed a linear best fit; for the others there was a relatively flat slope for values less than 2, and then steeper increases in mean ratings up to the maximum value of 2.73. Effect size (explained variance) is somewhat lower for this predictor than it was for L_{ave}.

Table 3.20: Luminance variability (log(Lmax/Lmin)) multivariate and within-subjects contrasts statistics.

	df=11,25			*df*=1,35			
	Multivariate			Linear		Quadratic	
	Wilks' lambda	*F*	$\eta^2_{partial}$	*F*	$\eta^2_{partial}$	*F*	$\eta^2_{partial}$
pleasantness	0.117	17.11***	0.88	201.02***	0.85	18.99***	0.35
cramped-spacious	0.213	8.38***	0.79	91.47***	0.72	7.41**	0.18
tense-calm	0.169	11.14***	0.83	74.34***	0.68		
boring-exciting	0.131	15.05***	0.87	184.53***	0.84	19.97***	0.36
visual comfort	0.448	2.80*	0.55	13.02***	0.27	8.22**	0.19

* = p≤0.05, ** = p≤0.01, *** p≤0.001

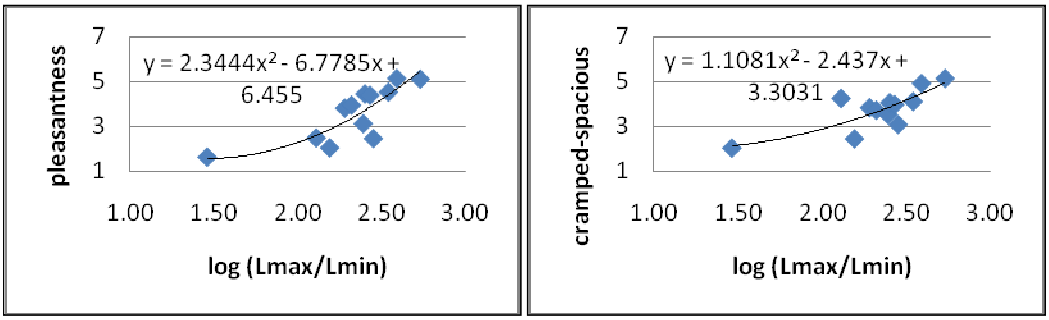


Figure 3.28: Mean ratings for the seven-scale questionnaire for semantic differentials unpleasant-pleasant and cramped-spacious, in terms of $\log(L_{max}/L_{min})$;L_{max} is the maximum luminance of the image and L_{min} is the minimum luminance of the corresponding scene.

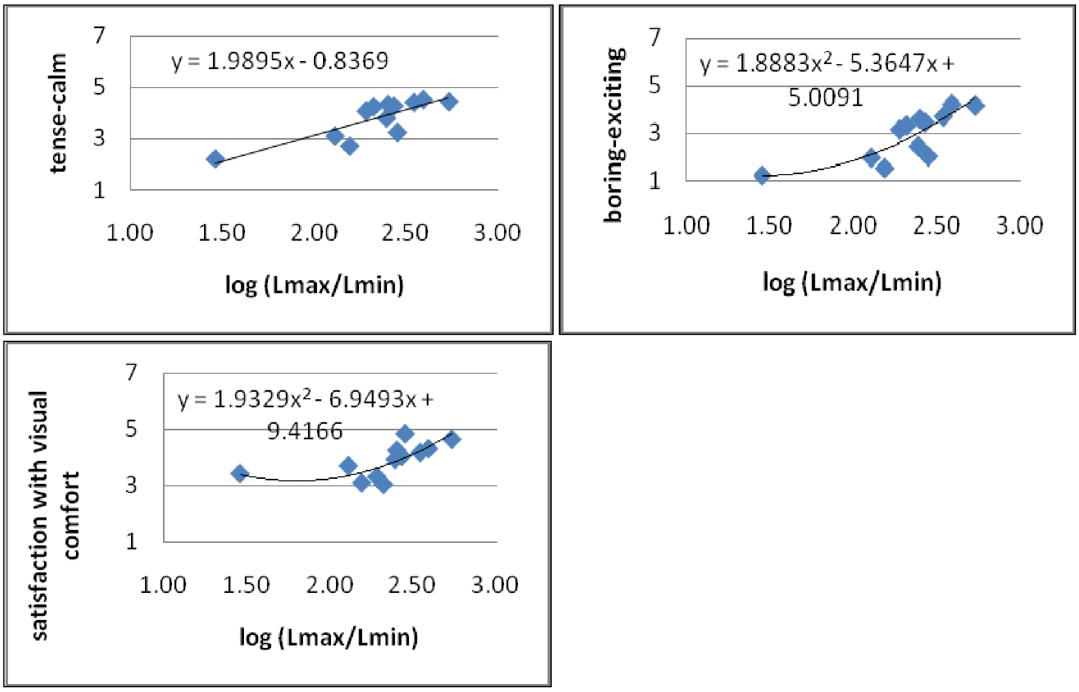


Figure 3.29: Mean ratings for the Likert item satisfaction with visual comfort and semantic differential tense-calm and boring-exciting, in terms of $\log(L_{max}/L_{min})$, 1 stands for very unsatisfied and 7 stands for very satisfied.

3.7.8.6 Effects of View Size

The percentage of the view to the outside was calculated depending on panel type and panel openness (Table 3.21). First the accessible window area of the images was calculated. In descending order these were; desk+, seated privacy, seated privacy+, hybrid, standing privacy and three layers. Open blinds were assumed not to block the view and had a blind coeffiecient of 1. Closed blinds block the view to the outside, therefore they had blind coefficient = 0. The average window luminance for desk+open and desk+tilted was calculated using Photosphere. Average window luminance for desk+tilted was 54% of the desk+open window luminance. Therefore 0.54 was taken as tilted blind coefficient. Normalized accessible window area (with the desk+ panel area representing 100% of the available view area for this scenario) was multiplied by blind coefficient to calculate access to the view.

Table 3.21: Relative view sizes of the scenes.

	TL,SP+C, SPC, DC	StPT	HT	SP+T	SPT	DT	SP+O	SPO	DO
relative view size (%)	0	3	22	30	43	54	54	81	100

Table 3.22 gives the statistics of relative view multivariate and within-subjects contrasts. Figure 3.30 shows the curves with respect to relative view size. The trends are positive, as expected, but not linear. There is a flattening around 50-60% of the relative view. The largest effect sizes are for the ratings of pleasantness and satisfaction with view.

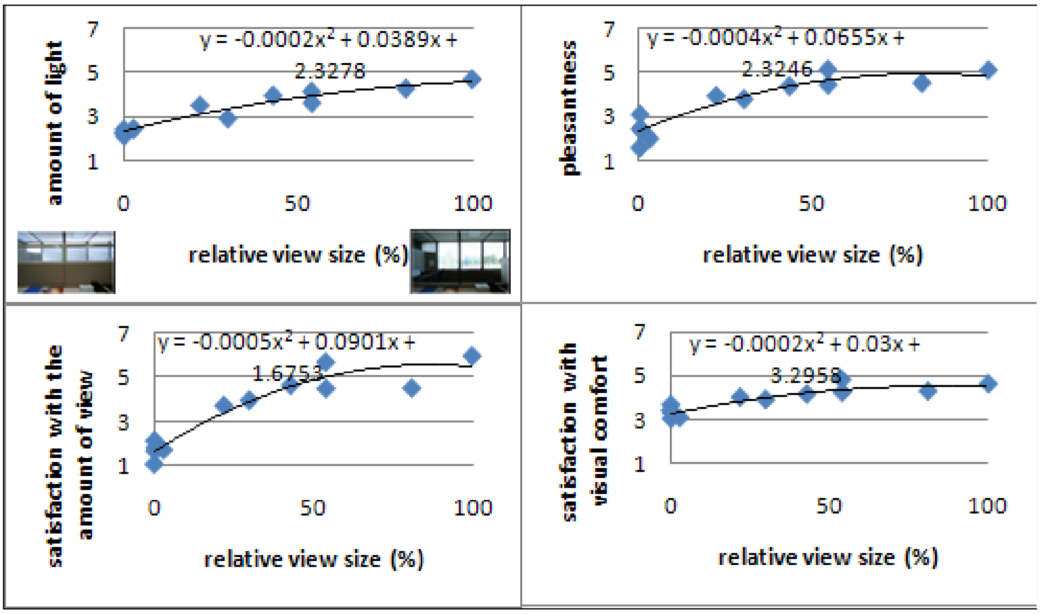


Figure 3.30: Mean ratings for the amount of light, pleasantness, satisfaction with the amount of view and satisfaction with visual comfort, 1 stands for very unsatisfied and 7 stands for very satisfied.

Table 3.22: View size multivariate and within-subjects contrasts statistics.

	df=11,25			*df*=1,35			
	Multivariate			Linear		Quadratic	
	Wilks' lambda	*F*	η^2*partial*	*F*	$\eta^2_{partial}$	*F*	$\eta^2_{partial}$
amount of light	0.184	10.06***	0.82	120.51***	0.77	14.08***	0.29
pleasantness	0.117	17.11***	0.88	150.07***	0.81	35.30***	0.50
amount of view	0.038	57.89***	0.96	265.15***	0.88	40.82***	0.54
visual comfort	0.448	2.80*	0.55	19.26***	0.35	5.48*	0.13

* = p≤0.05, ** = p≤0.01, *** p≤0.001

3.8 Discussion

3.8.4 Hypotheses Tested

Previous research established that viewing HDR images on an HDR monitor can result in judgements of space appearance and satisfaction that are similar to judgements of the real space, particularly when there is daylight (Newsham et al., in press; see Chapter 3). In the present study, HDR images of an open-plan office were used to explore how the combination of panel height, panel material and venetian blind position affects occupant satisfaction. Planned comparisons were conducted to test effects involving three extra images which bracketed the possible effects. Multivariate tests of the full factorial design (MANOVA) were examined to isolate the effects of panel height, blinds position, and the presence of a neighbour. In the last part of the analysis, trends in relation to the photometric properties of images were examined. All hypotheses of the study were at least partially supported, and some of them very strongly.

H1: As panel height gets lower, ratings for satisfaction with lighting and spaciousness increase, and ratings for privacy decrease.

The hypothesis proposed a simple main effect of panel height, but the results showed that the effect of panel height on ratings relating to satisfaction with lighting (amount of light and visual comfort) differed as a function of the position of the blinds (Table 3.8). In general, the expected effects of lower panel heights on judgements were apparent when the blinds were open or tilted but diminished when they were closed.

For judgements of the room appearance, the interactions between blind position and the SP/SP+ contrast showed that with closed blinds, SP had the worse appearance, but with blinds tilted it had the better appearance of the two. For the contrast between D and SP there were simple main effects (Table 3.12) in which D resulted in higher ratings of pleasantness, excitement, tenseness, and spaciousness.

For satisfaction with privacy, the results support the hypothesis, with simple main effects showing that as the panel height increased, ratings for privacy increased (Table 3.12 and 3.13).

Overall, this hypothesis was supported.

H2: Presence of Neighbour in the images will affect subjects' ratings for privacy.

The results showed that the main effect for neighbour (neighbours being undesirable) was moderated by the panel height and by the blind position. Having a neighbour was least pleasant when the neighbour was most in view (D+, blinds open; Table N6); blocking the sight of the neighbour with the solid SP panels increased the satisfaction ratings, but adding the glass panel for SP+ did not make any further difference. Similarly, people did not like having a neighbour when the neighbour blocked the view out (open blinds). On the other hand, when the blinds were closed, having the neighbour in view or not made no difference to judgements of privacy. When the blinds were closed and there was no view out, having a person in the scene did not affect the perception of privacy (Figure 3.13).

H3: As the view size increases, ratings for satisfaction with lighting and amount of view increase.

This hypothesis was supported but as an interaction between panel height and blind position. There were interactions of Panel X Blind on satisfaction with view and satisfaction with visual comfort. With closed blinds (i.e. no view), there were few or no differences between panel heights on satisfaction with view or amount of light as might be expected; however, lower panels were preferred on these outcomes when the blinds were open or tilted. Thus, any degree of venetian blind openness was preferred to closed blinds. The examination of percentage of view area showed that pleasantness, satisfaction with the amount of view and satisfaction with visual comfort are all positively related to the relative view size (Figure 3.30). The trends are not linear; there is a flattening around 50-60% of the relative view.

As the view size and resulting average luminances increased, pleasantness, satisfaction with view and satisfaction with visual comfort increased. Almost all of these curves are non-linear, indicating that there are limits to the increases. In particular, there is less increase for all ratings with average luminances above ~ 175 cd/m^2. Whether there may be a higher value at which these judgements would begin to decline is not known. Visual comfort curves are all flatter than the others because luminances of all the scenes are within the visual comfort limits.

H4: Regarding satisfaction with privacy, Hybrid will perform as well as Standing Privacy, and regarding satisfaction with view and satisfaction with lighting, Hybrid will perform better than Standing Privacy.

The results supported H4. No difference was found between Hybrid and Standing Privacy regarding privacy (Table 3.5). Figure 3.8 shows that H4 was supported regarding satisfaction with view and satisfaction with lighting.

3.8.5 Office Design Preferences

The MANOVA results show that the way blinds are used (which can be easily changed) modifies the perception of the office as it is defined by its cubicle panels (which are more static). The examination of the contrast of open and closed blinds showed that open blinds were preferred to closed blinds for all dependent variables except for privacy, whereas blind position (open or closed) did not affect privacy ratings. Further investigations showed that open blinds had slightly higher ratings than tilted blinds, regarding amount of light and satisfaction with the amount of view; and for all other dependent variables, open and tilted blinds had very close ratings. The viewers' ability to complete the whole scene in the mind with tilted blinds may account for the difference in ratings being slight between open and tilted blinds. This also suggests that when daylighting systems such as mirror, prismatic or lens systems and light shelves are used (Littlefair, 1990) at least some view should be preserved for the occupants.

Increasing the panel height from SP to SP+ by adding a layer of semi-transparent panels on top of a layer of opaque panels provided the occupants further satisfaction with privacy, without decreasing the ratings of pleasantness, spaciousness, excitement and visual comfort. Examination of interactions and main effects showed that Seated Privacy+ panel height with open or tilted blinds gave the optimum ratings.

Veitch et al (2005) found that people with access to daylight or a window were more satisfied with lighting than those without; and having a window in the workspace resulted in more satisfaction with lighting than only having access to daylight. The results presented in the thesis confirm that satisfaction with lighting increases when there is a view provided to occupants by open or tilted blinds, rather than blocking the view with closed blinds. Furthermore the results also show that view size was positively related to satisfaction with lighting. This confirms the findings of Newsham et al (2009). Newsham et al examined the percentage of view provided to occupants and highlighted the relationship between access to outside view through a window and satisfaction with lighting. This link was found through data collected from offices that differed in type of ambient lighting system, task lighting and furniture layout, even though windows were located only at the top one third of the north facing walls, failing to provide the full view including the horizon. Newsham et al's study differs from the current study, in that not all windows were in the principal line of sight of the participant, whereas in the current study all subjects were facing in the direction of the windows. Results of Newsham et al's study were based on experience in a real space, not viewing images, which adds validity to this study.

Although windows have a number of benefits, it should be noted that the thermal comfort of the employees with offices adjacent to windows should be considered, while providing view and other benefits to occupants in rear cubicles. A recommendation would be having a circulation or common-use zone adjacent to window-walls, and then starting the cubicle zone. This method would take the open-plan office closest to the window a bit further away from the window and enhance the well-being of all employees who use the corridor with exposure to daylight and restorative effects of windows.

Previous research also showed that panel height is related to privacy (Veitch et al., 2003), with higher panels resulting in greater privacy, as was found in the present study. Balancing view and privacy is an important cubicle design parameter. Our results showed that the hybrid panel solution could provide a good compromise: let some daylight penetrate into the open-office, while providing some privacy.

The hybrid panel height also provides an opportunity for daylight harvesting, permitting daylight to penetrate deeper into the space, offsetting electric lighting and resulting in energy savings.

3.8.6 Limitations and Research Directions

The results of this study did not show any visual discomfort, probably because of the luminance limitations of the HDR device and the time of day when the photographs were taken. Nor did it reference workplace satisfaction due to thermal effects associated with daylight, which would be most significant during the parts of the day with maximum daylight. The time of day of photo capture was chosen such that the maximum luminance of the images did not exceed the maximum luminance that could be displayed on the HDR monitor (4000 cd/m^2), which resulted in the photographs being taken in the late afternoon in this southeast-facing room. Naturally-occurring sky luminances at other times of day and under other weather conditions would exceed this level and could cause discomfort.

Furthermore, almost all of the curves examining relationships between ratings and average image luminance, luminance variability, and relative view are non-linear, where there is less increase for all ratings with average luminances above ~ 175 cd/m^2. Whether there may be a higher value at which these judgements would begin to decline is not known because luminances of all the scenes are within the visual comfort limits. None of the scenes in this study had very dark or very bright patches and no visual discomfort was found; Veitch et al (2005) also found that uniformity was preferred to having high contrasts between direct sunlight and shadows. As a further study, it is recommended to repeat this experiment with an HDR monitor that can display luminances up to a higher level to cover a higher range not studied in this experiment.

Loe (1994) studied factor scores against $\log(L_{max}/L_{min})$ in a conference room with no windows for the scale mainly below a value of 2. This study used HDR images of an open-plan office with windows, displayed on an HDR display, and therefore has the advantage of including daylight in the analysis. This takes Loe's study one step further by exploring the dependent variables against $\log(L_{max}/L_{min})$ for scale values mainly between 2-3. The plots showed the expected positive slopes for pleasantness, spaciousness, excitement and satisfaction with visual comfort (Figure 3.28 and 3.29).

Figure 3.31 and 3.32 give comparisons of the results of these studies. The mean data given in Loe's paper was used in this comparison and therefore, statistical analysis could not be done. In Loe et al's study real spaces were rated on a bipolar scale where 0 represented left pole and 85 represented right pole. In this study, images were rated on a seven-point scale questionnaire. The ratings of Loe's study were normalized to a seven-point scale and then results of both studies (that were normalized within the scale of each study) were plotted. The scale for pleasantnesss in Loe's study was in reverse order (1 stood for pleasant and 7 stood for unpleasant); therefore pleasantness ratings were reverse coded and then plotted.

Luminance data given in Loe's study on a horizontal band, width 40 degrees (B40), covers an area not included in images of this study (i.e. walls on both sides), thus central circle data, angular subtense 40 degrees (C40) was used. The images of this study contained slightly more ceiling and wall surface than images in Loe's study.

In this study the luminance readings changed in relation to position of blinds and partitions, whereas Loe et al's study included diverse light sources (i.e. combinations of spotlights, overtable lights, uplights, wallwashers). All subjects saw the real spaces in Loe' s study, but in this study subjects observed the images only.

Figure 3.31 gives results from both studies with respect to luminance variability, $\log(L_{max}/L_{min})$. Trends are positive for unpleasant-pleasant and tense-calm for the present study. Results for visual comfort are in the same band for both studies. As luminance variability increases in the conference room, it is rated as less spacious, on the other hand the office with daylight in the present study was rated as more spacious as luminance variability increased. The location of dark patches also

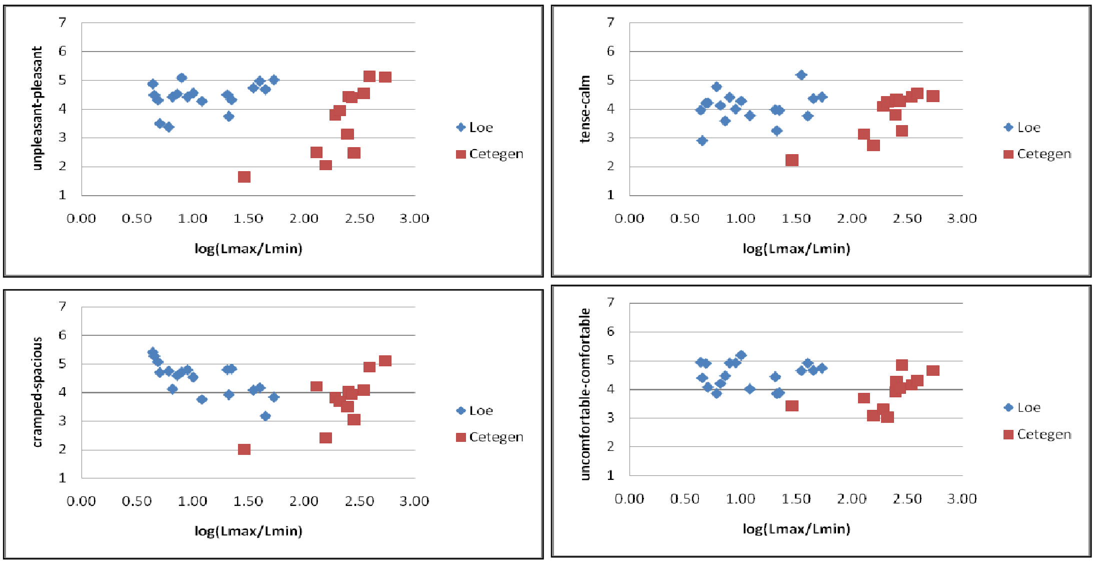


Figure 3.31: Mean ratings for semantic differentials unpleasant-pleasant, tense-calm, cramped- spacious, and mean ratings regarding visual comfort, in terms of $\log(L_{max}/L_{min})$, 1 stands for very unsatisfied and 7 stands for very satisfied.

affected spacious-cramped ratings. Where dark patches are on the walls and ceilings, spaces are rated as cramped. The results of these two studies follow their own patterns and cluster within themselves. This shows that the method of examining small portions of the scale independent of each other and then adding them together cannot give solid results. Experiments should be conducted covering a large scale of luminance variability. It should be noted, however, that high luminance variability cannot be reached using electric light sources only. Windows should be present in indoor environments.

Figure 3.32 shows results from this and Loe's study with respect to normalized maximum luminances. The curves for pleasantness follow a similar trend, flattening around 55% of maximum luminance in Loe's study and around 85% of L_{max} in this study. The curve for tense-calm has a negative slope for Loe's study, whereas in this study there is a positive slope. As mentioned earlier no daylight was available in Loe's study, and maximum luminances were between 6 cd/m^2 and 423 cd/m^2. In the current study daylight was available in majority of the scenes and maximum luminances were between 96 cd/m^2 and 1932 cd/m^2. Although the luminances were much higher, the office illuminated with daylight was rated less tense. Trends for cramped-spacious are positive in both studies.

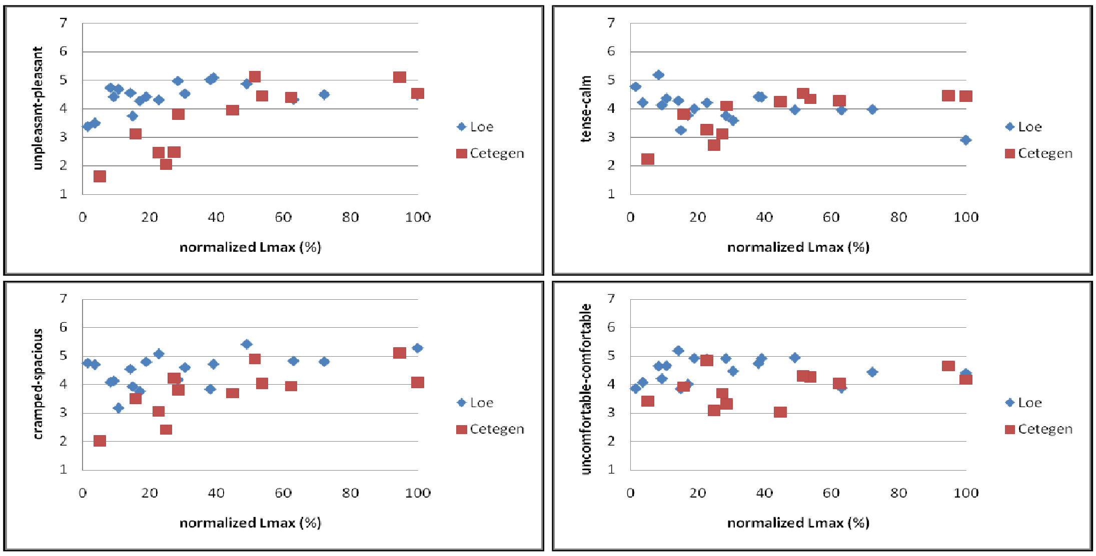


Figure 3.32: Mean ratings for semantic differentials unpleasant-pleasant, tense-calm, cramped-spacious, and mean ratings regarding visual comfort, in terms of normalized L_{max} (%) for each study, 1 stands for very unsatisfied and 7 stands for very satisfied**.**

To study the effects of luminance variability and to find out whether at some level there exists a decline, future work using a wide range of stimuli (which also includes dark and bright patches) covering a large scale of log(L_{max}/L_{min}) is recommended.

Windows provide a view to the outside. Satisfaction with windows depends on the information content of the windows and dynamic properties of the view (Markus, 1967). Ne'eman and Hopkinson (1970) reported that preferred window size depends on the content of the view, distance from the window and viewing angle. The office used in this study had a natural view, which has been associated in a European study with reduced discomfort and increased at-home sleep quality (Aries, Veitch, & Newsham, 2007). Further study is recommended to find the optimum office window view size depending on various possible view types.

Collins (1976) stated that the smaller the office and the more stress is involved in a job, the more important the windows become for the employees' well-being and increased efficacy, but she expected that acceptable window size, type of view, desire for daylight and need for privacy might differ depending on the culture and climate. Windows and view are preferred in all cultures studied to date, nevertheless the size and shape of the windows depends on local architectural practices. A study conducted in England with subjects of various cultural backgrounds showed that there is a greater tolerance of discomfort glare for "interesting" images (Tuaycharoen & Tragenza, 2005).

The results of this study may or may not apply to Turkey, depending on the regional climate and background of the employees, as these determine expectations regarding panel height (and privacy), and preferred window size. However, the results are expected to be relevant to open-plan offices in Istanbul, as the employees may be more Western in their outlook. Dogrusoy and Tureyen (2007) conducted a field study in Izmir, Turkey in six office buildings (62% of the offices were open-plan offices) with participation of two hundred and twenty one employees to explore the window shape preferences and found that large-sized uninterrupted window walls and horizontally continuous windows that provided the largest view sizes were the most preferred window types. This finding is generally consistent with the findings of this study.

Yildirim et al (2007) conducted a study in Ankara, Turkey to study the window proximity (occupants of the first and second rows of open-plan offices, regarding distance with respect to windows) and partition height (1.2 m and 1.4 m), and found that employees working in the first row of open-plan offices (closest to the window) with the highest panel height (1.40 m) were the most satisfied. Yildirim et al reported that employees with offices near a window had more positive notion of the space than those away from a window. Employees occupying the second row offices (from windows) were less satisfied with privacy and lighting than employees with offices near windows. These results support the findings of Boubekri and Haghighat (1993). The occupants at the window-row offices prefer having high panels that provide privacy, but on the other hand high panels block the view for the second-row employees. It is clear that a compromising solution should be found not only for employees occupying these two rows, but also for those who have offices in the interior. Further studies are recommended to find the optimum window size and shading type to provide good quality lighting for each climatic region of the country.

Occupants' opinions of the space judged from images on an HDR display show the expected relationships between panel height, neighbour presence, and view size. On balance, for the second row in, a hybrid panel seems to offer the best compromise between view and privacy. The results relate well to previous literature that has primarily involved judgements in full-size or real offices, which adds to the confidence in the validity of results based on viewing HDR images on an HDR display.

4. GENERAL EVALUATION AND CONCLUSION

The main goal of this dissertation is to show that a High Dynamic Range (HDR) display can be used as a tool in the lighting design process in the design development stage and at the bidding and negotiation phase, to enhance communications between the lighting designer and his clients. To accomplish this goal, an investigation was performed to validate that HDR display technology represents the real world. The first phase of the investigation showed that HDR images can be used as a surrogate for real spaces in aesthetic aspects of lighting quality research when the HDR images are calibrated to correctly represent real space luminance. The second phase was a practical exercise using the HDR images, focusing on lighting quality in an open-plan office, the results of which are consistent with previous lighting quality studies. It takes these previous studies further by including daylit scenes in the images.

The first phase formed the foundation for the second phase and further use of the HDR display technology. The demonstration of validity of the HDR technology is important to justify the use of the tool in lighting research and lighting design. The first experiment demonstrated that HDR images presented on an HDR display are rated as significantly more realistic than conventional computer images, when the images contained relatively high areas of high luminance, which in this study was the result of windows and daylight in the scene. This shows that the HDR display may be used as a surrogate for experiencing a real space to investigate lighting engineering problems both for research, and the design process, for spaces with a wide range of luminances. HDR displays, when used to display images with a small range of luminances, show no loss of realism over other technologies.

In the second phase of the dissertation, occupants' opinions of the space judged from images on an HDR display showed the expected relationships between panel height, neighbour presence, and view size. The results relate well to previous literature that has primarily involved judgements in full-size or real offices, which adds to the confidence in the validity of results based on viewing HDR images on an HDR display.

The investigations in this dissertation involved constructing the stimuli in a careful way to frame realism by applying the full range of possible luminances in the chosen scene; no truncation method was used. To reach the goal of realism, data collection in Phase 1 for LDR and HDR images was conducted at the same time of the day that the participants would visit the real spaces. The results relate well to previous literature that has primarily involved judgements in full-size or real offices, which adds to the confidence in the validity of results based on viewing HDR images on an HDR display.

In both experiments individual differences (age, sex, vision) were controlled for; therefore, they are not a source of bias. Neither experiment was designed to detect any individual differences. These would be between-subjects differences and would require larger samples to study. Generalization of the results is quite strong because the participants were from all across the age spectrum; the limitations are mostly as regards to the season and time of day for the images, and would require an advanced HDR display that can display higher luminances and contrast ratios to get the full range of luminances and contrasts possible for the environment.

This dissertation demonstrates that HDR displays are useful for design. HDR displays could be used to show clients renderings of spaces that do not exist yet, with realistic portrayals of how daylight will appear under varying conditions. HDR technology may be used for virtual reality systems used for training purposes; e.g. aircraft simulators. Computer game makers, particularly those developing simulation games, are increasing their interest in HDR technology in their quest towards improving realism. The findings of this dissertation show that luminance-matched HDR images shown on an HDR display provide highly realistic simulation of real spaces, particularly for scenes including daylight. The findings of the dissertation show that the computer game makers may benefit from using HDR technology which will result in providing realistic images on their simulation games and increasing client satisfaction.

This dissertation shows that HDR displays are useful to answer research questions. The second part of the study shows that luminance differences as small as 26 cd/m^2 can be detected on an HDR display. Therefore, an HDR display can be used in the study of lighting engineering problems. For instance, currently there exists no generally accepted glare model to predict discomfort from daylight; an HDR display with high-enough luminance could be used as a research tool to study glare. Osterhaus (2008) examined the correlation between mean and median values of luminance histograms of HDR images and subjects' discomfort glare ratings. The findings of this thesis are expected to lead to further studies investigating glare by using HDR images displayed on HDR displays that simulate real life scenes in terms of luminance.

This dissertation suggests that the HDR device is a promising tool for lighting research, and adds to the body of knowledge of how well HDR displays can simulate reality. Nevertheless, like most early applications of a technology, there is room for improvement in future studies that may seek to replicate and extend these findings. There were shortcomings in the experiment that should be considered when interpreting the results. First, the results were drawn from a small set of interior scenes and should be confirmed for a larger set of interior and exterior scenes with a wider variety of luminance profiles.

As well as the potential photometry errors described in section 2.3.2.2, there was one source of error that was particular to the scenes in experiment 1 featuring daylight. The images were all taken on sunny afternoons several weeks prior to data collection with participants. The experiment was conducted during the afternoon, and the most common sky type at this location and time of year was a clear sky. Nevertheless, there were inevitable differences between the luminance conditions experienced by the participants in the real spaces, and those prevailing when the images were taken. This might serve to suppress the perceived reality of the HDR images featuring daylight.

Another issue is the exposure time to each image. In the first phase of the dissertation exposure time was limited to 30 seconds due to unavoidable scheduling issues associated with other experiments that the participants were involved in on the same day. Such short exposures are common in other published research in this field, but it is possible that longer adaptation times might have yielded different results. It is also the case that participants had more than 30 seconds of exposure to the real spaces. They walked into the space, got seated and settled, and then had the exposure time. For practical purposes, the duration was more regulated for the images than the real scenes, which would tend to increase differences between the two.

It is also obvious that the potential field of view for the images and the real spaces they represented was substantially different. This was a limitation of the HDR hardware available at the time of the study. Larger HDR displays are under development that might address this issue. Alternatively, future studies could exclude the laboratory surroundings with baffles, and position the participant's head closer to the screen, although this might be perceived as a very artificial situation, and could bias responses for other reasons.

HDR technology has the potential to make cross-cultural research studies easier. Participants with various cultural backgrounds can be exposed to the same stimuli in their native countries. This would enable the researchers to investigate their research problems working with a wide range of participants in order to generalize the results for a wider population; or to study the cultural differences in perception of lighting and glare.

The HDR hardware used, although capable of much higher luminances than conventional displays, was not capable of reproducing the maximum luminances possible in the studied scenes. Again, future development might raise this maximum luminance, and one would expect this would lead to greater perceived realism.

The field of view and view size of the images of the current displays differ from real life scenes; however these drawbacks may be overcome in the future by facilitating larger displays as they become available.

HDR displays can be used with HDR images from computer renderings of spaces that do not yet exist. Together with climate-based daylight modelling it would be possible to look at the same space, pre-construction, and under a variety of daylight and weather conditions; it would be possible to visually evaluate various glazing and shading options, as well as various choices for luminaires, locations, and interior finishes.

The results imply that there may be successful applications of HDR displays in lighting design and architectural contexts. Even before a building exists, looking at a good rendering of the spaces may be useful in the decision making process. The findings also suggest that HDR displays may be useful as artificial window installments in situations where real windows are impractical.

The first phase of the research established that viewing HDR images on an HDR monitor can result in judgements of space appearance and satisfaction that are similar to judgements of the real space, particularly when there is daylight. The second phase provided results focusing on lighting quality in an open-plan office using HDR images.

High Dynamic Range (HDR) display can be used as a tool for lighting research and lighting design. HDR images can be used as a surrogate for real spaces.

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APPENDICES

APPENDIX A: Images and luminance tables for Phase 1

Figure A.1 : Measurement points in the corridor.

Table A.1: Luminance measurements in the real space and when displayed on the HDR image display in HDR and conventional mode. Exposures used in HDR image were 1 – 1/500 s.

Point	cd/m2			% difference between real and .HDR
		on HDR display		
	real	.HDR	.JPEG	
1	725	665	157	8.3
2	680	730	161.5	-7.4
3	875	940	161	-7.4
4	673	700	157	-4.0
5	24.6	23	26	6.5
7	27	26.7	30	1.1
8	17.9	20	22.8	-11.7
12	54.9	31	37.7	43.5
13	24.5	29.8	32	-21.6
14	29.6	44.8	43.3	-51.4
15	25.2	27.4	32.3	-8.7
16	25.4	22.4	26	11.8
19	30	57.6	65	-89.5
20	31	29.6	35.4	4.5
21	24.5	23.4	29	4.5
22	41.7	41.6	49.2	0.2
23	34.4	24.9	30	27.6
24	33.1	21	24.9	36.6
25	12.3	9.1	9	26.0
27	22.90	22.7	26.5	0.9

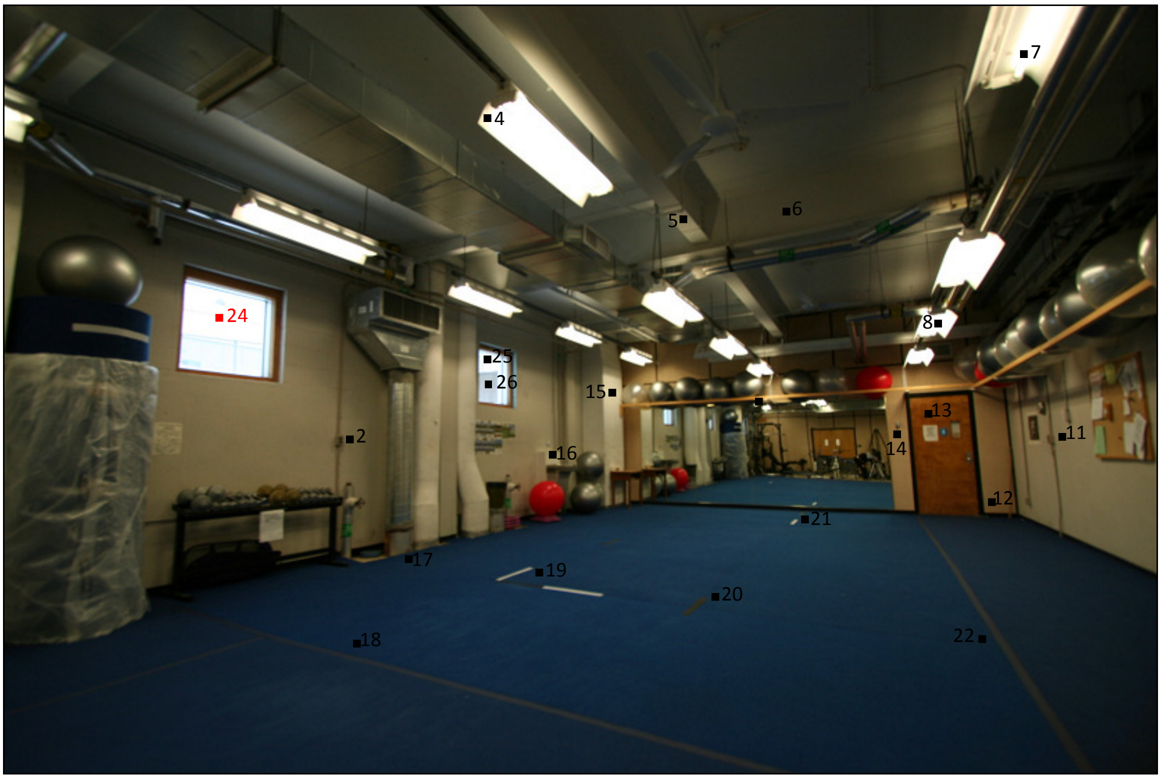


Figure A.2 : Measurement points in the gym.

Table A.2: Luminance measurements in the real space, and when displayed on the HDR image display in HDR and conventional mode. Exposures used in HDR image were 1 – 1/500 s.

	cd/m2			% difference
Point		on HDR display		between
	real	.HDR	.JPEG	real and .HDR
2	28	31	33	-10.8
4	702	620	109	11.7
5	42	59	46.7	-39.9
6	15	17	14	-15.6
7	2075	991	148	52.2
8	2230	920	119	58.7
11	49	44.4	48.5	9.7
12	27	20.5	21	24.6
13	22	29	28	-31.2
14	44	47.9	48	-9.9
15	112	131	100	-17.0
16	54	55.8	56	-3.9
17	7	10.3	10	-38.8
18	7	9.2	8	-23.2
19	10	13.4	12.6	-40.1
20	10	12	11	-20.3
21	13	17	16	-28.2
22	9	7.8	7	16.3
24	509	486	154	4.4
25	463	445	133	3.8
26	104	137	109	-32.2

Figure A.3 : Measurement points in the mezzanine.

Table A.3: Luminance measurements in the real space, and when displayed on the HDR image display in HDR and conventional mode. Exposures used in HDR image were 1 – 1/500 s.

Point	cd/m2			% difference between real and .HDR
		on HDR display		
	real	.HDR	.JPEG	
1	200	196	120	2.0
2	1975	1650	174	16.5
3	381	393	144	-3.1
6	6430	1030	149	84.0
9	6200	1455	158	76.5
10	144	305	156	-111.8
11	76	130	111	-71.1
13	126	117	90	7.1
14	72	100	92	-38.9
15	133	174	105	-30.8
17	40.4	70	66	-73.3
18	21.7	35	45	-61.3
19	18.3	22	30	-20.2
20	13.85	18.7	23	-35.0
21	26.2	26.7	34	-1.9
22	15.85	24	28	-51.4

Figure A.4 : Measurement points in the lobby.

Table A.4: Luminance measurements in the real space and when displayed on the HDR image display in HDR and conventional mode. Exposures used in HDR image were 1/4 – 1/500 s.

Point	cd/m2			% difference between real and .HDR
		on HDR display		
	real	.HDR	.JPEG	
1	1822	1200	140	34.1
2	2236	1546	127	30.9
3	2275	1503	130	33.9
4	2350	1598	167	32.0
5	2735	2465	164	9.9
6	1142	1165	134	-2.0
7	2575	2430	153	5.6
8	568	603	112	-6.2
9	363	369	85	-1.8
10	221	207	48	6.3
11	254	276	67	-8.9
12	47	67	21	-41.8
13	178	217.8	63.5	-22.6
14	61	85.2	20.8	-39.0
15	86	89	17	-3.2
16	65	96	31	-47.4
17	81	57	13	29.3
18	338	251	65	25.6
20	114	112	23	1.3
21	489	458	118	6.2
22	98	98	21	0.5

Figure A.5 : Measurement points in the open-plan office.

Table A.5: Luminance measurements in the real space, and when displayed on the HDR image display in HDR and conventional mode. Exposures used in HDR image were 2 – 1/500 s.

	cd/m2			% difference
Point		on HDR display		between
	real	.HDR	.JPEG	real and .HDR
1	65	70	65	-7.9
2	202	188	130	6.7
3	40	59	38	-48.4
4	1733	804	116	53.6
5	22	37	18.8	-66.6
6	24	27	18	-11.0
7	213	200	144	5.9
8	81	93	94	-14.3
9	26	24	17	7.2
11	8	9	3.8	-6.8
12	25	25	15.3	-0.5
13	26	20	14.6	24.0
14	31	26	20	16.4
15	7	10	3.4	-36.2
16	106	102	101	3.7
17	11	22	16	-109.5
18	54	56	57	-4.3
19	79	59	61	24.9
20	3	3.4	1.3	-18.9
21	12	8	2.2	30.4
22	4	4	3.8	7.0
25	180	180	133	0.1

Figure A.6 : Measurement points in the staircase.

Table A.6: Luminance measurements in the real space, and when displayed on the HDR image display in HDR and conventional mode. Exposures used in HDR image were 1/15 – 1/500 s.

	cd/m2			% difference
Point		on HDR display		between
	real	.HDR	.JPEG	real and .HDR
1	405	377	21	6.9
2	562	528	41	6.0
3	538	647	60	-20.4
4	519	522	55	-0.6
5	500	516	39	-3.2
6	933	964	96	-3.4
7	1275	1057	113	17.1
10	1300	923	100	29.0
11	698	640	74	8.2
12	9375	2571	180.2	72.6
13	1000	808	96	19.2
14	128	174	17	-36.5
15	117	127	12	-8.5
17	987	682	63	30.9
18	287	353	33	-23.2
19	164	190	15	-15.9
20	600	569	47	5.2
21	165	196	13	-19.1
22	707	597	49	15.6
26	1435	980	93	31.7

Chi-Square (χ^2) analysis

Chi-Square (χ^2) analysis of variance explores the relationship between two discrete variables; expected frequencies are examined in relation to observed frequencies. When the value of Chi-Square is small, the null hypothesis is accepted, if the value of Chi-Square is large then the null hypothesis is rejected.

$$\chi^2 = \Sigma [(O-E)^2 / E]$$

where;
O = the observed frequency in each category
E = the expected frequency in each category

The summation is made over all categories. Expected frequencies are calculated using the following formula:
E = (Row total / Grand total) * Column total

Degrees of freedom is calculated as follows:
D.f. = (No. of rows - 1) * (No. of columns - 1)

The relevant statistical significance (p-values) are observed form the table of χ^2 distribution.

APPENDIX B: Image luminance iso-plots for Phase 1

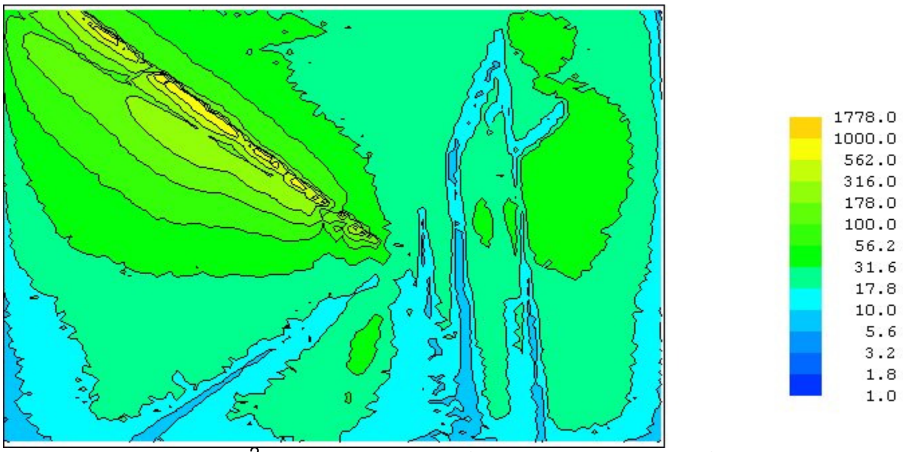


Figure B.1 : Luminance (cd/m^2) $\log_{10}$ iso-plot of the HDR image of the corridor, as displayed on the HDR display, taken with a video photometer.

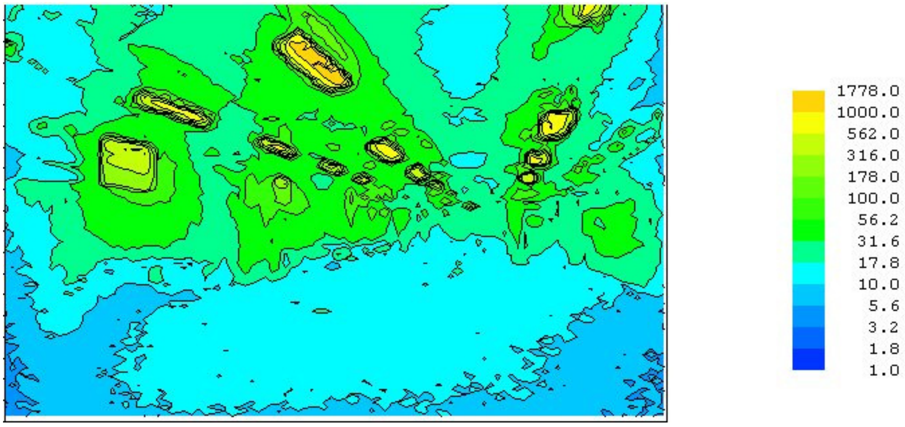


Figure B.2 : Luminance (cd/m^2) $\log_{10}$ iso-plot of the HDR image of the gym, as displayed on the HDR display, taken with a video photometer.

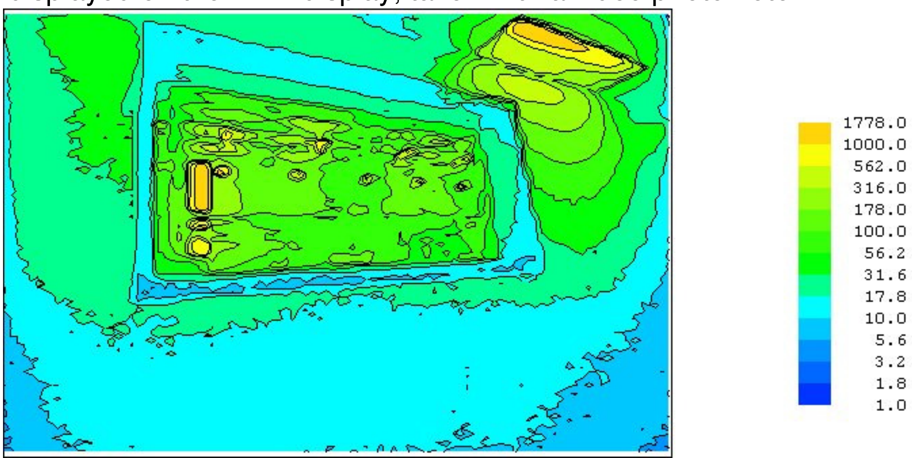


Figure B.3 : Luminance (cd/m^2) $\log_{10}$ iso-plot of the HDR image of the mezzanine, as displayed on the HDR display, taken with a video photometer.

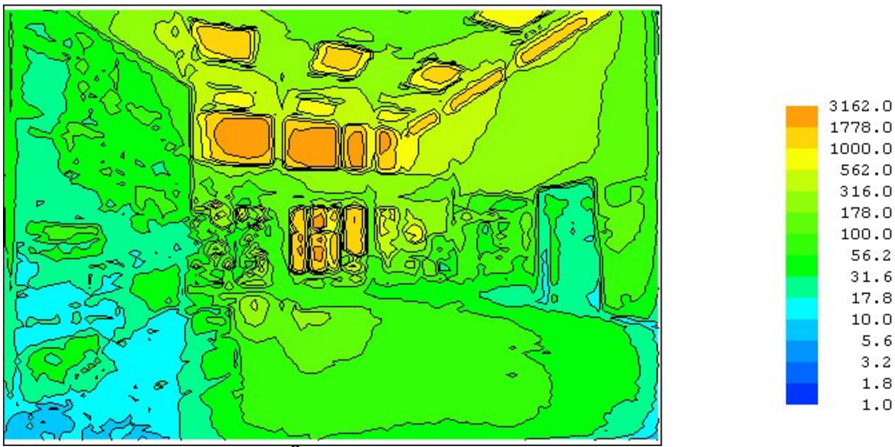


Figure B.4 : Luminance (cd/m^2) $\log_{10}$ iso-plot of the HDR image of the lobby, as displayed on the HDR display, taken with a video photometer.

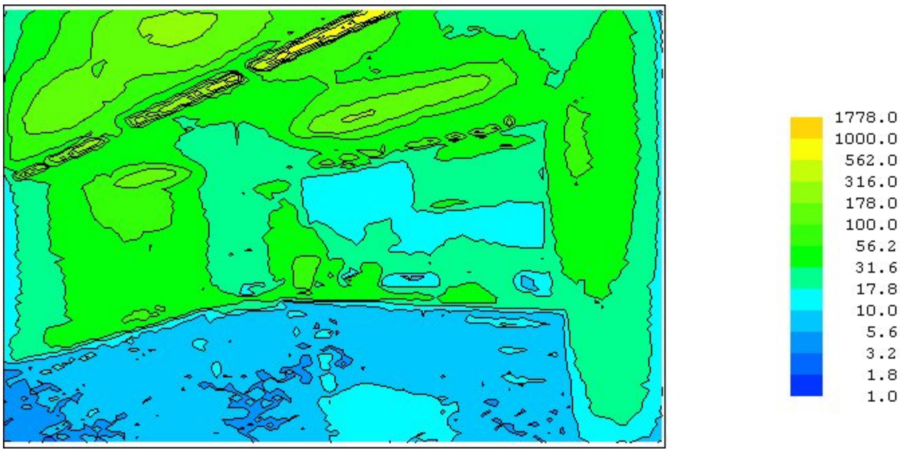


Figure B.5 : Luminance (cd/m^2) $\log_{10}$ iso-plot of the HDR image of the open-plan office, as displayed on the HDR display, taken with a video photometer.

Figure B.6 : Luminance (cd/m^2) $\log_{10}$ iso-plot of the HDR image of the staircase, as displayed on the HDR display, taken with a video photometer.

APPENDIX C: Image luminance iso-plots for Phase 2

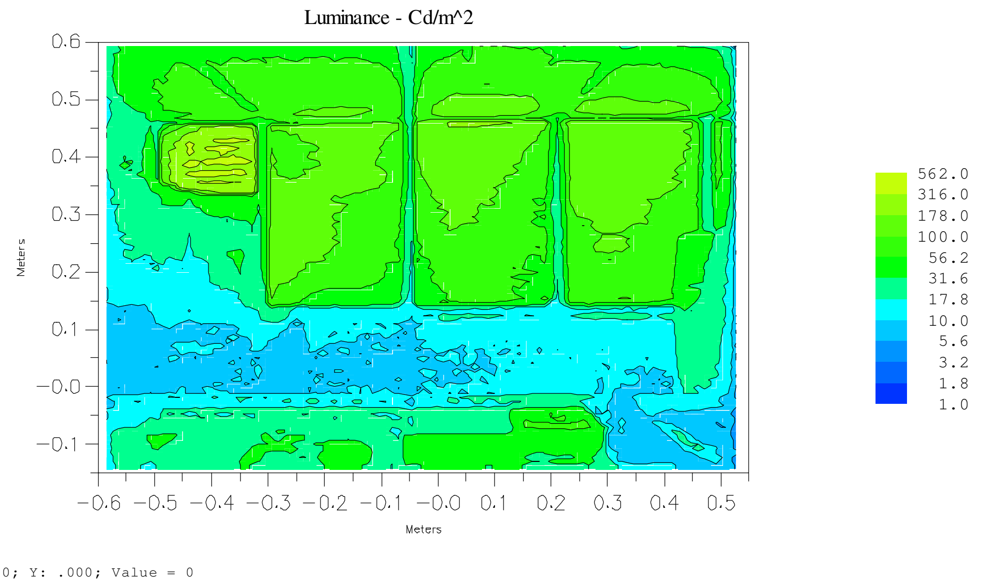


Figure C.1 : Luminance (cd/m^2) $\log_{10}$ iso-plot of the HDR image of desk+closed (panel height: desk+, blinds: closed), as displayed on the HDR display, taken with a video photometer.

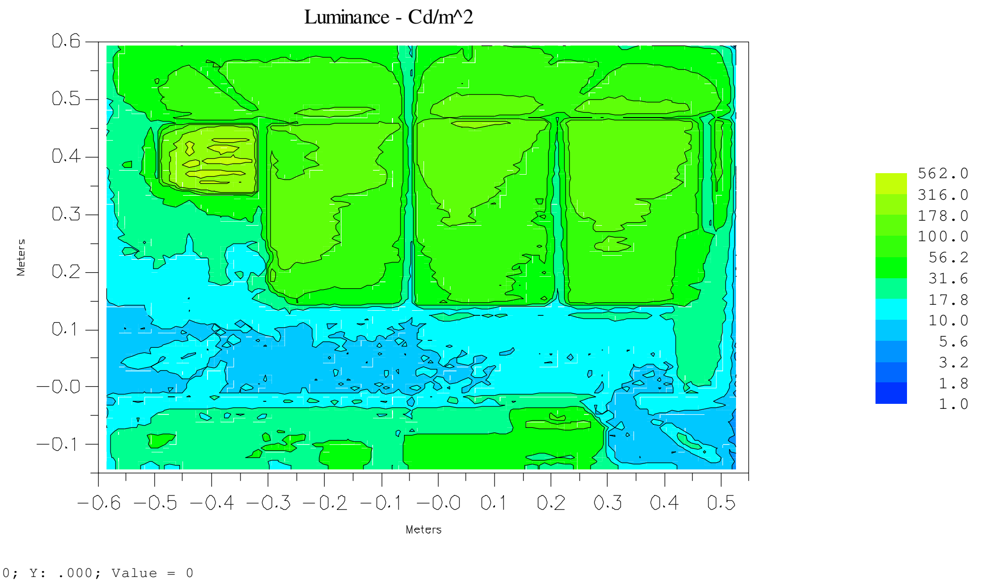


Figure C.2 : Luminance (cd/m^2) $\log_{10}$ iso-plot of the HDR image of desk+closed-m (panel height: desk+, blinds: closed, with neighbour), as displayed on the HDR display, taken with a video photometer.

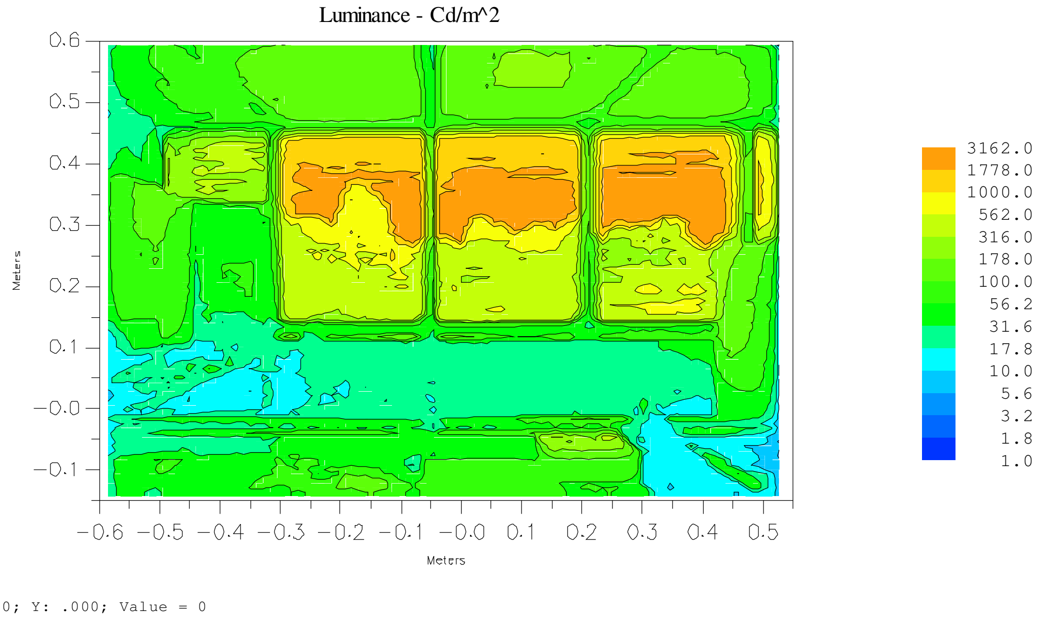


Figure C.3 : Luminance (cd/m^2) $\log_{10}$ iso-plot of the HDR image of desk+hor (panel height: desk+, blinds: horizontal), as displayed on the HDR display, taken with a video photometer.

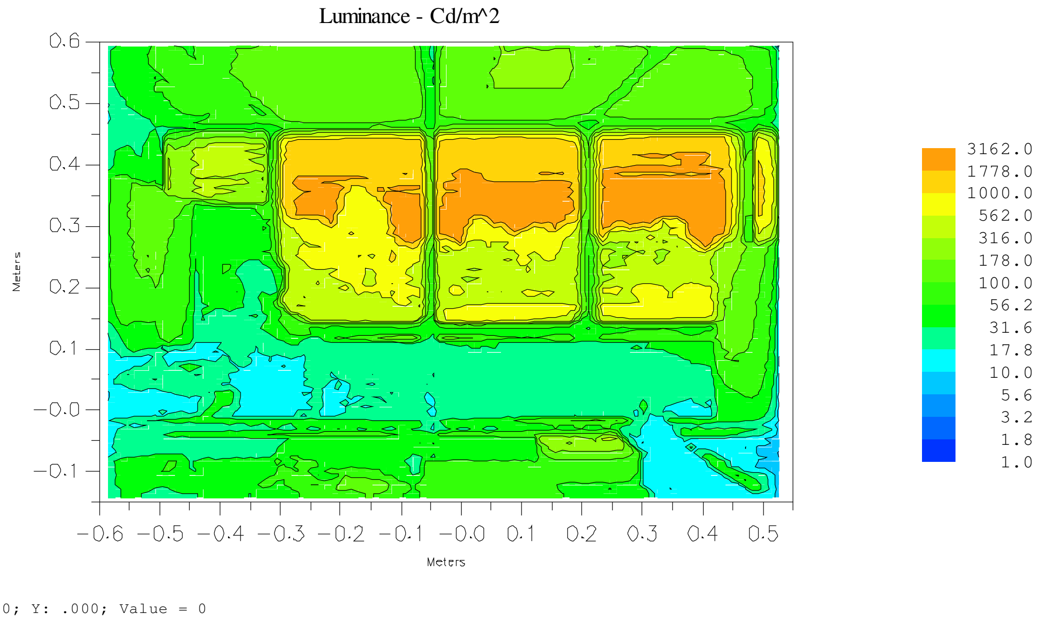


Figure C.4 : Luminance (cd/m^2) $\log_{10}$ iso-plot of the HDR image of desk+hor-m (panel height: desk+, blinds: horizontal, with neighbour), as displayed on the HDR display, taken with a video photometer.

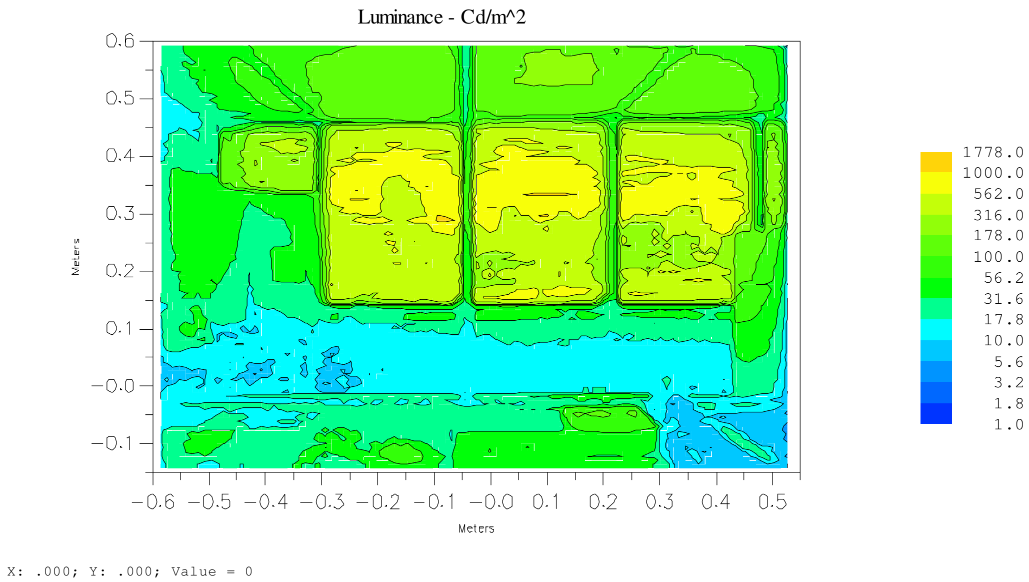


Figure C.5 : Luminance (cd/m^2) log$_{10}$ iso-plot of the HDR image of desk+tilted (panel height: desk+, blinds: horizontal), as displayed on the HDR display, taken with a video photometer.

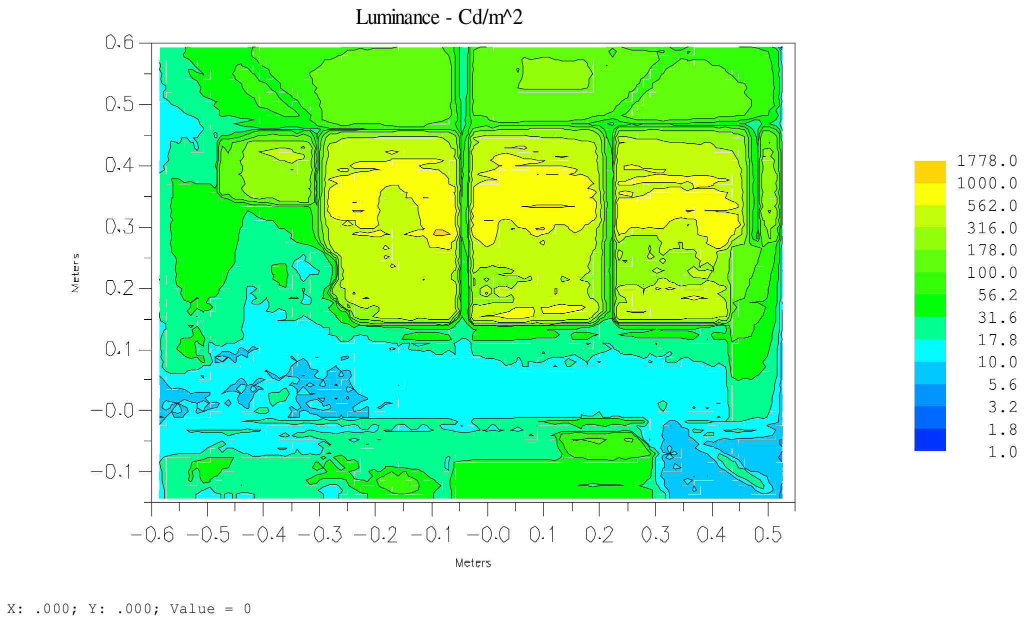


Figure C.6 : Luminance (cd/m^2) log$_{10}$ iso-plot of the HDR image of desk+tilted-m (panel height: desk+, blinds: tilted, with neighbour), as displayed on the HDR display, taken with a video photometer.

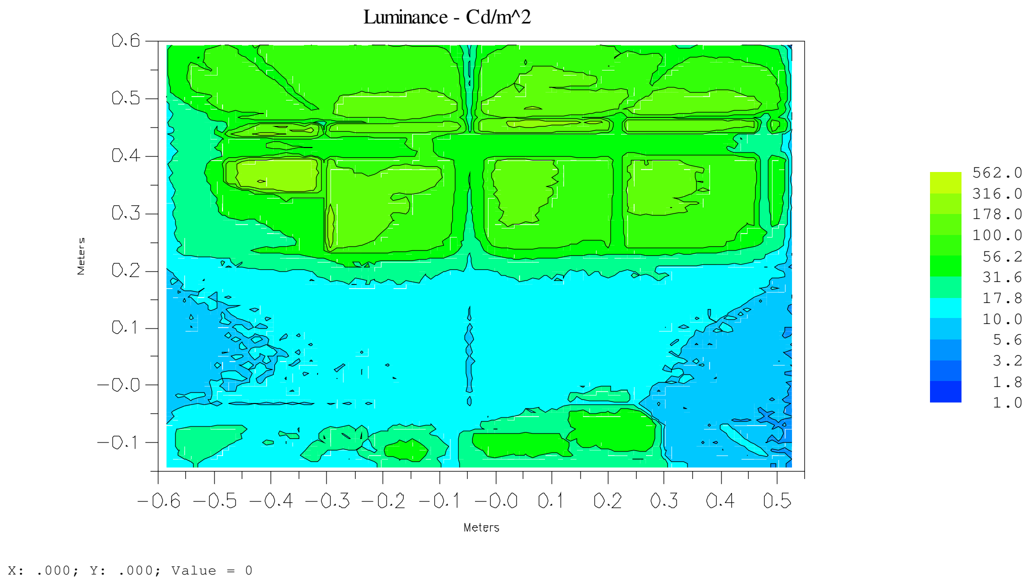


Figure C.7 : Luminance (cd/m^2) $\log_{10}$ iso-plot of the HDR image of seated privacy+closed (panel height: seated privacy+, blinds: closed), as displayed on the HDR display, taken with a video photometer.

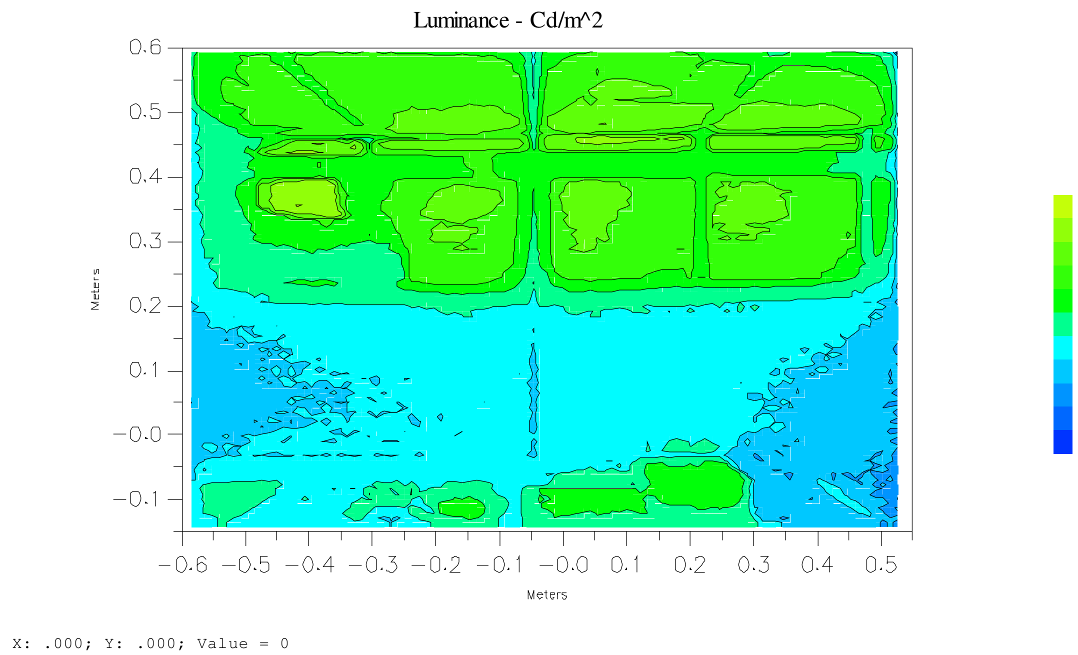


Figure C.8 : Luminance (cd/m^2) $\log_{10}$ iso-plot of the HDR image of seated privacy+closed-m (panel height: seated privacy+, blinds: closed, with neighbour), as displayed on the HDR display, taken with a video photometer.

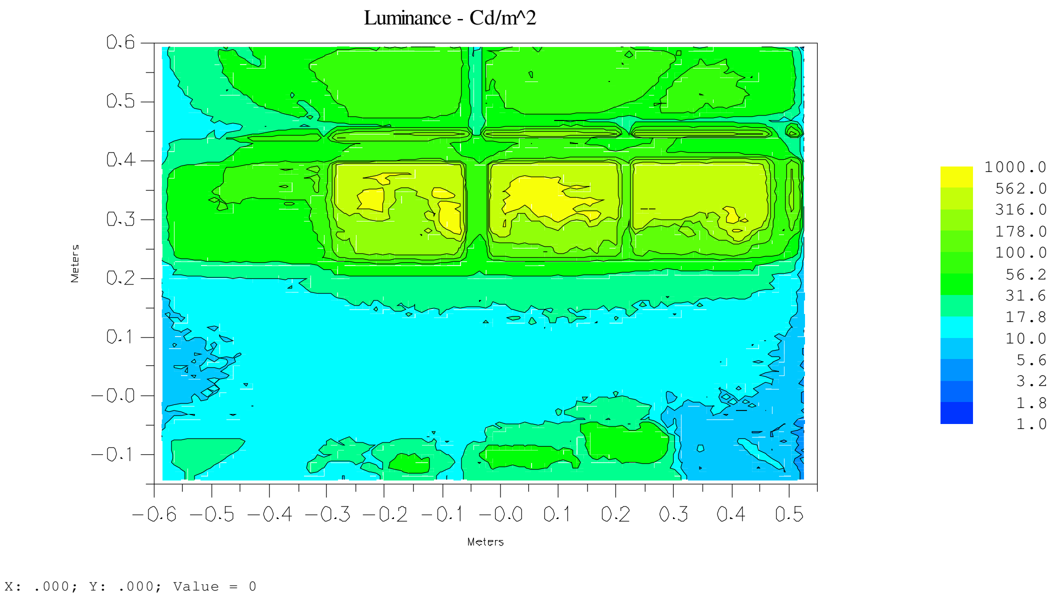


Figure C.9 : Luminance (cd/m^2) log$_{10}$ iso-plot of the HDR image of seated privacy+horizontal (panel height: seated privacy+, blinds: horizontal), as displayed on the HDR display, taken with a video photometer.

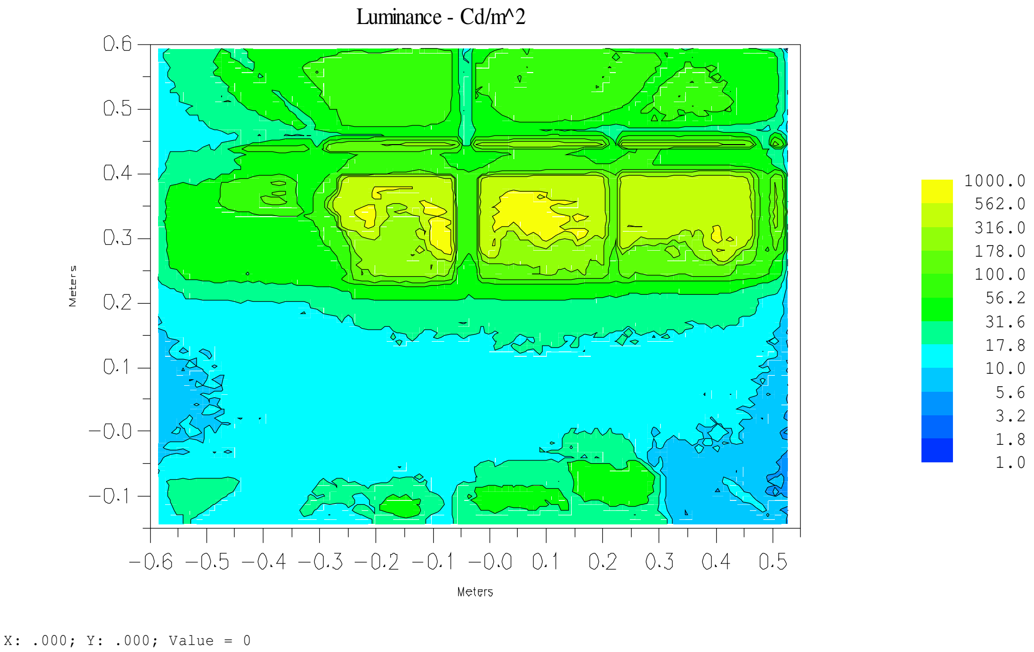
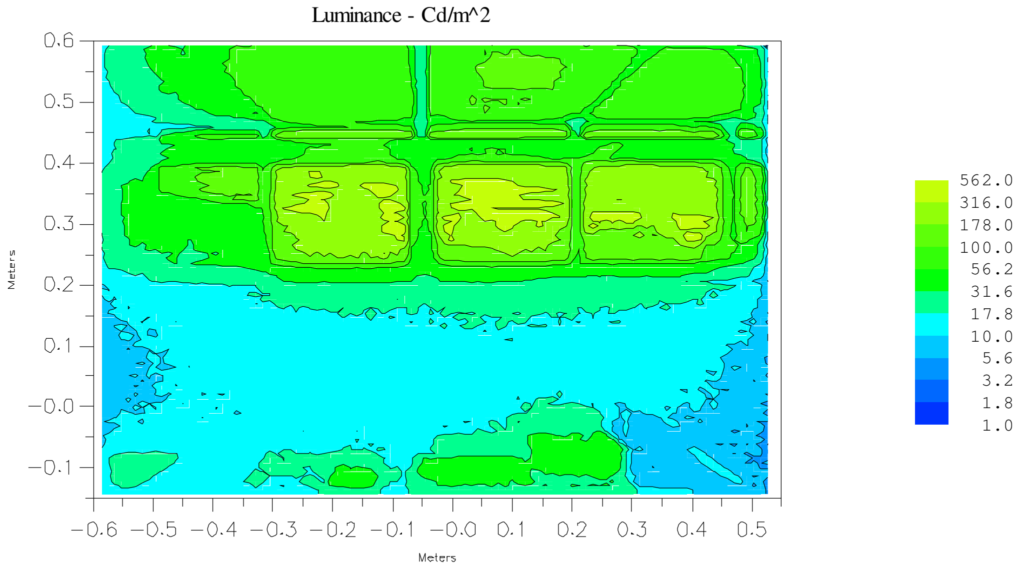
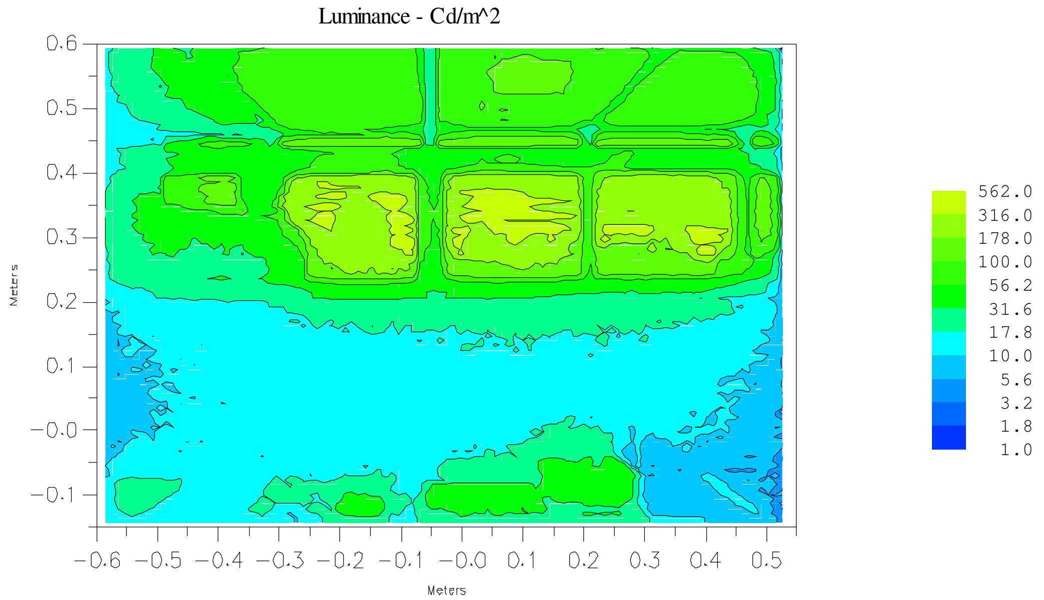


Figure C.10 : Luminance (cd/m^2) log$_{10}$ iso-plot of the HDR image of seated privacy+horizontal-m (panel height: seated privacy+, blinds: horizontal, with neighbour), as displayed on the HDR display, taken with a video photometer.



X: .000; Y: .000; Value = 0

Figure C.11 : Luminance (cd/m^2) log$_{10}$ iso-plot of the HDR image of seated privacy+tilted (panel height: seated privacy+, blinds: tilted), as displayed on the HDR display, taken with a video photometer.



X: .000; Y: .000; Value = 0

Figure C.12 : Luminance (cd/m^2) log$_{10}$ iso-plot of the HDR image of seated privacy+tilted-m (panel height: seated privacy+, blinds: tilted, with neighbour), as displayed on the HDR display, taken with a video photometer.

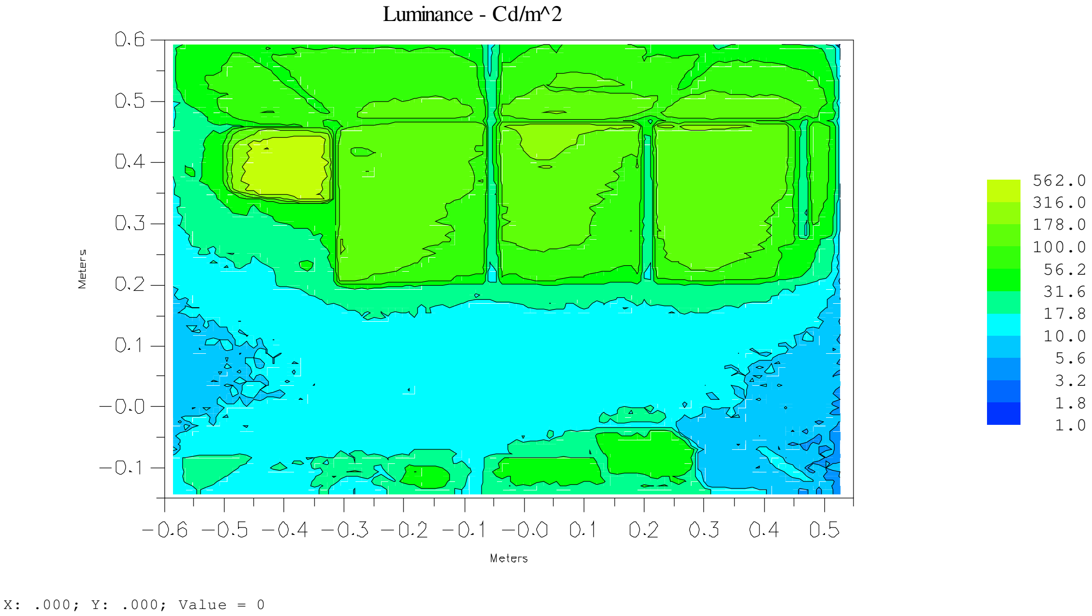


Figure C.13 : Luminance (cd/m^2) $\log_{10}$ iso-plot of the HDR image of seated privacy-closed (panel height: seated privacy, blinds: closed), as displayed on the HDR display, taken with a video photometer.

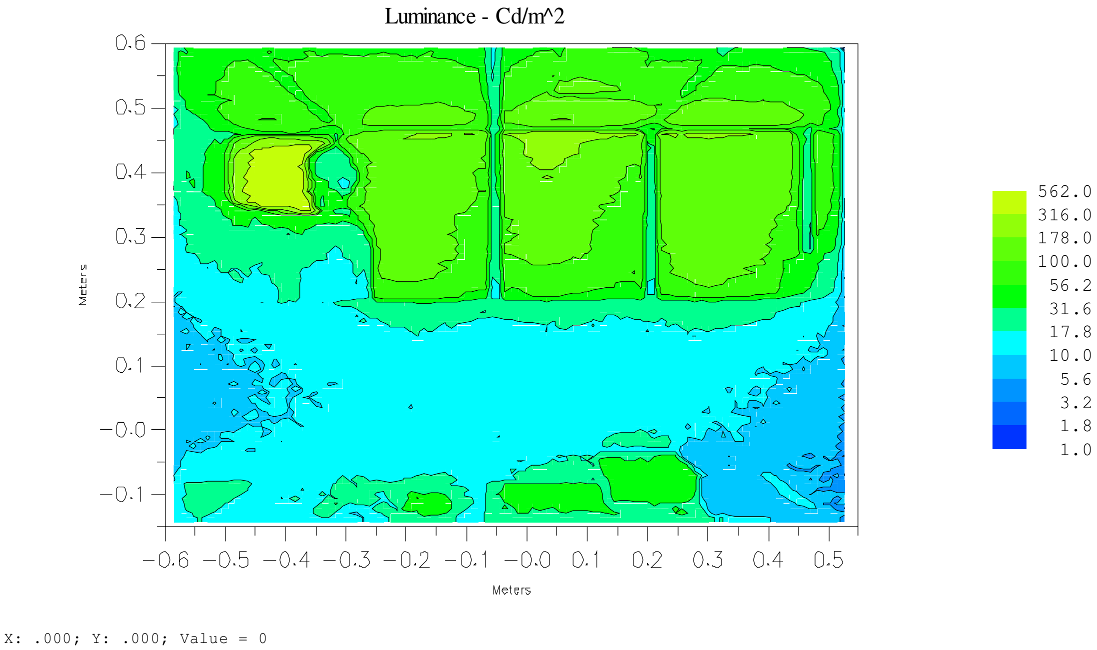


Figure C.14 : Luminance (cd/m^2) $\log_{10}$ iso-plot of the HDR image of seated privacy-closed-m (panel height: seated privacy, blinds: closed, with neighbour), as displayed on the HDR display, taken with a video photometer.

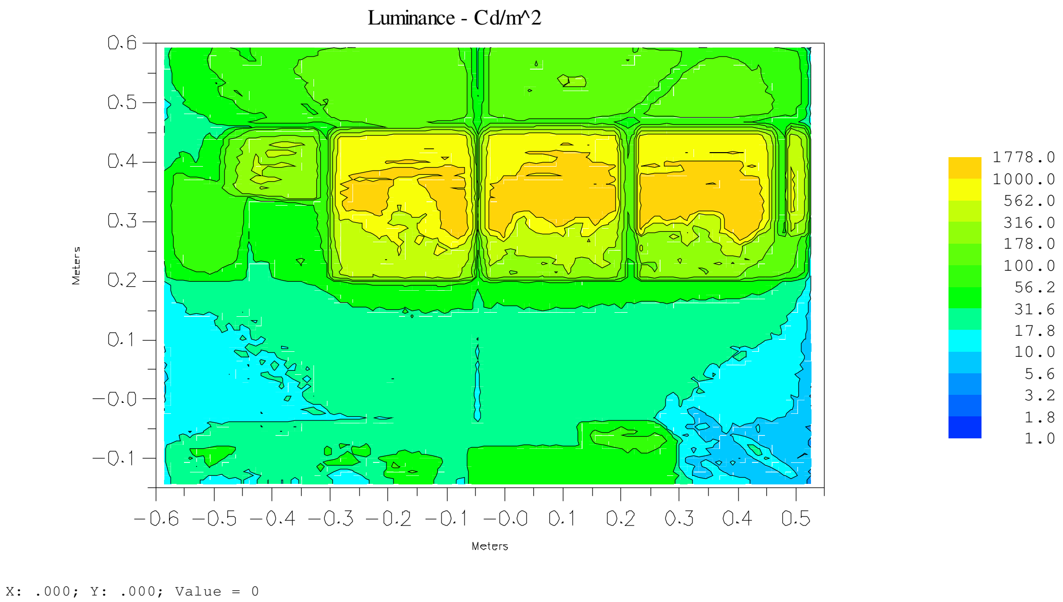


Figure C.15 : Luminance (cd/m^2) $\log_{10}$ iso-plot of the HDR image of seated privacy-horizontal (panel height: seated privacy, blinds: horizontal), as displayed on the HDR display, taken with a video photometer.

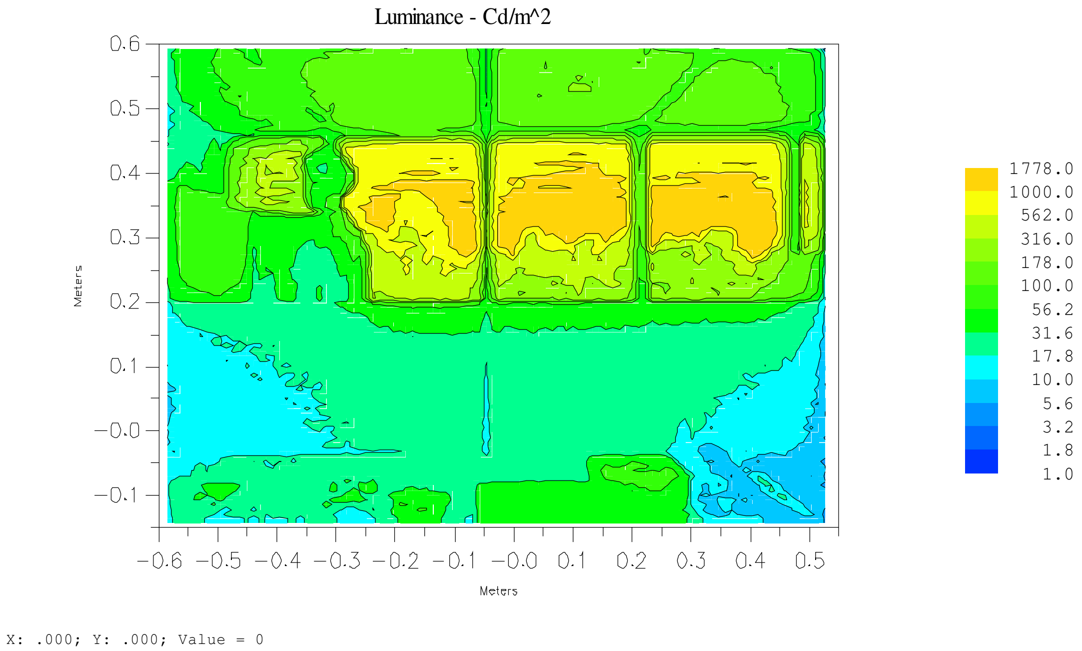


Figure C.16 : Luminance (cd/m^2) $\log_{10}$ iso-plot of the HDR image of seated privacy-horizontal-m (panel height: seated privacy, blinds: horizontal, with neighbour), as displayed on the HDR display, taken with a video photometer.

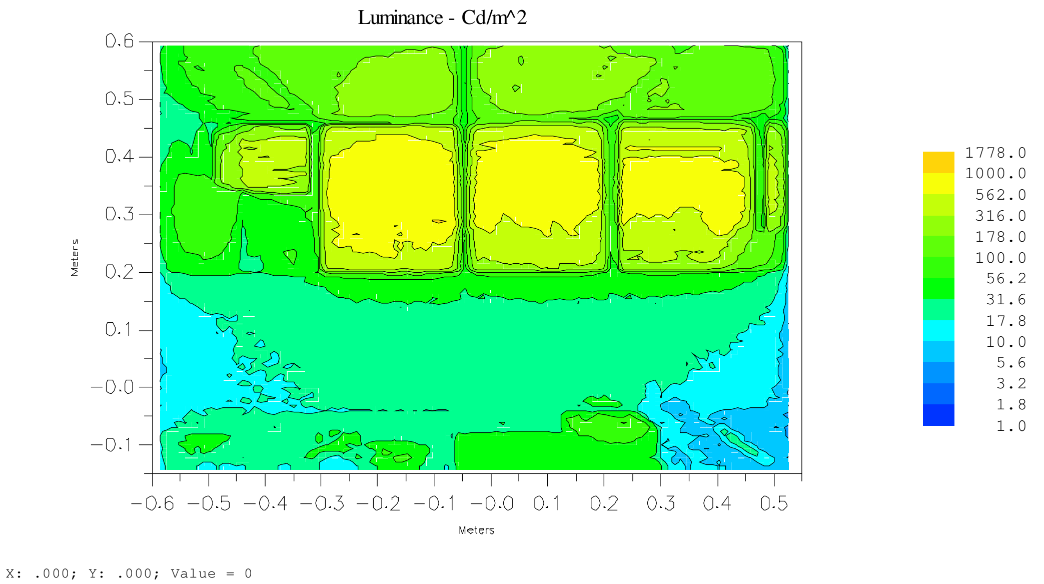


Figure C.17 : Luminance (cd/m^2) log$_{10}$ iso-plot of the HDR image of seated privacy-tilted (panel height: seated privacy, blinds: tilted), as displayed on the HDR display, taken with a video photometer.

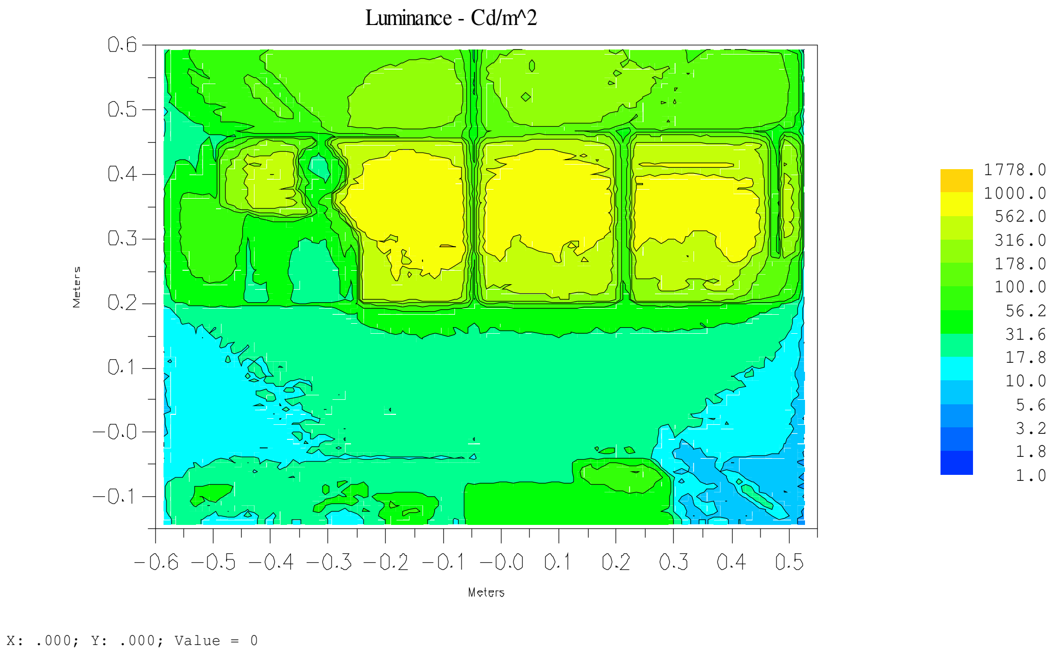


Figure C.18 : Luminance (cd/m^2) log$_{10}$ iso-plot of the HDR image of seated privacy-tilted-m (panel height: seated privacy, blinds: tilted, with neighbour), as displayed on the HDR display, taken with a video photometer.

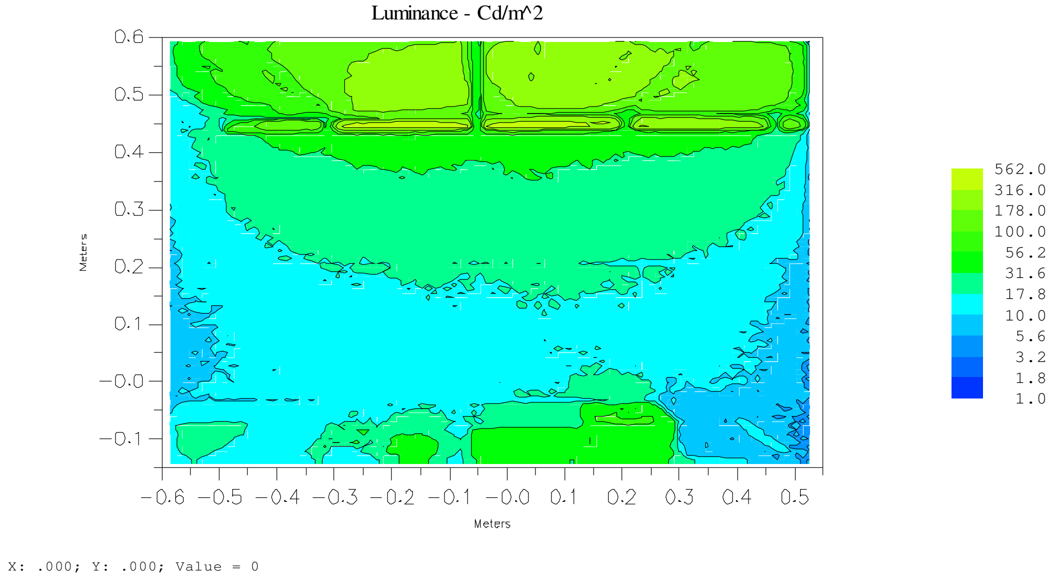


Figure C.19 : Luminance (cd/m^2) log$_{10}$ iso-plot of the HDR image of standing privacy-tilted (panel height: standing privacy, blinds: tilted), as displayed on the HDR display, taken with a video photometer.

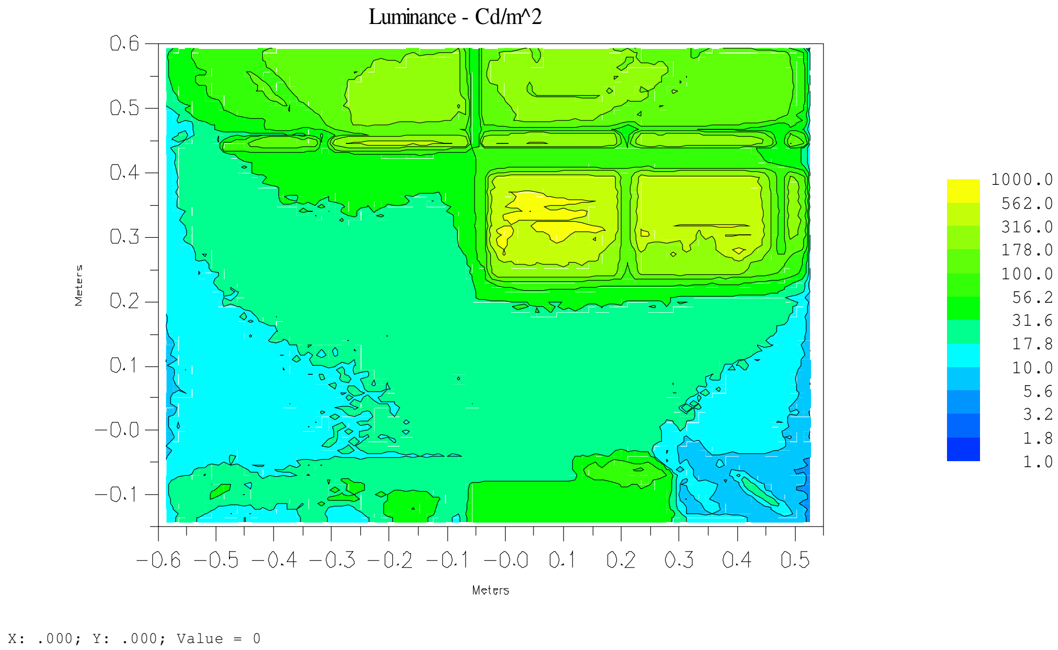


Figure C.20 : Luminance (cd/m^2) log$_{10}$ iso-plot of the HDR image of hybrid-tilted (panel: hybrid, blinds: tilted), as displayed on the HDR display, taken with a video photometer.

Note: There is no plot for the three layers image. It's apparent from the information in the luminance tables (Table D12) that there was very little variability in that view, which had no window

APPENDIX D: Luminance readings and charts for Phase 2

Table D.1: Luminance readings for desk+open.

	L measurements			
	real space	Photosphere	HDR display	
Points			without neighbour	with neighbour
1	122	74	124	134
2	129	75	120	129
3	123	85	124	135
4	1688	1620	1200	1200
5	3600	2850	1787	1730
6	850	602	468	637
7	8	7	12	13
8	95	78	73	77
9	29	20	40	42
10	250	116	168	185

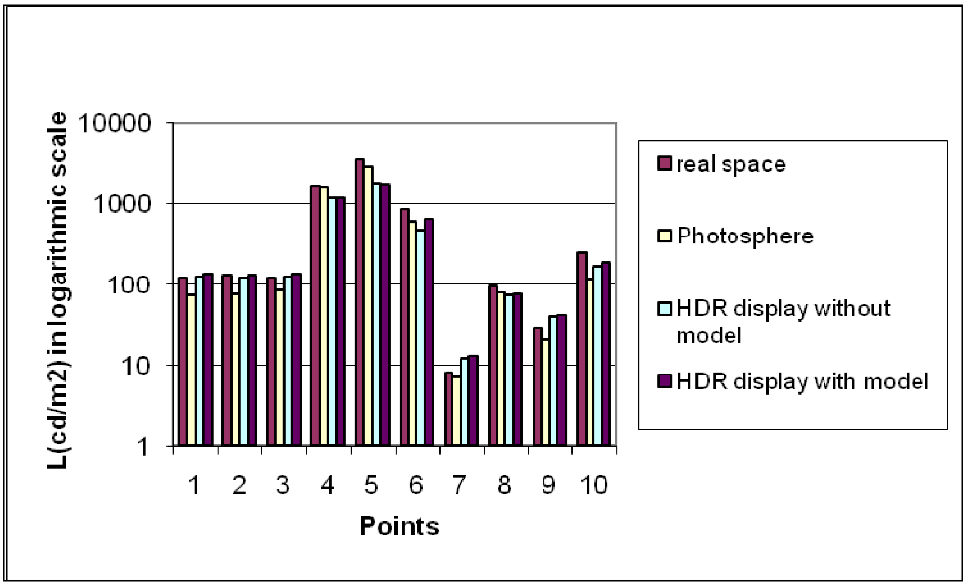


Figure D.1 : Luminance charts for desk+open.

Table D.2: Luminance readings for desk+tilted.

Points	L measurements real space	Photosphere	HDR display without neighbour	with neighbour
1	147	139	173	173
2	162	135	154	158
3	163	159	185	187
4	517	537	546	543
5	946	918	950	928
6	1035	1100	658	640
7	7	6	9	10
8	87	76	55	59
9	24	22	38	38
10	193	135	167	166

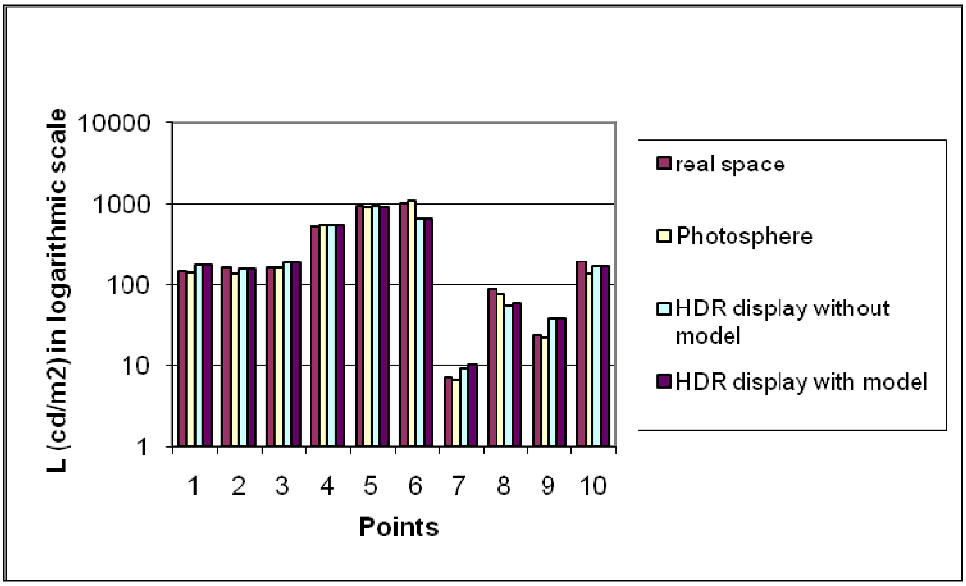


Figure D.2 : Luminance chart for desk+tilted.

Table D.3: Luminance readings for desk+closed.

Points	L measurements			
	real space	Photosphere	HDR display	
			without neighbour	with neighbour
1	90	83	100	98
2	146	129	138	135
3	136	137	161	158
4	216	238	249	247
5	78	85	86	83
6	73	66	72	72
7	4	4	6	6.2
8	61	58	37	38
9	13	13	33	32
10	45	37	45	46

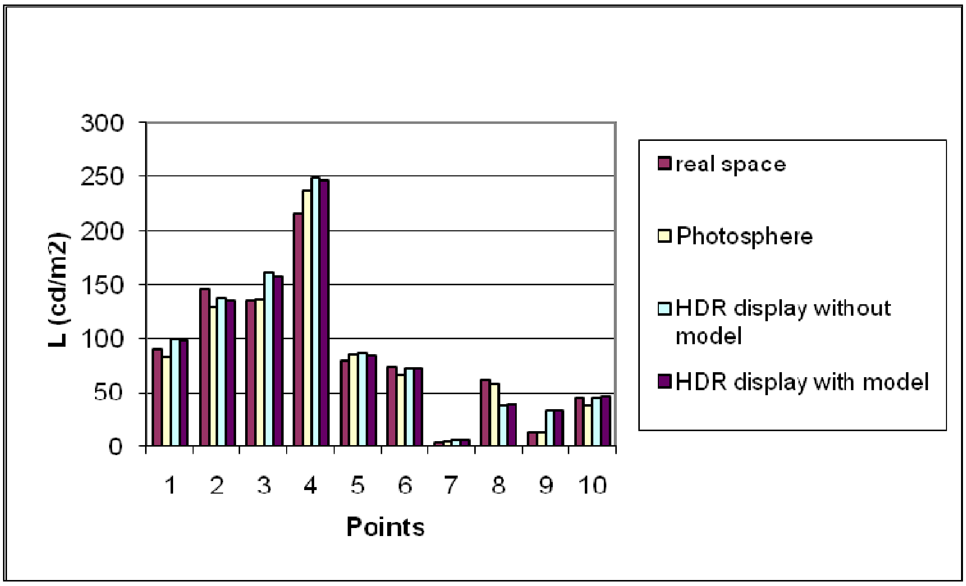


Figure D.3 : Luminance chart for desk+closed.

Table D.4: Luminance readings for seated privacy-open.

	L measurements			
	real space	Photosphere	HDR display	
Points			without neighbour	with neighbour
1	132	126	147	150
2	130	110	126	127
3	133	134	142	143
4	1575	1810	1226	1274
5	2775	3200	1730	1769
6	23	24	21	20
7	21	21	17	17
8	65	57	43	43
9	29	28	41	
10	282	218	210	207

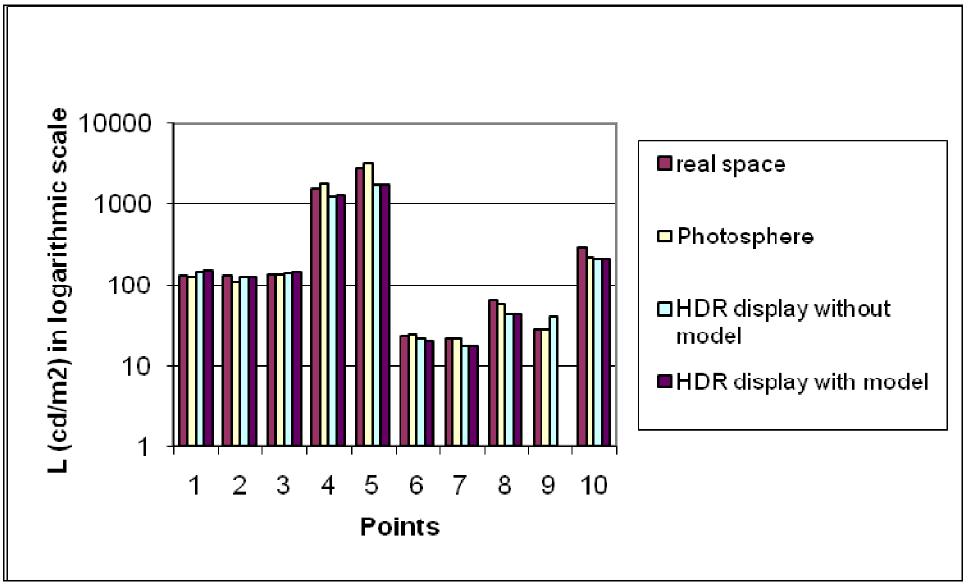


Figure D.4 : Luminance chart for seated privacy-open.

Table D.5: Luminance readings for seated privacy-tilted.

	L measurements			
	real space	Photosphere	HDR display	
Points			without neighbour	with neighbour
1	214	210	247	254
2	230	197	217	219
3	231	244	268	269
4	779	771	800	732
5	1368	1350	1070	1101
6	23	23	24	26
7	22	21	20	23
8	69	61	48	50
9	33	31	50	
10	294	217	216	215

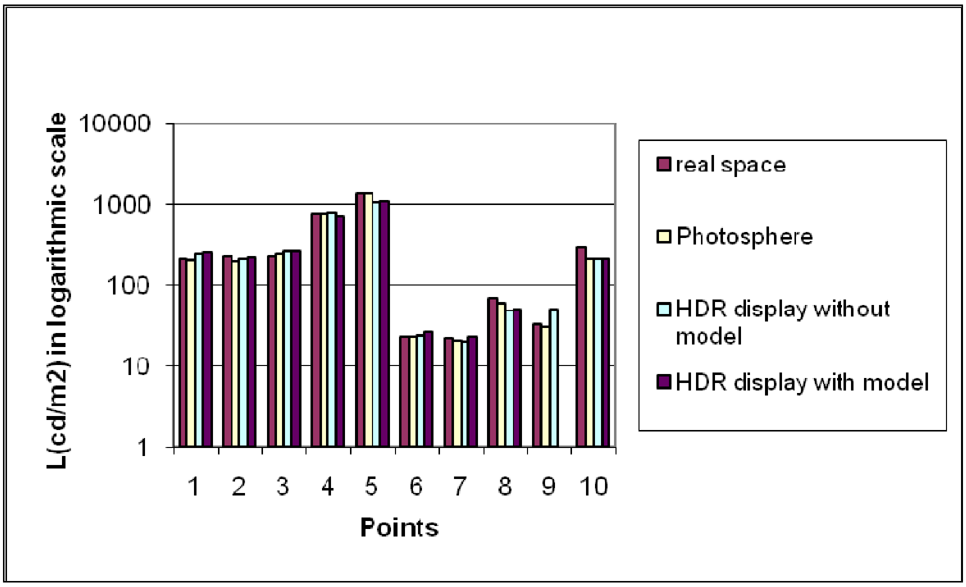


Figure D.5 : Luminance chart for seated privacy-tilted.

Table D.6: Luminance readings for seated privacy-closed.

	L measurements			
	real space	Photosphere	HDR display	
Points			without neighbour	with neighbour
1	101	94	115	116
2	173	153	153	151
3	152	152	169	170
4	228	256	241	242
5	89	96	101	102
6	15	16	16	15
7	15	16	12	12
8	52	48	33	34
9	14	14	38	
10	57	45	58	58

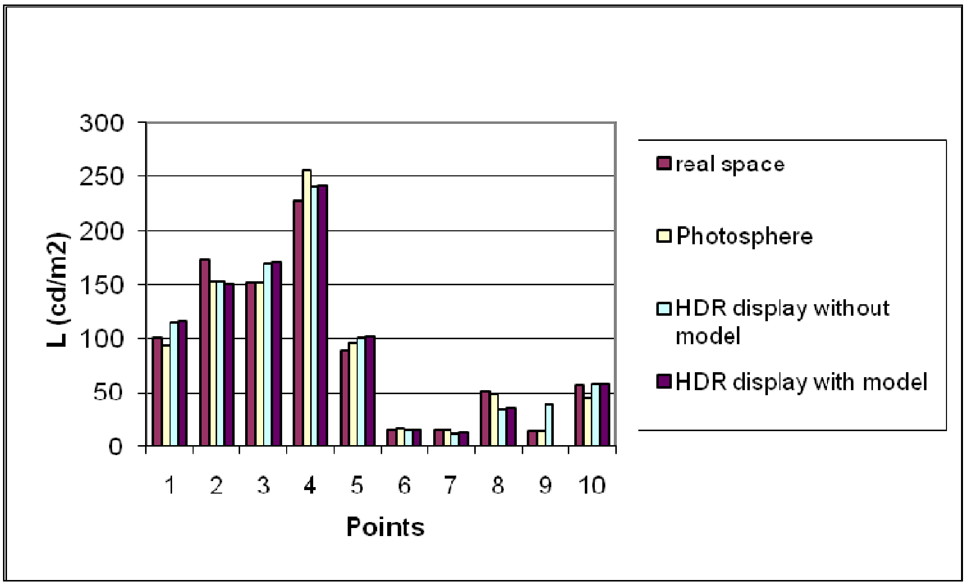


Figure D.6 : Luminance chart for seated privacy-closed.

Table D.7: Luminance readings for seated privacy+open.

Points	L measurements			
	real space	Photosphere	HDR display	
			without neighbour	with neighbour
1	61	63	73	74
2	70	62	67	69
3	66	70	77	78
4	1180	1150		
5	1307	1500	993	1012
6	18	18	13	14
7	17	17	11	11
8	56	48	30	35
9	59	57	52	49
10	135	108	116	114

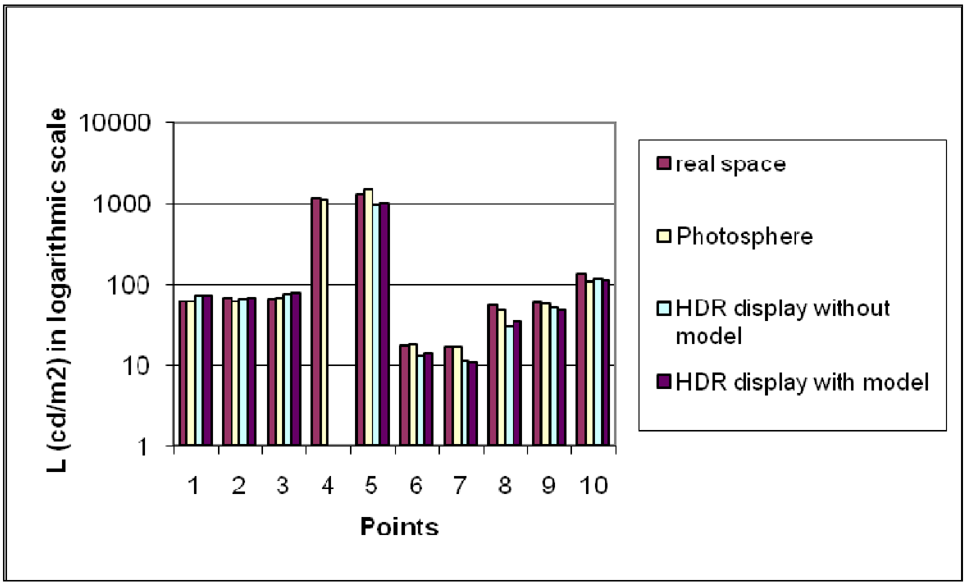


Figure D.7 : Luminance chart for seated privacy+open.

Table D.8: Luminance readings for seated privacy+tilted.

Points	L measurements			
	real space	Photosphere	HDR display	
			without neighbour	with neighbour
1	90	83	106	108
2	108	90	100	100
3	107	105	122	122
4	376	292		
5	605	555	500	500
6	17	16	15	14
7	17	15	11	12
8	57	46	32	33
9	47	39	44	41
10	102	70	87	89

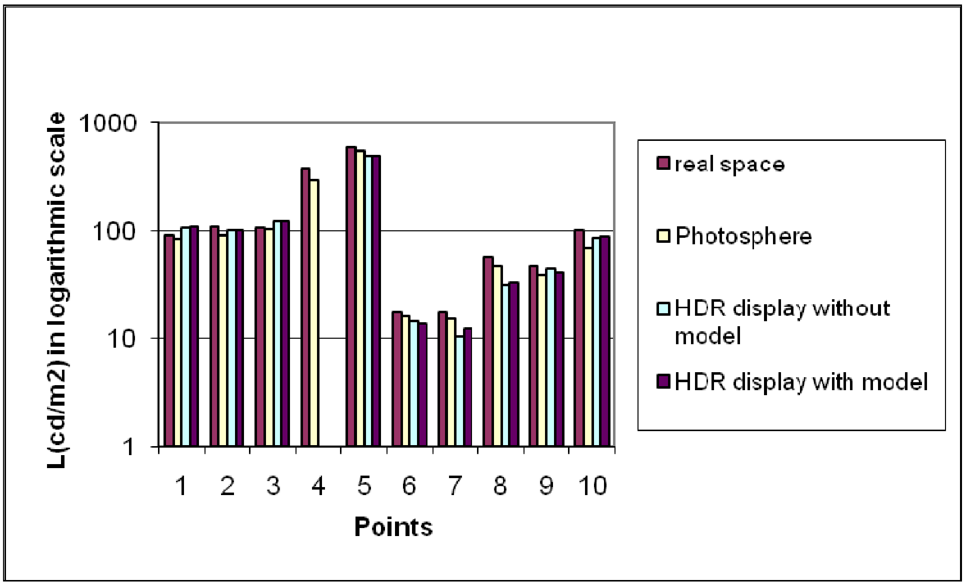


Figure D.8 : Luminance chart for seated privacy+tilted.

Table D.9: Luminance readings for seated privacy+closed.

	L measurements			
	real space	Photosphere	HDR display	
Points			without neighbour	with neighbour
1	117	113	135	134
2	184	173	166	166
3	161	175	187	188
4	243	271	225	228
5	74	80	96	97
6	15	17	15	15
7	16	16	13	13
8	52	49	35	35
9	31	33	53	50
10	55	42	46	47

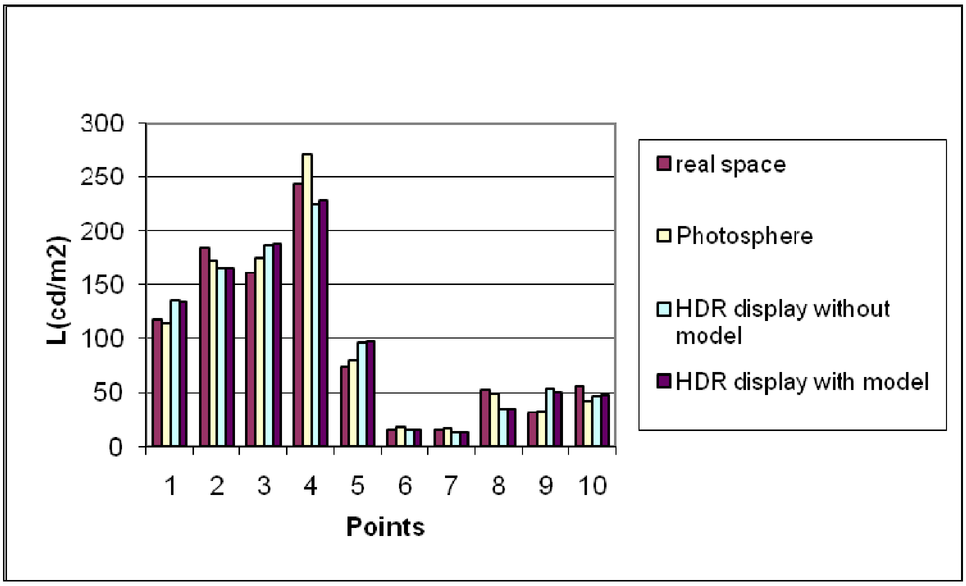


Figure D.9 : Luminance chart for seated privacy+closed.

Table D.10: Luminance readings for standing privacy-tilted.

	L measurements		
Points	real space	Photosphere	HDR display
1	232	221	276
2	245	205	236
3	254	254	299
4	877	743	569
5	25	23	27
6	20	20	16
7	20	19	15
8	64	55	42
9	23	20	22
10	23	16	16

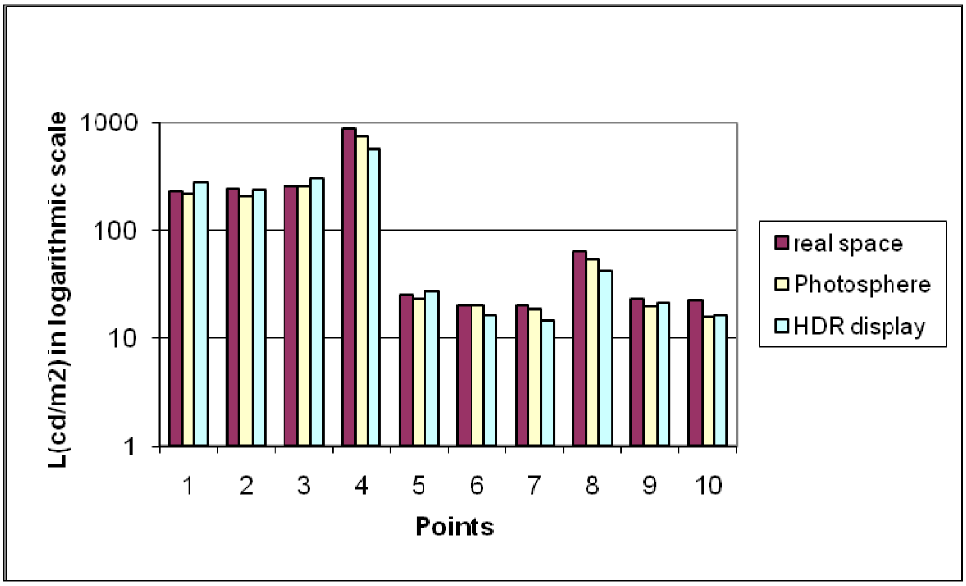


Figure D.10 : Luminance chart for standing privacy-tilted.

Table D.11: Luminance readings for hybrid-tilted.

	L measurements		
Points	real space	Photosphere	HDR display
1	240	219	286
2	257	203	236
3	266	251	296
4	861	681	504
5	1092	1050	885
6	22	21	24
7	21	19	21
8	67	56	48
9	24	20	29
10	265	177	188

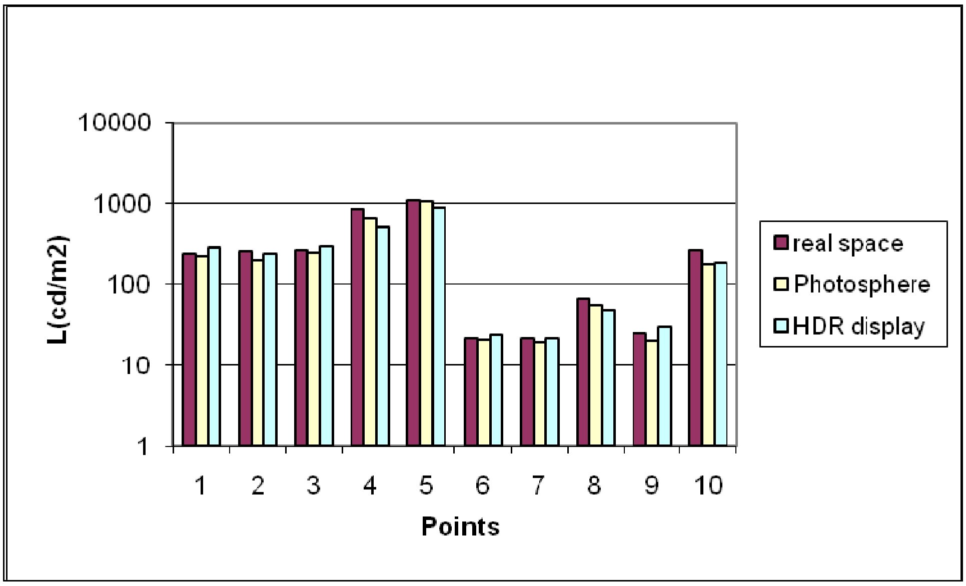


Figure D.11 : Luminance chart for hybrid-tilted.

Table D.12: Luminance readings for three-layers.

	L measurements		
Points	real space	Photosphere	HDR display
1			
2			
3			
4			
5	27	28	31
6	23	25	21
7	23	22	20
8	68	63	55
9	26	24	27
10	26	20	17

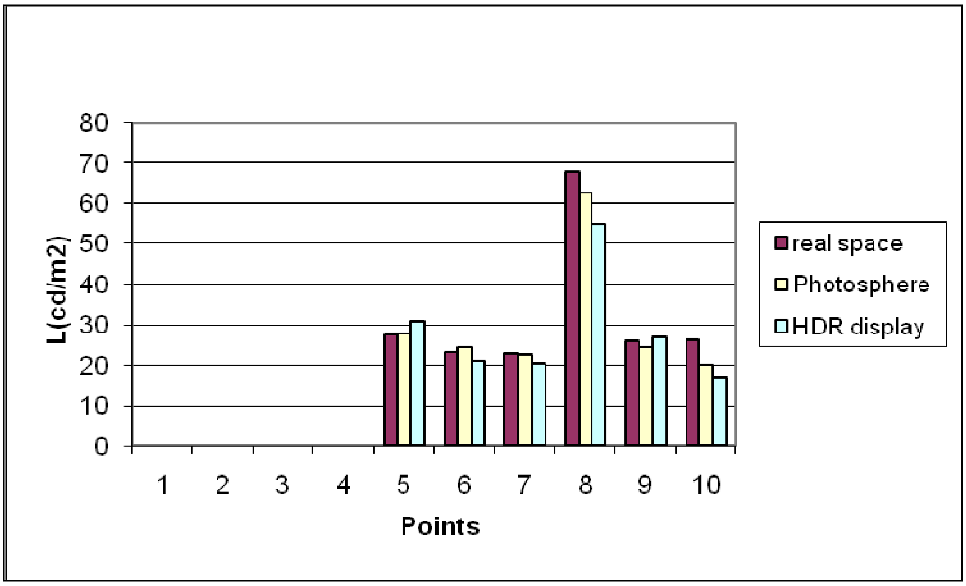


Figure D.12 : Luminance chart for three-layers.

APPENDIX E: Measuring points for the images at Phase 2

Figure E.1 : Measuring points for desk+.

Figure E.2 : Measuring points for seated privacy.

Figure E.3 : Measuring points for seated privacy+.

Figure E.4 : Measuring points for standing privacy.

Figure E.5 : Measuring points for hybrid.

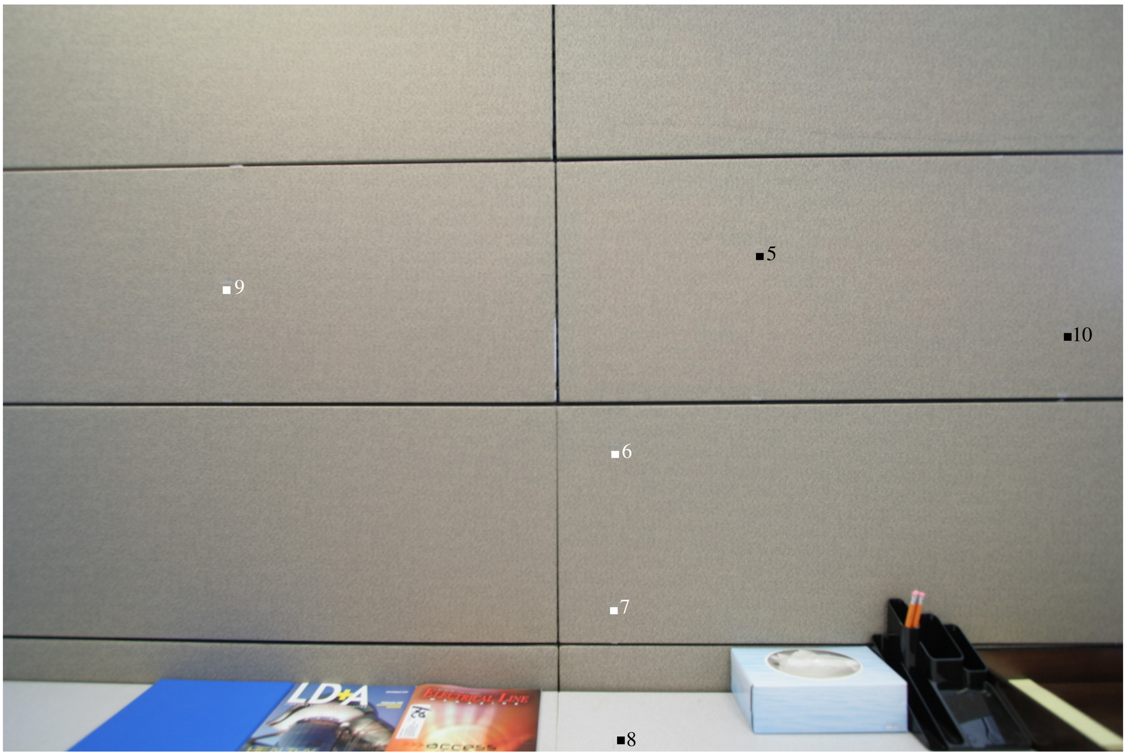


Figure E.6 : Measuring points for three layers.

APPENDIX F: Average Luminance of images acquired by Prometrics camera

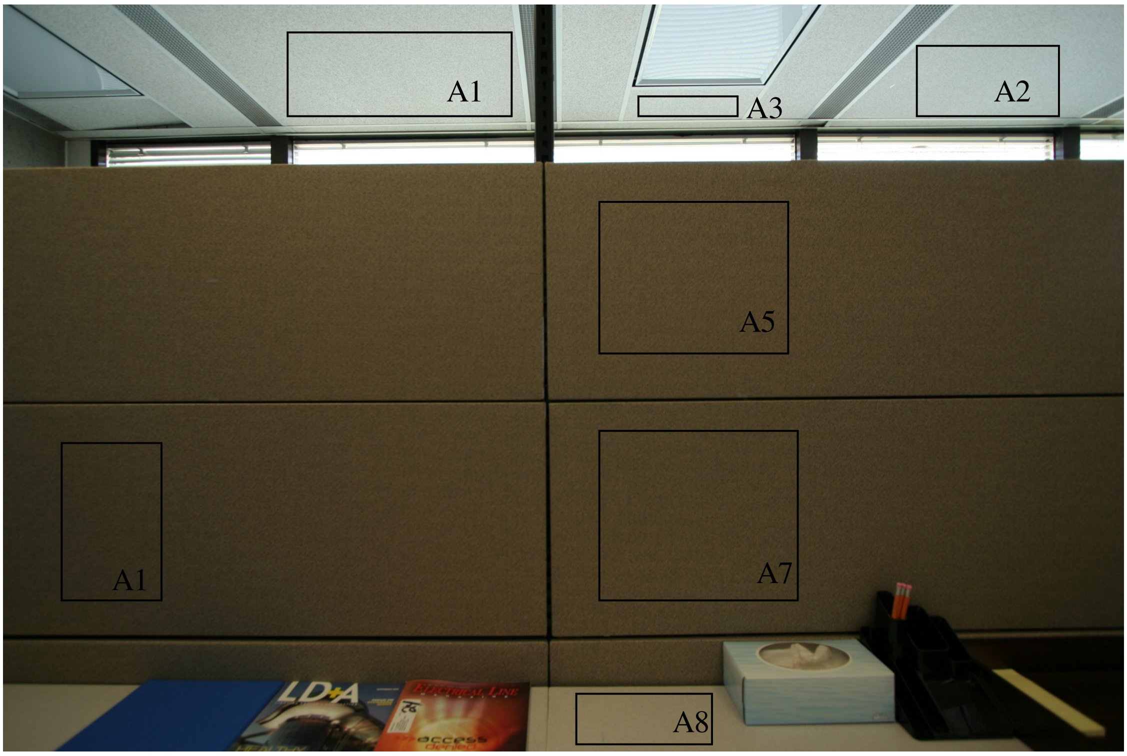


Figure F.1 : Areas selected on each image to obtain Luminance readings over an area.

Table F.1: Average L of patches on the images.

	Laverage							
	overall image	A1	A2	A3	A5	A7	A8	A11
desk+open	258	106	107	110	1389	20.2	62	32
desk+open,with N	263	114	113	116	1298	21	64	36
desk+tilted	163	140	124	143	673	15.6	52	22
desk+tilted with N	165	142	129	148	684	16.3	55	23.6
desk+closed	56	79	103	119	111	8.9	35	8.5
desk+closed,with N	56	80	104	121	113	9.1	36	9.1
seated priv-open	237	129	114	128	1312	21.8	44	14.7
seated priv-open,with N	227	128	113	126	1292	21.7	45	14.3
seated priv-tilted	197	203	167	203	871	22.8	48	15.2
seated priv-tilted,with N	190	207	171	206	878	24.8	52	16.3
seated priv-closed	56	90	110	128	119	13.2	34	9.3
seated priv-closed,with N	56	95	118	135	124	14.6	35	9.6
seated priv+open	108	67	61	68	797	14.7	33	9.6
seated priv+open,with N	95	61	55	62	710	13.5	30.3	8.8
seated priv+tilted	70	86	79	97	383	13.3	33	8.4
seated priv+tilted,with N	69	88	81	99	377	14.4	35	8.8
seated priv+closed	49	106	128	144	104	14.4	36	10
seated priv+closed,with N	46	104	126	142	102	14.4	36	9.8
standing priv-tilted	51	224	169	227	28.8	15.4	42	9.3
hybrid-tilted	108	235	184	230	651	22.9	49	12.9
three layers	24.4	44	21.9	31.1	30.7	20	52	11.9

Table F.2: Image statistics.

	stdev	75th	25th	90th	10th	# pixels above 1000 cd/m2	Lmax (cd/m2)	Lmin (cd/m2)
		PERCENTILE						
desk+open	585	357	35	1450	20	6297	2608	5
desk+open, with N	561	387	34	1401	20	6314	2452	5
desk+tilted	223	282	21	525	13	123	1274	3
desk+tilted, with N	220	267	20	515	13	104	1283	2
desk+closed	51	81	16	114	10	0	371	3
desk+closed, with N	51	80	16	114	10	0	372	2
seated priv-open	327	175	23	862	17	3475	1338	4
seated priv-open, with N	324	155	23	842	16	3374	1355	3
seated priv-tilted	233	236	24	604	18	15	1041	4
seated priv-tilted, with N	224	206	23	574	17	10	1041	4
seated priv-closed	63	90	14	133	10	0	464	2
seated priv-closed, with N	59	84	14	129	10	0	469	2
seated priv+open	135	63	15	237	12	0	669	3
seated priv+open, with N	133	62	15	229	11	0	678	3
seated priv+tilted	79	75	15	185	11	0	444	2
seated priv+tilted, with N	79	72	15	181	11	0	457	3
seated priv+closed	43	71	13	105	10	0	332	1
seated priv+closed, with N	40	67	13	98	10	0	324	2
standing priv-tilted	68	38	15	164	11	0	448	3
hybrid-tilted	123	110	20	244	15	0	686	3
three layers	10	28	17	38	13	0	82	3

APPENDIX G: Questionnaire in English for Phase 2

Scene # 1

Imagine that what you see on the screen is the view from your desk in an open plan office.
How would you judge this open plan office?
Please mark the oval that represents your personal feeling about this office. There are no right or wrong answers. If the word on the left is appropriate, mark the oval on the far left; if the word on the right is appropriate, mark the oval on the far right. If you have an intermediate opinion, mark an oval somewhere between the two extremes. If you don't have an opinion one way or the other, or have a neutral opinion, mark the middle oval.

1. too much light	○	○	○	○	○	○	○	too little light
2. unpleasant	○	○	○	○	○	○	○	pleasant
3. spacious	○	○	○	○	○	○	○	cramped
4. tense	○	○	○	○	○	○	○	calm
5. exciting	○	○	○	○	○	○	○	boring

6. How would you feel about the amount of privacy you would have in this office?

○	○	○	○	○	○	○
very unsatisfied	unsatisfied	somewhat unsatisfied	neutral	somewhat satisfied	satisfied	very satisfied

7. How would you feel about the amount of view through the window?

○	○	○	○	○	○	○
very unsatisfied	unsatisfied	somewhat unsatisfied	neutral	somewhat satisfied	satisfied	very satisfied

8. How would you feel about the amount of visual comfort you would have in this office? (a visually comfortable space does not cause eye-strain)

○	○	○	○	○	○	○
very satisfied	satisfied	somewhat satisfied	neutral	somewhat unsatisfied	unsatisfied	very unsatisfied

APPENDIX H: Questionnaire in French for Phase 2

Marche à suivre

Nous désirons connaître votre opinion sur des scènes affichées sur un écran d'ordinateur. Veuillez inscrire vos évaluations dans ce livret en utilisant une nouvelle page par scène.

Le chercheur vous indiquera à quel moment vous devez évaluer la scène. Après le message de sollicitation, assurez-vous de passer à une nouvelle page du livret et visualisez la scène. On vous laissera du temps pour vous habituer à la scène. Le chercheur vous indiquera à quel moment vous devez commencer à évaluer la scène. Pendant votre évaluation vous pouvez faire un retour sur la scène aussi souvent que vous voulez.
Lorsque vous avez fini d'évaluer une scène, informez le chercheur que vous avez terminé. Le chercheur affichera la scène suivante, et vous pourrez passer à la page suivante du livret. Soyez certain d'utiliser une nouvelle page pour chaque scène. Vous reprendrez ces étapes jusqu'à ce que toutes les scènes aient été évaluées.

Comment indiquer vos évaluations

Il y a huit questions vous permettent d'évaluer l'aspect visuel de chaque scène. Noircissez l'ovale qui correspond à votre impression personnelle de la scène. Formez-vous une opinion basée sur votre point d'observation et en tenant compte de l'ensemble de la scène. Il n'y a pas de bonnes ou de mauvaises réponses. Pour les cinq premières évaluations, si l'expression de gauche est appropriée, noircissez l'ovale situé à l'extrême gauche; si l'expression de droite est appropriée, noircissez l'ovale situé à l'extrême droite. Si votre opinion se situe entre ces deux extrêmes, noircissez un ovale intermédiaire. Si vous n'avez pas d'opinion dans un sens ou dans l'autre ou si vous êtes neutre, noircissez l'ovale du centre.

Si vous noircissiez le deuxième ovale à partir de la gauche, cela indique que vous estimez qu'il y a vraiment trop de lumière :

trop de lumière ○ ● ○ ○ ○ ○ ○ pas assez de lumière

En revanche, si vous noircissiez le troisième ovale à partir de la droite, cela signifie que vous estimez qu'il y a trop peu de lumière dans le bureau, mais de façon moins catégorique :

trop de lumière ○ ○ ○ ○ ● ○ ○ pas assez de lumière

Si vous êtes indifférent, vous pouvez noircir l'ovale qui se trouve au centre de l'échelle. Si vous changez d'avis, il vous suffit d'effacer cette marque et de noircir un autre ovale. Vous trouverez les définitions courantes des adjectifs sur une feuille séparée.

Veuillez répondre à toutes les questions. Merci de votre participation.

Scène n° 1

Imaginez que ce que vous voyez à l'écran est la vue que vous avez de votre poste de travail dans un bureau à aires ouvertes. *Comment évaluerez-vous ce bureau à aires ouvertes?*

Veuillez noircir l'ovale qui représente votre impression personnelle de ce bureau. Il n'y a pas de bonnes ou de mauvaises réponses. Si l'expression de gauche est appropriée, noircissez l'ovale situé à l'extrême gauche; si l'expression de droite est appropriée, noircissez l'ovale situé à l'extrême droite. Si votre opinion se situe entre ces deux extrêmes, noircissez un des ovales intermédiaires. Si vous n'avez pas d'opinion dans l'un ou dans l'autre sens ou si vous êtes neutre, noircissez l'ovale du centre.

1. trop de lumière ○ ○ ○ ○ ○ ○ ○ pas assez de lumière
2. désagréable ○ ○ ○ ○ ○ ○ ○ agréable
3. spacieux ○ ○ ○ ○ ○ ○ ○ exigu
4. tendu ○ ○ ○ ○ ○ ○ ○ calme
5. excitant ○ ○ ○ ○ ○ ○ ○ ennuyeux
6. Comment vous sentiriez vous dans ce bureau pour ce qui est du niveau d'intimité?

○	○	○	○	○	○	○
Très insatisfait	insatisfait	plutôt insatisfait	neutre	plutôt satisfait	satisfait	très satisfait

7. Comment vous sentiriez-vous pour ce qui est de la quantité de la vue sur l'extérieur?

○	○	○	○	○	○	○
Très insatisfait	insatisfait	plutôt insatisfait	neutre	plutôt satisfait	satisfait	très satisfait

8. Comment vous sentiriez-vous dans ce bureau pour ce qui est du niveau de confort visuel que vous auriez? (Un espace visuellement confortable ne cause pas de fatigue oculaire.)

○	○	○	○	○	○	○
Très insatisfait	insatisfait	plutôt insatisfait	neutre	plutôt satisfait	satisfait	très satisfait

APPENDIX I: Adjective Definitions in English for Phase 2

pleasant:	the scene looks nice or attractive
unpleasant:	the scene looks ugly or unattractive
spacious:	the scene has ample space or room; looks large and commodious
cramped:	the scene looks confined or restricted in space
tense:	the scene causes feelings of anxiety
calm:	the scene looks peaceful and quiet, or free from anxiety
exciting:	the scene causes feelings of happiness and enthusiasm
boring:	the scene looks neither interesting nor exciting
privacy:	the scene is free from public attention, interference or intrusion

APPENDIX J: Adjective definitions in French for Phase 2

Définition des adjectifs

Agréable :	La scène paraît plaisante ou attrayante.
Désagréable :	La scène paraît laide ou peu attrayante.
Spacieux :	La scène comporte de grands espaces, semble vaste et commode.
Exigu :	La scène semble confinée ou l'espace semble restreint.
Tendu :	La scène engendre des sentiments d'anxiété.
Calme :	La scène semble paisible et tranquille ou ne cause pas d'anxiété.
Excitant :	La scène provoque des sentiments de bonheur et d'enthousiasme.
Ennuyeux :	La scène ne semble ni intéressante ni excitante.
Intimité :	La scène est à l'abri des regards indiscrets, des dérangements ou des intrusions.

APPENDIX K: Demographics questionnaire in English for Phase 2

Questionnaire
We would like to know a bit about you. This information, like all of the other answers you give, will be kept strictly confidential.

1. What is your sex?
   - ☐ Male
   - ☐ Female
2. How old are you?
   - ☐ 18 to 29
   - ☐ 30 to 39
   - ☐ 40 to 49
   - ☐ 50 to 59
   - ☐ 60 and older
3. What type of correction lenses do you have today?
   - ☐ None
   - ☐ Reading Glasses
   - ☐ Distance Glasses
   - ☐ Bi- or Trifocal Lenses
   - ☐ Gradual or Multi-focal Lenses
   - ☐ Contact Lenses
4. What type of job do you have?
   - ☐ Administrative
   - ☐ Technical
   - ☐ Professional
   - ☐ Managerial
5. What best describes the type of office space you work in?
   - ☐ Private office
   - ☐ Open office with partitioned cubicles
   - ☐ Workstation with no partitions
6. How many people occupy your office room?
   - ☐ only me
   - ☐ me + one person
   - ☐ me + 2-3 others
   - ☐ me + 4 or more others
7. For how long have you had this office?
   _____years_____months

8. Which of these best describes your access to windows in your current office?
☐ I have a window next to my desk
☐ I don’t have my own window, but I can see one from where I sit
☐ I can’t see a window from where I sit

APPENDIX L: Demographics questionnaire in French for Phase 2

Questionnaire

Nous voudrions connaître quelques détails à votre sujet. Toutes vos réponses resteront strictement confidentielles.

1. Quel est votre sexe?
   - ☐ Masculin
   - ☐ Féminin
2. Quel est votre âge?
   - ☐ 18 - 29
   - ☐ 30 - 39
   - ☐ 40 - 49
   - ☐ 50 - 59
   - ☐ 60 et plus
3. Quel(s) genre(s) de verre(s) correcteur(s) portez-vous aujourd'hui?
   - ☐ aucun
   - ☐ lunettes de lecture
   - ☐ lunettes pour myopie
   - ☐ lentilles bifocales ou trifocales
   - ☐ lentilles à foyer progressif
   - ☐ lentilles cornéennes
4. Quelle est la catégorie qui décrit le mieux votre emploi?
   - ☐ Administrative
   - ☐ Technique
   - ☐ Professionnelle
   - ☐ Gestionnaire
5. Lequel décrit le mieux votre bureau actuel?
   - ☐ bureau privé
   - ☐ aire ouverte avec bureau à cloisons
   - ☐ poste de travail sans cloisons
6. Il y a combien de personne qui occupe votre espace de bureau?
   - ☐ Seulement moi
   - ☐ Moi + une personne
   - ☐ Moi + 2 à 3 autres
   - ☐ Moi + 4 autres ou plus

APPENDIX L: Demographics questionnaire in French for Phase 2

7. Depuis combien de temps occupez-vous ce bureau?
   ______année(s)______mois

8. Présentement, parmi les phrases suivantes, laquelle décrit le mieux votre accès aux fenêtres à partir de votre bureau?

☐ J'ai une fenêtre à côté de mon pupitre
☐ Je n'ai pas ma propre fenêtre, mais je peux en voir une d'où je suis assis.
☐ Je ne peux pas voir de fenêtre d'où je suis assis

APPENDIX M: Planned comparisons' mean and standard deviations

	DO mean	DO SD	TL mean	TL SD
amount of light	4.69	1.01	2.31	1.21
pleasantness	5.11	1.45	1.61	1.05
spaciousness	5.11	1.51	2.00	1.24
tenseness	4.44	1.71	2.22	1.35
excitement	4.17	1.44	1.25	0.50
privacy	2.56	1.56	5.56	1.52
amount of view	6.03	1.25	1.06	0.23
visual comfort	4.64	1.53	3.42	1.99

Figure M.1 : Planned comparison between Desk+blinds open (DO) versus three layers of panels (TL), mean ratings and standard deviations.

	HT mean	HT SD	StPT mean	StPT SD	SP+T mean	SP+T SD
amount of light	3.53	0.74	2.47	1.28	2.94	1.07
pleasantness	3.94	1.43	2.03	1.30		
spaciousness	3.69	1.09	2.42	1.34		
tenseness	4.25	1.32	2.72	1.77		
excitement	3.33	1.37	1.56	1.05		
privacy	5.19	1.12			4.75	1.30
amount of view	3.75	1.59	1.72	1.70		
visual comfort	4.03	1.52	3.08	1.86		

Figure M.2 : Planned comparisons of Hybrid (HT) versus Seated Privacy+ (SP+T) and Hybrid (HT) versus Standing Privacy (StPT), mean ratings and standard deviations, statistically significant results are given in the chart.

APPENDIX N: Panel X Blind X Neighbour mean ratings and Standard Error

Table N.1 : Panel X Blind X Neighbour mean ratings and Standard Error for amount of light.

			Desk+		SP		SP+		Panel means		
			No N	with N	No N	with N	No N	with N	No N	with N	Grand
Blind	open	mean	4.69	4.64	4.28	4.50	3.64	3.25	4.20	4.13	4.17
		SE	0.17	0.17	0.15	0.20	0.21	0.18			
	tilted	mean	4.14	4.17	3.97	4.33	2.94	3.25	3.69	3.92	3.80
		SE	0.13	0.17	0.15	0.18	0.18	0.17			
	closed	mean	2.31	2.25	2.17	2.11	2.44	2.58	2.31	2.31	2.31
		SE	0.20	0.18	0.15	0.14	0.16	0.20			
mean by Neighbour			3.71	3.69	3.47	3.65	3.01	3.03			
mean by Panel			3.70		3.56		3.02				

Table N.2 : Panel X Blind X Neighbour mean ratings and Standard Error for pleasantness.

			Desk+		SP		SP+		Panel means		
			No N	with N	No N	with N	No N	with N	No N	with N	Grand
Blind	open	mean	5.11	4.51	4.53	3.97	4.44	3.58	4.69	4.02	4.36
		SE	0.24	0.27	0.23	0.26	0.24	0.21			
	tilted	mean	5.14	4.28	4.39	4.42	3.81	3.69	4.44	4.13	4.29
		SE	0.24	0.30	0.20	0.28	0.25	0.25			
	closed	mean	2.47	2.17	2.44	2.42	3.11	3.36	2.68	2.65	2.66
		SE	0.20	0.19	0.22	0.18	0.24	0.26			
mean by Neighbour			4.24	3.65	3.79	3.60	3.79	3.55			
mean by Panel			3.95		3.69		3.67				

Table N.3 : Panel X Blind X Neighbour mean ratings and Standard Error for spaciousness.

			Desk+		SP		SP+		Panel means		
			No N	with N	No N	with N	No N	with N	No N	with N	Grand
Blind	open	mean	5.11	4.92	4.08	3.86	4.03	3.25	4.41	4.01	4.21
		SE	0.25	0.24	0.20	0.24	0.22	0.19			
	tilted	mean	4.89	4.75	3.94	4.08	3.81	3.36	4.21	4.06	4.14
		SE	0.24	0.27	0.20	0.21	0.21	0.24			
	closed	mean	4.22	4.00	3.06	3.08	3.50	3.69	3.59	3.59	3.59
		SE	0.27	0.30	0.22	0.20	0.24	0.21			
mean by Neighbour			4.74	4.56	3.69	3.68	3.78	3.44			
mean by Panel			4.65		3.69		3.61				

Table N.4 : Panel X Blind X Neighbour mean ratings and Standard Error for tenseness.

			Desk+		SP		SP+		Panel means		
			No N	with N	No N	with N	No N	with N	No N	with N	Grand
Blind	open	mean	4.44	3.97	4.42	3.47	4.33	3.78	4.40	3.74	4.07
		SE	0.29	0.28	0.22	0.22	0.22	0.22			
	tilted	mean	4.53	3.89	4.28	3.61	4.08	3.67	4.30	3.72	4.01
		SE	0.27	0.29	0.22	0.21	0.24	0.26			
	closed	mean	3.11	2.83	3.25	2.86	3.81	3.83	3.39	3.18	3.28
		SE	0.25	0.23	0.28	0.22	0.28	0.26			
mean by Neighbour			4.03	3.56	3.98	3.31	4.07	3.76			
mean by Panel			3.80		3.65		3.92				

Table N.5 : Panel X Blind X Neighbour mean ratings and Standard Error for excitement.

			Desk+		SP		SP+		Panel means		
			No N	with N	No N	with N	No N	with N	No N	with N	Grand
Blind	open	mean	4.17	4.19	3.72	3.22	3.61	2.86	3.83	3.43	3.63
		SE	0.24	0.25	0.21	0.24	0.23	0.21			
	tilted	mean	4.22	3.86	3.47	3.56	3.17	2.72	3.62	3.38	3.50
		SE	0.27	0.29	0.21	0.24	0.21	0.21			
	closed	mean	2.00	2.19	2.06	2.08	2.47	2.67	2.18	2.31	2.25
		SE	0.17	0.17	0.16	0.18	0.20	0.24			
mean by Neighbour			3.46	3.42	3.08	2.95	3.08	2.75			
mean by Panel			3.44		3.02		2.92				

Table N.6 : Panel X Blind X Neighbour mean ratings and Standard Error for privacy.

			Desk+		SP		SP+		Panel means		
			No N	with N	No N	with N	No N	with N	No N	with N	Grand
Blind	open	mean	2.56	2.06	3.78	2.78	4.75	4.11	3.69	2.98	3.34
		SE	0.26	0.20	0.25	0.20	0.23	0.24			
	tilted	mean	2.61	2.44	3.31	2.83	4.75	3.58	3.56	2.95	3.25
		SE	0.29	0.29	0.22	0.22	0.22	0.23			
	closed	mean	2.17	1.61	3.53	2.50	4.31	4.39	3.33	2.83	3.08
		SE	0.27	0.18	0.28	0.22	0.26	0.24			
mean by Neighbour			2.44	2.04	3.54	2.70	4.60	4.03			
mean by Panel			2.24		3.12		4.31				

Table N.7 : Panel X Blind X Neighbour mean ratings and Standard Error for amount of view.

			Desk+		SP		SP+		Panel means		
			No N	with N	No N	with N	No N	with N	No N	with N	Grand
Blind	open	mean	6.03	6.19	4.56	4.92	4.53	4.03	5.04	5.05	5.04
		SE	0.21	0.16	0.27	0.23	0.26	0.25			
	tilted	mean	5.75	5.58	4.69	4.61	4.00	3.47	4.81	4.56	4.69
		SE	0.23	0.26	0.21	0.23	0.29	0.24			
	closed	mean	1.83	1.69	1.67	1.58	2.14	2.06	1.88	1.78	1.83
		SE	0.21	0.20	0.21	0.14	0.24	0.21			
mean by Neighbour			4.54	4.49	3.64	3.70	3.56	3.19			
mean by Panel			4.51		3.67		3.37				

Table N.8 : Panel X Blind X Neighbour mean ratings and Standard Error for visual comfort.

			Desk+		SP		SP+		Panel means		
			No N	with N	No N	with N	No N	with N	No N	with N	Grand
Blind	open	mean	4.64	4.56	4.31	4.17	4.25	3.72	4.40	4.15	4.27
		SE	0.26	0.26	0.24	0.23	0.23	0.23			
	tilted	mean	4.83	4.67	4.17	4.17	3.92	3.83	4.31	4.22	4.26
		SE	0.28	0.28	0.23	0.23	0.24	0.25			
	closed	mean	3.31	2.89	3.03	3.19	3.69	3.58	3.34	3.22	3.28
		SE	0.29	0.24	0.23	0.26	0.25	0.26			
mean by Neighbour			4.26	4.04	3.83	3.84	3.95	3.71			
mean by Panel			4.15		3.84		3.83				

APPENDIX O: Panel_SPvsSP+ X Blind-L Univariate Test Results

Figure O1 shows that position of the blinds contrasted the subjects regarding pleasantness for seated privacy and seated privacy+ panel heights. The univariate tests show that images with horizontal blinds were rated as more pleasant, than images with closed blinds. When blinds were closed, Seated Privacy+ was rated as less unpleasant than Seated Privacy.

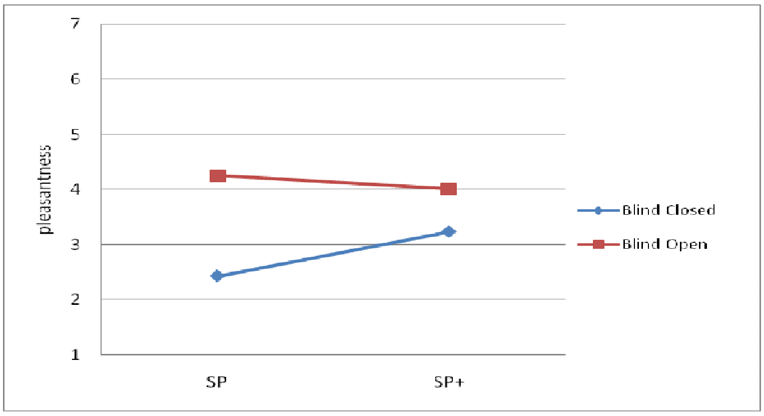


Figure O.1 : Ratings for pleasantness for images with Seated Privacy and Seated Privacy+ Panel height, under closed and open blind conditions, 1 stands for unpleasant and 7 stands for pleasant.

The univariate results in Figure O2 show that images with seated privacy panel height were rated as less boring when the blinds were open in comparison to when they were closed.

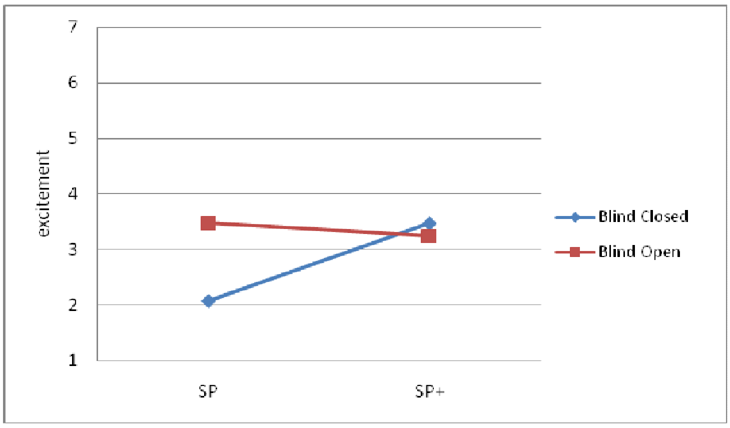


Figure O.2 : Ratings for excitement for images with Seated Privacy and Seated Privacy+ Panel height, Blinds closed and open, 1 stands for boring and 7 stands for exciting.

The position of the blinds contrasted the subjects regarding satisfaction with the amount of view for images with seated privacy and seated privacy+ panel heights. Figure O3 shows that when blinds were open, the ratings were closer to somewhat satisfied with the amount of view, and when blinds were closed, ratings were closer to unsatisfied with the amount of view.

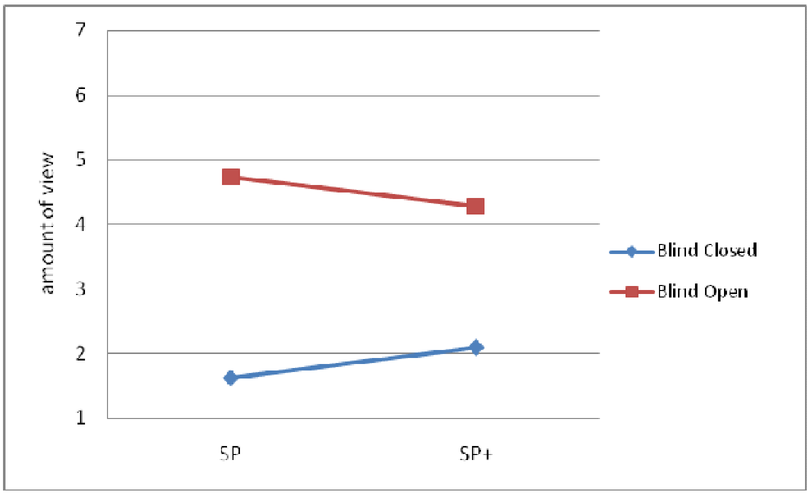


Figure O.3 : Ratings for amount of view for images with Seated Privacy and Seated Privacy+ Panel height, under closed and open blind conditions, 1 stands for very unsatisfied and 7 stands for very satisfied.

The position of the blinds contrasted the subjects regarding satisfaction with visual comfort for images with seated privacy and seated privacy+ panel heights. Figure O4 shows the univariate test results. When blinds were open, scenes with seated privacy and seated privacy+ panel height were rated slightly above the neutral line; whereas when blinds were closed, ratings were below the neutral line. When the blinds were closed, subjects rated the scenes with seated privacy panel height as somewhat unsatisfying regarding visual comfort. Ratings for seated privacy+ were closer to neutral.

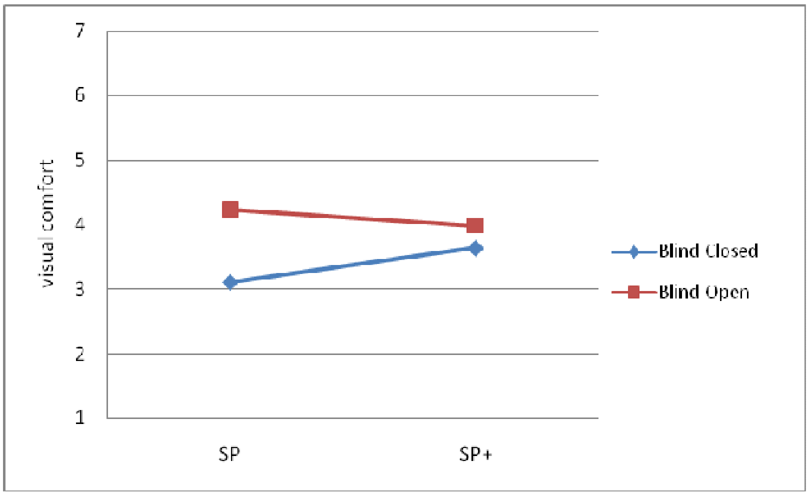


Figure O.4 : Ratings for visual comfort for images with Seated Privacy and Seated Privacy+ Panel height, under closed and horizontal blind conditions, 1 stands for very unsatisfied and 7 stands for very satisfied.

APPENDIX P: Panel_SPvsSP+ X Blind-Q Univariate Test Charts

Figure P1 shows that images with open blinds had higher ratings, than images with tilted and closed blinds. The univariate tests show that when blinds were closed, Seated Privacy+ was rated to have more light than Seated Privacy. On the other hand, when blinds were tilted or open, Seated Privacy was rated higher than Seated Privacy+.

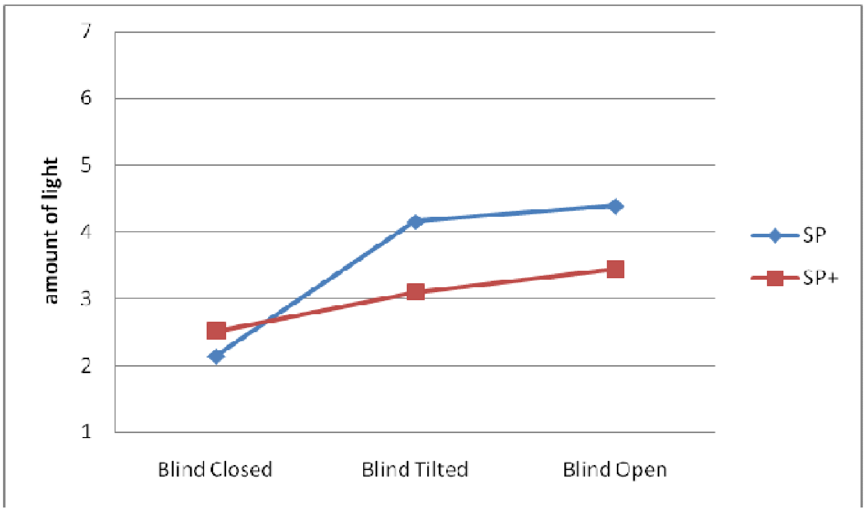


Figure P.1 : Ratings for amount of light for images with Seated Privacy and Seated Privacy+ Panel height, under closed, tilted and open blind conditions, 1 stands for too little light and 7 stands for too much light.

For images with Seated Privacy+ panel height, the position of blinds did not affect subjects' ratings of spaciousness. Figure P2 shows that when blinds were open and tilted, images with Seated Privacy panels were rated as more spacious, in comparison to when the blinds were closed.

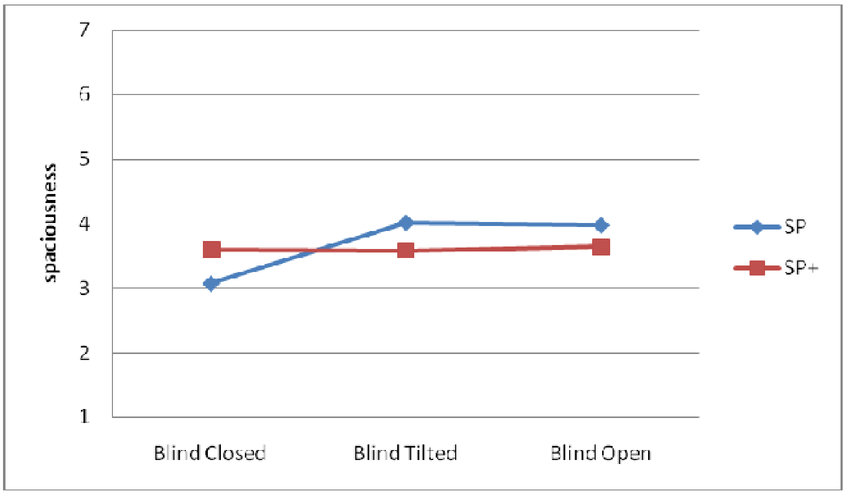


Figure P.2 : Ratings for spaciousness for images with Seated Privacy and Seated Privacy+ Panel height, under closed, tilted and open blind conditions, 1 stands for cramped and 7 stands for spacious.

The univariate results in Figure P3 show that blind position did not affect subjects' ratings for images with Seated Privacy+ panel height. When blinds were tilted or open, images with Seated Privacy panel height were rated as more calm, than when blinds were closed.

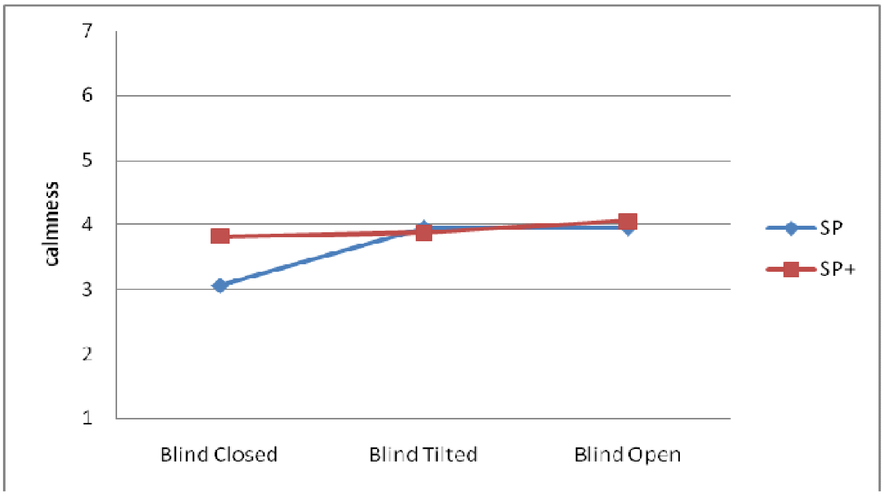


Figure P.3 : Ratings for calmness for images with Seated Privacy and Seated Privacy+ Panel height, Blinds closed, tilted and open, 1 stands for tense and 7 stands for calm.

The position of the blinds affected the subjects' ratings regarding excitement for images with seated privacy+ panel height. Figure P4 shows that Seated Privacy+ images had lower ratings as blinds got more closed.

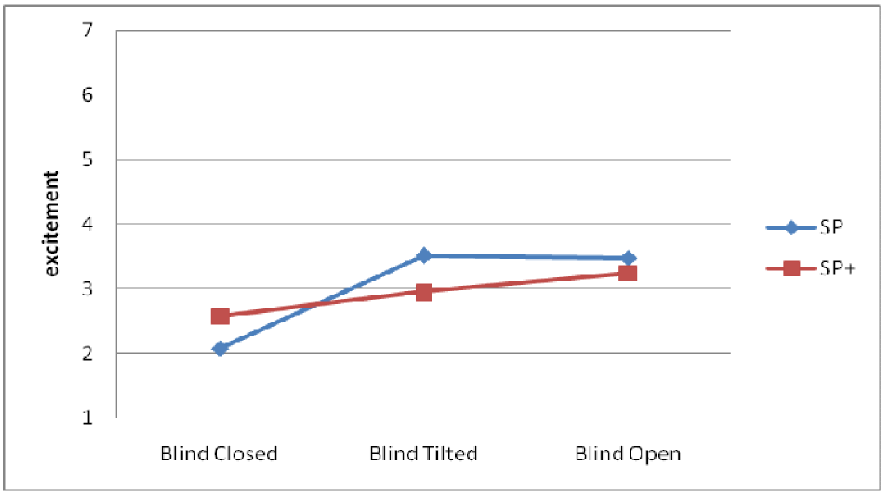


Figure P.4 : Ratings for excitement for images with Seated Privacy and Seated Privacy+ Panel height, under closed, tilted and open blind conditions, 1 stands for boring and 7 stands for exciting.

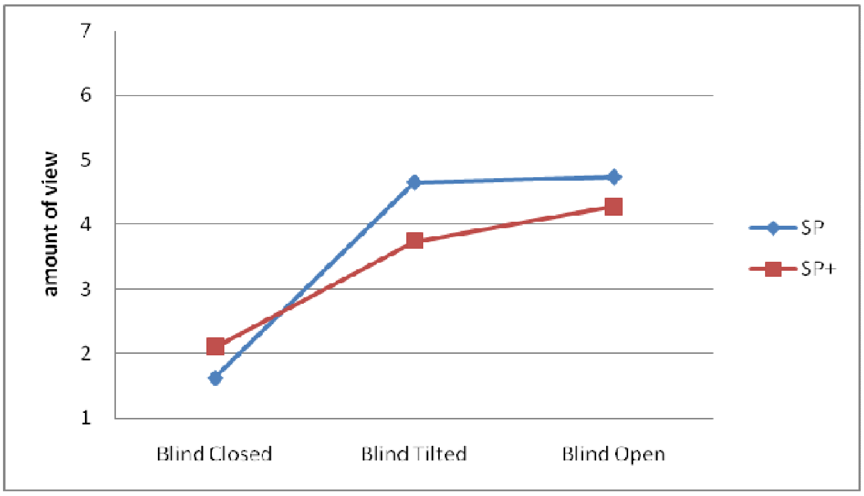


Figure P.5 : Ratings for amount of view for images with Seated Privacy and Seated Privacy+ Panel height, under closed, tilted and open blind conditions, 1 stands for very unsatisfied and 7 stands for very satisfied.

The position of the blinds contrasted the subjects regarding satisfaction with the amount of view for images with seated privacy and seated privacy+ panel heights. Figure P5 shows that images with Seated Privacy+ panel height had higher ratings when blinds were open and tilted, than when blinds were closed. For images with

Seated Privacy panel height, ratings did not differ from each other for open and tilted blinds. For these images, ratings were much higher for tilted and open blinds, than closed blinds.

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