Research note

Daylighting and Its Impact on Depth Perception in a Daylit Space

Nan-Ching TAI

Department of Architecture, Tamkang University

Received February 14, 2011, Accepted December 20, 2011

ABSTRACT
Visual perception within a daylit environment changes according to spatiality, sky conditions, time, and the point of observation. This paper focuses on the complex interrelationships among the architectural configuration of skylights, luminance distribution patterns resulting from changing sky conditions, and the perception of spatial depth. This study employed lighting simulation techniques that incorporate physically based rendering and perceptually based tone mapping to generate a pictorial environment. Daylighting conditions were parametrically changed and psychophysical experiments were conducted to measure the perception of distance to visual targets within architectural scenes illuminated by various daylighting conditions. Results reveal that perceived distance to visual targets increases with a decrease in the luminance contrast between the target and background. This paper concludes that variations in luminance within a space influence perceptions of spatial depth, providing the possibility of enriching the experience of architectural scenes through the incorporation of daylighting in design strategies.

KEYWORDS: depth perception, psychophysical experiment, lighting simulation, daylighting

1. Introduction
An architectural space is a built environment, within which the points of observation can be determined by planned circulation and restricted by framed openings. As a result, manipulation of the physical settings can alter pictorial depth cues within the scene to enrich the spatial experience.

The effects of pictorial depth cues (i.e. relative size12), familiar size36, linear perspective5), relative height in visual field8), or texture gradient7) on depth perception have been extensively studied in real environments. Light and shade are known to be effective visual cues for shape perception and lighting has been employed as a design strategy to reveal architectural form. However, the impact of luminance distribution on depth perception has not been systematically studied and related design strategies are based primarily on experiential information.

Psychophysical experiments on depth perception often set up a test and a reference scene that are systematically controlled to isolate a particular depth cue. In this manner, differences in participants’ measured perceived distances to identical visual targets in two scenes can be used to reveal the quantitative effect of controlled depth cue on depth perception.

In physical environments, the dynamic characteristics of lighting pose challenges in terms of repeatability and precise parametric control. On the other hand, with proper 3D modeling, visualization, and display technologies, computer generated images can provide the flexibility to simulate various lighting conditions through the manipulation of input parameters including spatial configuration, materials, lighting, and the point of view of the occupant. Computational approaches provide a feasible solution with which to systematically study the impact of lighting as a pictorial depth cue. This paper utilizes physically based rendering and perceptually based tone mapping techniques to generate pictorial spaces that can reflect perceptual reality of physical environments for the study of depth perception. The objective of this study was to examine the complex interrelationships among the architectural configuration of skylights, luminance distribution patterns resulting from sky conditions, and the perception of spatial depth.

2. Lighting simulations
The RADIANCE Lighting Simulation and Rendering System9) is a physically based rendering program following the laws of physics in modeling light transport and the properties of light and materials. It employs Monte Carlo ray tracing to faithfully simulate global illumination, and output rendered scenes in a High Dynamic Range (HDR) image format encompassing a numerically accurate radiance map1011).

The 32-bit HDR (RGBE) format uses 8 bits for each R, G, B value and an additional 8 bits as a shared exponent12). This image format provides each pixel with an extended range of floating point values to retain corresponding luminance data of the real scene13).

Current conventional display devices are capable of
displaying a luminance range of no more than 3 logarithmic units, which is entirely insufficient for modeling the 14 logarithmic units of luminance that humans can perceive. To display HDR scenes, tone-mapping operators were developed to compress the full range of lighting data to within the range displayable on conventional display devices\(^\text{13}\). Several perceptually based tone-mapping operators were developed to model various aspects of the complex physiological and psycho-physical processes to mimic the visual processes of humans. Using appropriate tone-mapping operators makes it possible to display scenes with physically accurate high dynamic range as perceptually realistic low dynamic range images on conventional display devices.

Physically and perceptually accurate images have been employed to simulate experimental scenes in which the visual perception of lightness\(^\text{14,15}\), color\(^\text{16,17}\), and shape\(^\text{18}\) were investigated. Tai and Inanici (2009) repeated a classic experiment\(^\text{19}\) investigating the size-distance relationships in a computer-generated environment\(^\text{20}\). In this experiment, subjects were asked to estimate the size of a luminous disk located in a long dark corridor. The size and location of the disk were varied from trial to trial. Different conditions were controlled by restricting the availability of light to reveal the contextual information of depth cue within the scene.

Figure 1 illustrates the same size disk located at the same location under different conditions. In the “disk and corridor lighting” condition, the dim light from the disk and the ceiling provide full contextual information. In the “disk lighting alone” condition, only partial contextual information surrounding the disk is visible. In the “disk lighting alone with reduction tunnel” condition, the reflected light from the corridor’s surfaces is completely eliminated from the composed view.

The results of the computer-modified experiment agree with the results of the classic experiment. The more the contextual depth information is presented, the better the subject can gauge the actual size of the object based on its located distance. It is thus concluded that the size-distance relationship, which states that the two-dimensional perceived size of an object is derived from its third dimension of perceived distance\(^\text{21}\), can be observed in the virtual environment generated by the perceptually based computer simulation. It also demonstrates that a perceptual realistic computer-generated imagery can provide an alternative environment to conduct perceptual study on depth perception.

This study adopts the same computational framework. Experimental scenes were generated using the RADIANCE lighting simulation system. The resultant HDR scenes were tone-mapped with photographic tone-mapping operator\(^\text{22}\), which consistently performed well when compared to real physical scenes in various evaluation studies\(^\text{23–25}\).

### 3. Methodology

Figure 2 illustrates the architectural configuration to generate the experimental scenes. A corridor is open at one end and divided into two hallways at the other. The open end admits daylight to illuminate the entire interior space. The two hallways provide different lighting conditions in the left and right hallways through the installation of skylight and the manipulation of sky conditions.

Every experimental scene was generated using the

![Figure 1](image1.png)

**Figure 1** Different conditions of the experimental scenes used in the computer-modified experiment\(^\text{20}\) investigating the size-distance relationship: (a) disk and corridor lighting; (b) disk lighting alone; and (c) disk lighting alone with reduction tunnel

![Figure 2](image2.png)

**Figure 2** Architectural configuration for the experimental scenes
same viewpoint set toward the two hallways. Identical floating disks (12” in radius) were situated as visual targets at the perceived center of each hallway. These two disks were self-luminous light sources that emit constant light. The location of the construction, the properties of the materials, and parameters for rendering were kept constant in all scenes. Five conditions were created by the two variables of the presence of skylight and various sky conditions (Table 1).

In the base case (“no skylight” condition), the scene was illuminated with daylight admitted from the open rear end, the sky condition was set as March 21, 12:00pm with CIE intermediate sky. In other conditions, in addition to the daylight admitted from the open rear end, a 5’×10’ skylight was installed 24’ from the viewpoint above the left hallway. In “morning” condition, the sky condition was set at 7:00am on March 21 with CIE intermediate sky. In “noon” condition, it was set as March 21, 12:00pm with CIE intermediate sky. In “afternoon” condition, it was set as March 21, 18:00pm with CIE intermediate sky. In “noon with sun patch” condition, it was set as March 21, 12:00pm with CIE intermediate sky with sun patch.

Table 1 Conditions for experimental scenes

<table>
<thead>
<tr>
<th>Conditions</th>
<th>Sky Model:</th>
<th>Time:</th>
</tr>
</thead>
<tbody>
<tr>
<td>No Skylight</td>
<td>CIE Intermediate Sky</td>
<td>March 21, 12:00 PM</td>
</tr>
<tr>
<td>Morning</td>
<td>CIE Intermediate Sky</td>
<td>March 21, 07:00 AM</td>
</tr>
<tr>
<td>Noon</td>
<td>CIE Intermediate Sky</td>
<td>March 21, 12:00 PM</td>
</tr>
<tr>
<td>Afternoon</td>
<td>CIE Intermediate Sky</td>
<td>March 21, 18:00 PM</td>
</tr>
<tr>
<td>Noon with Sun Patch</td>
<td>CIE Intermediate Sky with Sun Patch</td>
<td>March 21, 12:00 PM</td>
</tr>
</tbody>
</table>

4. Procedure

Method of constant stimuli was used to measure the perceived distance to the visual target in the experimental scenes. In this method, test and reference scenes are presented simultaneously with different configurations of target locations. In general, the location of test target is fixed but the location of reference target is varied to, five, seven, or nine values separated by equal distance. The reference target with the greatest value is always perceived as greater than the test target, and the reference target with least value is always perceived as less than the test target.

Instead of adjusting the reference target to a range of distances to match the perceived distance to the test target, subjects are asked to report which target intuitively appears closer. The concept underlying this method is to determine when the test and reference targets are perceived as equal in depth. In this manner, the actual location of the reference target is considered the measured perceived distance to the test target.

Table 2 illustrates the experimental scene used in this study. The left hallway was the test scene and the right hallway was the reference scene. The two scenes were incorporated as one and presented simultaneously. The location of the left disk was fixed at 40’ from the viewpoint, and referred to as the standard disk. The disk on the right, referred to as the comparison disk, was situated in 7 different positions of 34’, 36’, 38’, 40’, 42’, 44’, and 46’ from the viewpoint. Variations in disk location were rendered under five different lighting conditions to generate a total of 35 scenes (700 × 700 dpi, with “Lighting Detail”, “Lighting Variability”, and “Image Quality” set as “High” and “Max. Reflections” set as “5” in RADIANCE). The rendered scenes were then flipped horizontally to create another set of mirrored images to avoid having the lighting effect only in the left hallway.

Eight subjects participated in this experiment. The subjects were aged between 21 and 36, with normal or corrected-to-normal vision. Images were displayed on the center of a LCD display of a 13” MacBook Pro in a dark room. After adapting to the dark environment, subjects were asked to view the display at a normal viewing angle and distance. Subjects were informed that the two disks floating in each hallway were identical in size, and were asked to report which disk appeared closer. Each image was presented to each subject 5 times randomly (the same configuration of the location of the standard and comparison disks under different lighting condition was thus presented 10 times in total). Subject’s responses were recorded as the number of times that the standard disk was reported as closer.

8
The experiment results were plotted as the proportion of scenes in which the standard disk was reported as “closer” as the function of the comparison disk’s location (Figure 3). Probit regression model was used to derive psychometric function for fitting each data set from five different conditions. The point of subjective equality (PSE) is where the 50% proportion line intersects the Probit regression curve. The PSE represents when the standard and comparison disks are perceived as equal in depth, thus the actual location of the comparison disk (reference target) can be considered as the measured perceived distance of the standard disk (test target).

The results demonstrate that in “no skylight” condition, the two disks were perceived as equal in depth when the two disks were configured at the same distance from the viewpoint (PSE=39.79±0.13). On the other hand, the PSE shifted to right in the condition when the skylight is presented. The perceived distance of the standard disk (test target) for “morning”, “noon”, “afternoon” and “noon with sun patch” increased from 40 feet to 41.78±0.15, 42.14±0.16, 41.12±0.14, and 42.98±0.16 feet.

6. Discussion
Table 3 illustrates the luminance distribution pat-
terns through the false color studies (generated with Photosphere software\textsuperscript{28}) of the original HDR scenes with the two disks configured at the same distance under different conditions. The disk luminance was the average luminance value of each disk; they remain approximately constant since the disks emit constant light. The background luminance was the average luminance value of area sampled from the back wall surrounding each disk; the back walls were illuminated by the daylight admitted from the open rear end and the additional skylight (for the left hallway).

Because the luminance contrast and the lighting distribution remained identical between the left and right hallways in the "no skylight condition", the standard disk 40’ away was perceived as equal in depth with the comparison disk located at the expected 40’. In the "morning", "noon", "afternoon" and "noon with sun patch" conditions, false color analysis suggests that luminance contrast between the disk and its background varied under different sky conditions throughout a day.

Figure 4 illustrates the effect of luminance contrast on perceived distance. The squares represent the ratio of luminance contrasts from original HDR scenes. The circles represent the same ratio from the tone-mapped images. In both cases, the perceived distance increases as the ratio decreases. These results thus suggest that the perceived distance of the disk increased with a decrease in the luminance contrast between the disk and its background.

Atmospheric perspective is a pictorial depth cue related to luminance contrast. It refers to objects in the distant background appear to have lower contrast than objects in the foreground\textsuperscript{21}. In a study on depth perception, O’Shea et al. (1994) demonstrated that 2D targets with higher luminance contrast appear closer to the observer\textsuperscript{29}. Results of this study reveal that this relationship can also be observed in a compact 3D built environment. The addition of a skylight reduced luminance contrast between the disk and its background, thereby increasing its perceived distance.

7. Conclusion and application

This study suggests that luminance contrast is an effective pictorial depth cue capable of increasing the perception of spatial depth. Most pictorial depth cues are size-related, such as relative size, familiar size, linear perspective, and texture gradient. Size-related pictorial depth cues are often from the result of geometric relationships within the physical configuration. For a particular point of view, it is relatively static because the geometrical relationship of the physical structure is permanent. The fact that the luminance contrast can be

<table>
<thead>
<tr>
<th>Conditions</th>
<th>Luminance (cd/m²)</th>
<th>Contrast Ratio</th>
<th>Perceived Distance (ft)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Disk Background</td>
<td>Disk Background</td>
<td>Disk Background</td>
</tr>
<tr>
<td>No Skylight</td>
<td>198</td>
<td>14.1</td>
<td>198</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1.002</td>
<td>39.79 ± 0.13</td>
</tr>
<tr>
<td></td>
<td>Left</td>
<td>Right</td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.957</td>
<td>41.7</td>
<td>0.15</td>
</tr>
<tr>
<td>Morning</td>
<td>Left</td>
<td>Right</td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.852</td>
<td>42.14</td>
<td>0.16</td>
</tr>
<tr>
<td>Noon</td>
<td>Left</td>
<td>Right</td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.985</td>
<td>41.12</td>
<td>0.14</td>
</tr>
<tr>
<td>Afternoon</td>
<td>Left</td>
<td>Right</td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.703</td>
<td>42.98</td>
<td>0.16</td>
</tr>
<tr>
<td>Noon with Sun Patch</td>
<td>Left</td>
<td>69.4</td>
<td>200</td>
</tr>
<tr>
<td></td>
<td>Right</td>
<td>Background</td>
<td>Background</td>
</tr>
</tbody>
</table>

* Luminance Contrast = [Disk Luminance - Background Luminance] / Disk Luminance
* Contrast Ratio = Luminance Contrast L / Luminance Contrast R

Figure 4 Luminance contrast ratio and perceived distance
used to increase or decrease the perceived distance can be thus significant in architectural design. It encourages possible design applications to incorporate the daylighting strategy into the structural configuration. Utilizing the ever-changing sky condition to enrich the spatial experience of the same architectural scene. Figure 5 illustrates one possible design application. The room is dedicated to the display of a piece of sculpture. In addition to view the art piece within the room, another viewing opportunity is created by incorporating a framed opening seen through a courtyard from another room. In this view, the sculpture serves as a visual target directing the visual attention to a composed scene upon entering the gallery. Figures 5a, 5b, and 5c illustrate the RADIANCE simulations of the same scene under the CIE intermediate sky throughout a day. Although the interior electronic illumination remains constant, the daylight introduced by the courtyard makes the luminance distribution of the scene dynamic. The luminance contrast between the sculpture and its immediate background changes as the foreground luminance changes, based on the daylight provided by different sky conditions. As a result, the perceived distance to the sculpture changes over the time, and the spatial experience of this daylight scene is enriched through the incorporation of the skylight.

Acknowledgements

The author would like to thank all colleagues and students who participated in the experiments and contributed to this study. Some of the materials presented in this paper were originally presented in the poster session of Illuminating Engineering Society (IES) 2009 Annual Conference held in Seattle, November 15–17, 2009. The author would also like to thank Dr. Mehlika Inanici at University of Washington, Department of Architecture for her guidance in lighting simulation, and Dr. John Palmer at the University of Washington, Department of Psychology for his suggestions related to the experiment.

References

(13) Reinhard, E.: High Dynamic Range Imaging: Acquisition, Display, and Image-Based Lighting” Morgan