The Virtual Lighting Laboratory: Per-pixel Luminance Data Analysis

Mehlika N. Inanici¹, and Mojtaba Navvab²

1 INTRODUCTION

The Virtual Lighting Laboratory (VLL) is an image based lighting analysis tool and methodology, which operates with physically-based High Dynamic Range (HDR) digital images. Through appropriate modeling, rendering, and image technology, physically based renderings and HDR Photographs can be used to extract per-pixel lighting information.

Extraction of per-pixel luminance data is done by converting the RGB values in each pixel of HDR imagery (that is, an RGBE image, also known as hdr) into CIE XYZ data using the CIE 1931 Standard Colorimetric Observer Functions. A detailed documentation of the study can be found in (Inanici 2004).

In VLL, per-pixel lighting data extracted from physically based renderings is processed through mathematical and statistical operations to perform lighting analysis with detail, flexibility and rigor that may be infeasible or impossible with the traditional lighting analysis approaches. The analysis in the VLL focus on the investigations of the following criteria to achieve the intended visual effect, performance, and comfort

- 1. ADEQUATE QUANTITY OF LIGHT
- 2. SUITABLE SPATIAL DISTRIBUTION OF LIGHT
- 3. SUFFICIENT DIRECTIONALITY OF LIGHT
- 4. ABSENCE OF GLARE; AND
- 5. SUFFICIENT SPECTRAL CONTENT OF LIGHT

The analyses in this paper have been limited to the study of the distribution and directionality of light. They are not exhaustive in nature; rather, they highlight some of the per-pixel analysis capabilities.

2 THE DESIGN SCENARIO

The analysis capabilities are demonstrated utilizing the HDR images of an office located in Ann Arbor, Michigan. The images are generated with the Radiance Lighting Simulation and Rendering System (LBNL 2000, Ward and Shakespeare 1997). The room dimensions are 3.7m by 3.7m (12 ft. by 12 ft.); it has an inclined ceiling (15°) with an average height of 3.4m (11 ft.). It is located on the fourth floor of an office building. The wall, floor, and ceiling materials have 57 percent,

¹The University of Washington, Department of Architecture, Box 355720, Seattle, WA, 98195; ²The University of Michigan, College of Architecture and Urban Planning, 2000 Bonisteel Boulevard, Ann Arbor, MI, 48108. inanici@u.washington.edu; moji@umich.edu

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71 percent, and 30 percent reflectivity, respectively. The office has integrated daylighting and electric lighting (Fig. 1).

Daylighting comes from a south facing unobstructed clear glass window that has 89.9 percent transmittance (10.2 m² - 110 ft²). In the base case, there is not



Fig. 1. The office space during the daytime and nighttime.



any daylight admission control system on the window. Electric lighting is supplied through task and ambient lighting systems. There are two direct/ indirect luminaires on the ceiling. Each luminaries has three fluorescent lamps rated at 2850 lumen output. The task lighting is a table lamp with an incandescent lamp rated at 1200 lumen output. The task and ambient lighting combination is chosen to provide approximately 500 lx on the table during nighttime. Hourly simulations are done for the 21^{st} of December from 9:00 to 17:00 with the CIE Clear Sky, and for the nighttime.

Three visual tasks have been specified for an optimum performance in the office:

- Reading a text displayed on the computer screen and recognition of the letters on the keyboard;
- Reading a text on a document placed at a typical reading distance in the proximity of the computer; and
- Looking through the window.

The paper task consists of black and white surfaces to represent the foreground (text) and the background (paper). Materials are matte with 10 and 85 percent reflectivity. A 25° viewing angle is maintained on the task plane. The computer screen also consists of black and white surfaces that represent the foreground and the background. Both surfaces are self-luminous (80 and 10 cd/m^2 , respectively) and the entire screen is covered with glass to mimic the luminosity and reflectivity of the physical computer screens.

Images are generated from different viewpoints to investigate the specific requirements of each space and task. Figure 2(a-c) demonstrates the viewer's sight for the specified visual tasks. The position of the viewer is important to study the amount and characteristics of the light reaching the eye. Figure 2(d-e)



Fig. 2. Set of analyzed images in VLL a) viewer looking at the computer screen (abbreviated in graphs as eye2pc), b) viewer looking at the paper task (eye2pap), c) viewer looking through the window (eye2win), d) computer view, e) paper view.

(computer-view and paper-view) demonstrate the volume seen by an illuminance meter, if physical measurements were to be taken on the task. These images are used to study the characteristics of the light on the tasks: The amount of light reaching the tasks can be derived from these images. It is also possible to identify and study the surfaces and light sources that have direct impact on the task. Conflicting lighting requirements between different tasks can be explored, prioritized, and/or optimized.

3 DATA ANALYSIS

3.1 SPATIAL DISTRIBUTION

The simplest and most crude way to look at the spatial distribution of light is to look at the average value accompanied with the maxima and minima. These values can be used as indicators of the quality of lighting design. The quantities that deviate significantly from the target values may indicate poor lighting conditions (Rea 2000).

In the physical world, spatial distribution of light is determined through multipoint measurements on surfaces. The major drawback is that large numbers of measurements have to be done in a grid pattern to determine the distribution on or across a surface. Obviously, the number of points determines the resolution of the distribution pattern as well as the precision of average calculations. The distributions can also be expressed in terms of the ratio of two quantities, such as the 'maximum to minimum', 'maximum to average', and 'average to minimum'. The maxima and minima have to be located in the field of view (FOV) for this kind of analysis. This is not always a straightforward task. Due to the spatial and temporal variations, measuring one point (or time) vs. another could produce different quantities and ratios, which can point to an ambiguous and nonrepeatable measuring process.

The VLL is a very convenient environment for studying the lighting distributions. It is a trivial task to calculate the average, and locate the minima and maxima from the lighting matrix. The resolution of the data is equivalent to the resolution of the image (that is, for a 1024 by 1024 image, the luminance resolution is more than million values), which cannot be matched with any physical measurement device.

Figure 3a shows the minimum, maximum and average luminance values on Dec. 21 when the viewer is looking at the computer screen. Since the variations are enormous, logarithmic scale is used. Figure 3b shows the 'maximum to minimum', 'maximum to average', and 'average to minimum' variations when the viewer is looking at the computer screen. As expected, the variations are problematic throughout the day, especially between 11:00 to 14:00 in particular.



Average, minimum, maximum, and point values provide a generic idea about the performance of lighting. However, they are not sufficient to describe and evaluate the lighting performance. Specifically, they are ineffective in describing the light distribution patterns over different architectural surfaces. As the next step, various analysis approaches are presented with specific focus on the actual task.

Luminance variations 'between the task and the immediate background', 'across the immediate task', and 'between the task and the ambient surfaces' are very distinct matters that have to be treated differently. Luminance variation between the task and the immediate background is needed to distinguish the details of the task. Adequate luminance variation contributes to the contrast variation by making parts of the task to appear distinct. Luminance variation across the immediate task is suggested to be kept within 3:1 range, where the task luminance is suggested to be higher than the immediate surrounding. Ceiling and walls are recommended to be within a 3:1 luminance ratio. Distant room surfaces are preferred to be within 10:1 luminance range (40:1 maximum). Luminance variation patterns may create a stimulating and interesting environment, which contributes to the well-being of the occupants. Luminance variation may also create a distracting and confusing environment through visual clutter, which is usually manifested by harsh reflections and irregular light-shade patterns in the environment. In the extreme situations, the consequences are

Fig. 3. Minimum, maximum, and mean luminance values throughout Dec. 21, a) when the viewer is looking at the computer screen, b) 'Maximum to minimum', 'maximum to average', and 'average to minimum' luminance ratios. veiling reflections, disability and discomfort glare. The luminance ratio recommendations are specified to avoid these adverse effects (NBI 2001; Rea 2000; Worthey 1989).

The scene in Fig. 4 is decomposed into elements, which are the computer screen, paper, wall behind the task, table, and the window. Minimum, maximum, and mean luminance values, luminance range and ratios are identified for the selected regions. This analysis again reveals the problems caused by the excessive daylight. Figure 5 shows the dynamics of the contrast on the paper throughout the day. 13:00 is the most troublesome time of the day.



Fig. 4. The scene is decomposed into architectural elements to study the luminance ratios.





In the VLL, the scenes can also be dissected into specific regions of the visual field, that is, foveal, binocular, and peripheral, to have a better understanding of the performance of the human vision (Fig. 6). The total human vision is 180° horizontally and 130° vertically. The central 120° is the binocular vision and the fovea is the central 2° visual field on the visual axis. Note that the boundaries of visual fields in the figure have been modified by the cosine of the polar angle to match the hemispherical fisheye projection. In all images generated from the viewer's point, the task is centered at the fovea, that is, the viewer is fixated at the task.

Figure 7 demonstrates the average luminance variations in the fisheye view, total vision, binocular vision, and foveal vision. In the scene where the viewer is looking at the computer screen (Fig. 7a), the extremes occur outside the human

Fig. 6. The decomposition of a scene into human field of view.





Fig. 7. Luminance variations in different parts of the visual field throughout Dec. 21 a) Eye2pc, b) Eye2paper, c) Eye2win. vision. Therefore, it might be misleading to process the data from the fisheye view. In the scene where the viewer is looking at the paper (Fig. 7b), the extreme variations occur in binocular vision and foveal vision. In the scene where the viewer is looking through the window (Fig. 7c), the variations are notable in the binocular vision. It is also interesting to study the luminance differences in different parts of the visual field when the occupant is looking at different tasks. Figure 8 demonstrates the luminance transition occurring when the occupant switches from the computer screen to the paper, and to the window. As a general rule, the occupant should not be exposed to a wide luminance range between consecutive tasks to avoid visual performance and comfort problems. The human visual system can be quite insensitive to large luminance differences in the total FOV, but it is very sensitive to small luminance differences in the foveal region. As seen in the figure, extreme variations occur at the fovea.



Total Vision (1:9)(binocular + Luminance 4000 1000 4000 peripheral) (1:38)2000 500 2000 (1:1)(1:1)(1:1)(1:1)(1:1)0 0 0 Avg. Eye2Pc Eye2win Eye2Pc Eye2win Eye2Pc Eye2win Eve2pap Eye2pap Eye2pap

Per-pixel analysis allows even more detailed study of the luminance variations. For instance, it can be used to calculate the criterion rating which quantifies the probability that a specific criterion is met within a defined area (Rea 2000). It can be expressed for various lighting quantities such as luminance, illuminance, contrast, and CCT. The Virtual Criterion Rating (VCR) is calculated as follows

$$VCR(\%) = \frac{\text{Number of pixels satisfying the criterion in a space/on a surface * 100}}{\text{Total number of pixels}}$$

(1)

The VCR has been exemplified through the target illuminance value on the paper task. It is necessary to achieve the target illuminance with a sound uniformity level across the task surface. As a guideline, it is suggested to study the task illuminance values to ensure that they are between 2/3 to 4/3 of the target value. The limits are still flexible and it is suggested to aim for achieving the 2/3to 4/3 range in 90 percent of the task locations. Task illumination levels do not have to be maintained throughout the whole space. Ambient lighting can be provided to illuminate the rest of the space and it is advised to be 1/3 of the task illumination level (NBI 2001; Rea 2000). The target value for the paper task is taken as 500 lx. Since the paper tasks have flexible limits, the acceptable range

ferent regions of the visual field as the viewer switches between the visual tasks (The ratios are given with respect to the computer task).

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is taken as 300-1000 lx, where 300 lx reflects the IESNA recommendation for visual tasks of high contrast and large size, and 1000 lx reflects the recommendation for visual tasks of low contrast and small size (Rea 2000). For nighttime, 84 percent of the pixels that correspond to the paper task satisfy the 300-1000 lx range. During daytime, the criterion rating is quite low since most of the illuminance values are above 1000 lx. In Fig. 9, the VCR and the contrast on the



Fig. 9. The VCR for illuminance on the paper throughout Dec. 21.

paper task are plotted on the same graph. The contrast values on the paper task are good at 9:00 and 10:00 despite the poor criterion ratings, because the body shadow on the paper blocks the excessive daylight partially on the paper.

Although it is effective to study the visual tasks separately, the task and ambient task lighting must work together. The luminance distribution patterns for the nighttime and daytime images are studied in per-pixel detail when the viewer is looking at the computer screen. The nighttime image is selected for relatively low luminance distribution and the daytime image (12:00) is selected for the high luminance distribution pattern. Figure 10 shows the mesh plot for the night scene. In this figure, the first mesh plot illustrates the luminance distribution in the total luminance range. The luminance peak corresponds to area lit by the task lamp. The close-up image is produced with block processing; that is, the 1024 by 1024 pixels have been processed in 128 by 128 blocks,



Fig. 10. Mesh plots for the luminance distribution at nighttime when the viewer is looking at the computer screen.

where each block represents an area of an 8 by 8 matrix. The maximum value of each block has been utilized. The data between 0 to 100 cd/m^2 is presented in the second plot, which provides an insightful information about the luminance distribution. It is apparent from this information that it might be deceptive to study only the average, minimum, and maximum values to understand the distribution pattern of the luminance data.

Another way to visualize this data is provided in Fig. 11. The first histogram demonstrates that the data is unimodal and skewed to the left. Although the data spreads from 0.0023 to 1953 cd/m^2 , 99.67 percent of the pixels have luminance values between 0 to 200 cd/m^2 . The second histogram shows the data for this range. The close up view reveals that most of the pixel values lie



between 0 to 20 cd/m² (58.81 percent). These graphs suggest that the luminance distribution pattern is somewhat in close range throughout the scene with few outlier pixels.

The mesh plots in Fig. 12 show the location and distribution of the variation in different scales for the daytime at noon. Figure 13 shows the histograms for the same time. Obviously, the luminance variation is much higher for this scene than the night scene. The average, maximum, and minimum luminance values are 2210, 261,579,980, and 1.5 cd/m^2 , respectively. The data is again unimodal and skewed to the left. Actually, 99.89 percent of the pixels are less than 10,000 cd/m², 91.10 percent of the pixels are less than 3000 cd/m², and 52.80 percent of the pixels lie between 0 and 500 cd/m². These histograms given in different luminance ranges suggest that, although luminance distribution pattern is quite nonuniform throughout the scene, the extreme value suggested by the maxima occurs in few pixels as outliers.





Fig. 12. Mesh plots for the luminance distribution on Dec. 21, at 12:00, when the viewer is looking at the computer screen.



Fig. 13. Luminance distribution histograms for Dec. 21, at 12:00, when the viewer is looking at the computer screen.

In general, it is difficult to interpret the high luminance value since it may indicate bad lighting quality such as poor visibility, discomfort, and visual clutter; or it may indicate good lighting quality such as highlights and sparkles. From a practical standpoint, the highlights, shadows, and shading patterns, and even the veiling reflections and glare, are all are produced in the same way, where the determining factor becomes the angular size of the light source (Cuttle 2003a). For example, a circular light, with a semi-subtense angle of 1° or less, creates a sharp, vivid image (highlight) on a glossy surface, casts shadows with quite sharp edges, and produces a shading pattern with maximum contrast level. A circular light with a semi-subtense angle of 10° creates blurred highlights and shadows, and produces reduced contrast. The circular light, with a semi-subtense angle of 90° and beyond creates a totally blurred image where contrast is diminished, shading patterns provide a reduced range of gray levels, shadows are absent, and highlights have spread into veiling reflections (Worthey 1991; Navvab 2001).

Highlights and sparkles can have luminance ratios of 5 or more logarithmic units. This might seem to be contradicting with the luminance ratio recommendations given earlier. The recommendations aim to prevent excessive luminance ratios in large visual areas that might create glare, veiling reflections, and transient adaptation problems. Highlights and sparkles, on the contrary, may provide visual information that contributes to visibility. For example, highlights from a dielectric material such as a shiny glass reveal the shape of the object; whereas the uniform lighting conditions in an integrating sphere cause the object to visually disappear. The highlights and sparkles may also contribute to the visual comfort by providing visual interest for distant eye focus, which is good for eye muscle relaxation. They can easily be avoided by a small movement of the head or task (Cuttle 2003a). It is possible to interpret luminance variations with the per-pixel data in the VLL. The interesting information in Fig. 10–13 is that the peak luminances occur in few pixels as outliers. The outliers potentially identify the positive peak luminances, rather than troublesome areas when the rest of the pixels fall into acceptable ranges. The highlights and sparkles add to the quality of the scene when they are meaningfully located since the eye is drawn to the bright parts in the scene. The location of the peak luminance can be studied with the mesh plots (Fig. 10 and 12).

3.2 DIRECTIONALITY

The directionality of light is a balance between the diffuse and directional components within the luminous environment. It gives an indication about the spatial distribution of light flow onto an element or into a space. Poor directionality may create shadows on the task or veiling reflections towards the viewing angle. Adequate directionality may distinguish the details of a task, reveal the surface textures, and model the 3D surfaces (CIE 1986).

Vertical to horizontal illuminance ratio (V/H ratio) is one of the performance indicators used for assessing the directionality of light. It is based on the ratio of the intensity of light coming from side to the intensity of light coming from the top (Love and Navvab 1994). Other directionality indicators developed in the past include mean cylindrical and semi-cylindrical illuminance, scalar (mean spherical) illuminance and semi-scalar (mean hemispherical) illuminance, vector illuminance, vector-to-scalar illuminance ratio, and cubic illumination (Ashdown 1998; Cuttle 2003a, 2003b; Lynes and others 1996). Some of these techniques have been implemented in physically based rendering tools (Ashdown 1998). In the VLL, a more direct approach is adopted. It is based on the definition of directionality: The diffuse and directional components of the luminous environment are separated as a unique feature of virtual photometry (Fig. 14); and the ratio of the directional-to-diffuse lighting is suggested as a new indicator.





The directional components include the direct light from sources and specular reflections, which refer to all non-Lambertian reflections and transmissions (including refraction, ideal reflection and directional scatterings). The diffuse reflections refer to the Lambertian components from all surfaces other than the light sources, which include 1) the skylight, 2) the diffuse reflection of solar radiation from outside surfaces, 3) the diffuse reflection of

skylight from outside surfaces, and 4) the diffuse interreflections within the interior space.

The diffuse and directional components of light are separated through image subtraction method. The first image includes the directional and diffuse components of the luminous environment. In the second image, the diffuse component is removed. The ability to isolate the diffuse component is essential for the directional-to-diffuse metrics. The subtraction of the second image from the first one produces the diffuse component (Fig. 15). The ratio of the directional and diffuse components is calculated with the average luminance values.







Fig. 15. Image subtraction method for determining the directional-to-diffuse ratio.



'Diffuse Light'

Figure 16 shows the directional-to-diffuse ratio when the viewer is looking at the paper task throughout Dec. 21. The sensitivity of the indicator is apparent when it is viewed side by side with the visual information, which illustrates the light and shade patterns of the direct sunlight in the scene. A typical assessment of the directional-to-diffuse luminance ratio should be studied in real world examples to relate the perceived directionality with the calculated ratio. Yet, the higher values point to strong directionality, and the lower values point to weak directionality. The time period between 9:00–12:00 has an increasingly strong directionality when the direct rays of sun are present in the scene and the time period after 14:00 has a weak directionality indicator when the scene is under shade. Note that there is an increase in the indicator after 15:00, which points to an increased effect of the directionality from the task lighting since the directionality from the opposite direction (window) is fading after this point. The scene at 12:00 has also been tested with the CIE overcast sky. As expected, the directional-to-diffuse ratio dropped to 1.4 with the CIE overcast sky, as compared to 2.5 with the CIE clear sky.

4 REMARKS

The examples presented in this paper are chosen to provide the framework of the capabilities and procedures for per-pixel lighting data analysis. Different design alternatives can be processed (Fig. 17), which provides a rich visual and numerical environment with a large variety of information and analysis capabilities that can assist and accelerate the design decision-making process for an appropriate daylight admission control system.

High resolution (per-pixel) measuring capabilities allow the user to employ a rich array of data analysis techniques:

• The scenes can be studied in terms of the luminance variations among different architectural elements and/or in different parts of the FOV. This kind of analysis is useful for providing a better understanding of lighting in relation to the performance of human vision; and for studying the luminance adaptaFig. 16. Directional-to-diffuse luminance ratios for Dec. 21 when the viewer is looking at the paper task.



tion and luminance transition occurring when the occupant switches between different visual targets.

• The different lighting components can be studied independently, which simplifies the description and understanding of the complex phenomena. The image subtraction method is suggested to isolate the effects of one parameter from the rest of the lighting data. For instance, it is possible to dissect the lighting data into layers, such as the directional and diffuse lighting compo-



Fig. 17. Office with a) clear glass, b) fritted glass, c) clear glass with horizontal blinds, d) clear glass with tilted blinds (30°).

nents. The directionality can be evaluated through a directional-to-diffuse luminance ratio. It is also possible to isolate the effects of the sun, by simulating the nonovercast skies with and without sun. The effect of the direct solar radiation can then be evaluated.

• Current lighting analysis techniques mostly utilize instantaneous, single lighting values (such as luminance, illuminance, CCT), which do not inform about the quantity and quality of light throughout a particular environment. It is appropriate to study the temporal and spatial variability as a dynamic phenomena instead of a mere amount of quantity at a certain time. Per-pixel analysis is suggested specifically to study spatial lighting distribution patterns. The rate of change in lighting quantities throughout time can also be studied with the image subtraction approach.

Lighting professionals and researchers can analyze the complex visual and numerical features of real world environments with detail, flexibility, and rigor to develop a better understanding of the complex processes underling lighting and vision which will overcome the shortcomings of the available lighting metrics, and further improve the theoretical foundation, usability and efficiency of architectural lighting analysis. In this respect, per-pixel analysis techniques presented here is the beginning of research that can be done in this area.

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