

LIGHTING IN REAL AND PICTORIAL SPACES

A computational framework to investigate the scene based lighting distributions and their impact on depth perception

NAN-CHING TAI and MEHLIKA INANICI
*University of Washington, Department of Architecture
Seattle, WA, 98195, USA.
tai@u.washington.edu, inanici@u.washington.edu*

Abstract. Architects often use two-dimensional media to represent, visualise, and study the three-dimensional qualities of un-built spaces. Knowledge of pictorial cues is a powerful design tool that can be used to enhance the spatial qualities of built environments. This paper draws from the recent developments in computer graphics (physically based renderings and perceptually based tone mapping techniques) and demonstrates the utilisation of a computational framework to generate pictorial spaces that can mimic perceptual reality. Computer simulation and psychophysical research methodologies are employed to examine the relationship between the lighting patterns introduced by architectural configurations and their impacts on depth perception. The research demonstrates that physically and perceptually based renderings can be used to study depth perception; and luminance contrast in an architectural scene is an effective pictorial cue that increases the perceived spatial depth.

Keywords. Depth perception; pictorial cue; lighting simulation; physically based rendering; high dynamic range imagery.

1. Introduction

Visual space perception is defined as the process of acquiring the three-dimensional (3D) understanding of an environment from two-dimensional (2D) retinal images and/or media. Sketches, drawings, and computer generated images have long been used to study the visual qualities of architectural spaces. Computer environments enable users to easily change the input

data and perform quantitative and qualitative analysis of alternative settings. Every computer modeling, simulation, and visualisation technique is based on approximations and simplifications. However, recent developments have enabled us to generate digital images that can be numerical and visual matches of the corresponding physical scenes. Therefore, these physically and perceptually based renderings provide unprecedented affordance for perceptual studies.

Psychophysics is a field that investigates the relationship between sensations and physical stimuli (Gescheider, 1984). It measures perceptual sensitivity in response to an environmental stimulus. Researchers have studied the effects of various pictorial cues (i.e., as occlusion, familiar size, relative size, and texture gradients) on space perception in real environments through this research methodology. However, perceptual studies in physical environments suffer from many challenges in controlling the complexities of studied environments and/or changing the variables that impact depth perception. Psychophysical experiments in physical environments are particularly challenging with experiments that involve dynamic lighting conditions. Daylighting provides variable luminous environments, where variability is the result of sun movement and climatic conditions. This challenge limited the scope of past research in depth perception.

Early computer graphics examples demonstrate lighting as one of the pictorial depth cues, but lighting is studied only to establish an object's relative location in a three-dimensional layout by the shadow it casts (Hubona et al., 2000; Meng and Sedwick, 2001), rather than to investigate how it is distributed in a scene to inform or enrich the space perception. Schwartz and Sperling (1983) demonstrated the use of perceived luminance as a pictorial cue. O'Shea, Blackburn and Ono (1993) argue that it is the contrast of luminance that cues the distance. However, the use of luminance contrast as a pictorial cue in this study is limited to flat patches, and therefore, does not adequately address to the spatial and luminous complexities of a built environment.

In this paper, physically based rendering and perceptually based tone mapping techniques are utilised to generate pictorial spaces that can provide surrogate models for physical environments to study depth perception. The objective of this study is to utilise a computational framework for investigating spatial depth; and to demonstrate the relationship between the configuration of physical structures, scene based lighting distributions, and perceived spatial depth.

2. Computer simulations

Physically based rendering tools use mathematical models to simulate the

complex physical processes to mimic the physical world (Greenberg et al., 1997). In this research, Radiance Lighting Simulation and Visualization system (Ward and Shakespeare, 1997) is used for generating physically based images. Radiance software models the light transport and material properties based on their governing physical equations; and the resultant rendered scene is a high dynamic range image that encompasses a numerically accurate radiance map. The numerical accuracy of Radiance renderings has been validated through lighting studies (Mardajevic, 2001).

Physical accuracy in rendering does not guarantee that the displayed images will provide a visual match to the corresponding physical environment. Computer hardware limits the dynamic range, color gamut, spatial resolution, and field of view occupied by the displayed image (Spencer et al., 1995). In perceptually based tone-mapping, hardware limitations are addressed with mathematical models that approximate the complex physiological and psychophysical processes to mimic the human visual processes (Ferwerda, 2001; Ramanarayanan et al., 2007). The accuracy and appropriateness of Radiance Renderings for psychophysical research studies have been demonstrated by Ruppertsberg and Bloj (2006) and Radiance has been employed to simulate experimental scenes to investigate visual performance in relation to lightness perception, color perception, and shape perception (Boyaci et al., 2003; Doerschner et al., 2004; Delahunt and Brainard, 2004; Fleming et al., 2004). These studies incorporate various visual aspects of objects in 3D environments. They also attest that psychophysical research studies can be effectively carried out in computer environments, which provide advantages over real world in allowing for controlled replication of variable manipulations and establishing cause-effect relationships.

The authors (Tai and Inanici, 2009) previously investigated whether the depth perception of a 2D representation on a computer screen can adequately predict the perceptual qualities of a real 3D environment. The evaluation is done by repeating a classical research study on depth perception (Holway and Boring, 1941) in a computer generated pictorial environment. By acquiring matching experiment results in physical and virtual environments, the credibility of using computer generated pictorial space is established through psychophysical studies. The computational framework incorporates experimental scenes that were generated by Radiance software as physically based lighting simulations. Subsequently, perceptually based tone mapping techniques are used to compress the high dynamic range pixel data into displayable range such that visual appearance can be reproduced. Although several tone mapping operators have been developed in the past two decades, Photographic (Reinhard et al., 2002) and Photoreceptor (Reinhard and Devlin,

tions, additional 5'x10' skylight was installed at 24' away from the viewpoint on the left and right hallways, respectively. In the "window at left" condition, a 5'x10' window was installed at 24' away from the viewpoint on the left side of the left hallway.

3.1. EXPERIMENT 1

The objective of the first experiment is to determine if the presence of additional lighting patterns would affect the perceptual judgment of spatial depth in comparison to the base case ("no skylight"). Locations of both right and left disks are varied to achieve 9 different relative distances. In scene "L0R", both disks are located 40' away from the viewpoint. In scene "L1r", the left disk was shifted 6" closer while the right disk was shifted back 6" to create a 1' displacement. Similarly, the left disk is 2', 3', and 4' closer than right disk in scenes "L2r", "L3r", "L4r" respectively. In scenes "11R", "12R", "13R", "14R", the right and left disk are shifted to a reversed position to create relative distances such that the right disk is closer 1', 2', 3', and 4', respectively. These nine configurations of disk locations are rendered with three different lighting conditions of "no skylight", "skylight at left" and "skylight at right" to generate a total of 27 experimental scenes.

The scenes were rendered with resolution of 700x700 dpi. The high dynamic range images were tone-mapped with Photographic (Reinhard et al., 2002) and Photoreceptor (Reinhard and Devlin, 2005) TMOs to generate two sets of test images. Images were displayed on the center of a LCD display in a dark room. Eight subjects participated in this study. Subjects are aged between 21 and 36, had normal or corrected-to-normal vision. They were given time to adapt to the dark environment; they were asked to sit in front of the display at a normal viewing distance and angle. They were instructed that each scene incorporates two identical disks floating at the center of each hallway; and they were asked to use verbal methods to report the disk that appears to be closer. In each session, 27 images were shown in a random order for 10 times. Each subject repeated the experiment for two times with two different sets of tone-mapped images. Each participant's responses were recorded as the number of times that the right disk is reported closer.

3.1.1. Results and Analysis

Perceptual studies on the evaluation of the tone-mapping operators consistently show that Photographic TMOs performs well when compared to real physical scenes (Kuang et al., 2006; Cadik et al., 2008). A more recently developed algorithm, namely Photoreceptor TMO, is also considered since

it is theoretically built to model the human photoreceptor behaviour. As an initial study, the test scene is tone mapped with these two operators and the subject's responses were analysed to determine whether different tone mappings impact the perceived distance. The result of pair sample T-test of the average of the numbers of right disk reported closer for each tone-mapped set shows that there is no statistical significant difference between the experiments results ($\alpha = 0.05$, two-tail, $t_{\text{calc}} = 1.862 < t_{\text{crit}} = 2.447$). Therefore, it is concluded that the choice of either the Photoreceptor or Photographic TMO does not have significant impact on the experiment results.

Figure 2a illustrates the experiment results from the image set of Photographic TMO. Subjects' responses are plotted as the proportion of scenes on which the right disk is reported "closer" as a function of the relative distance between the right and left disks. Probit regression curves provide an appropriate statistical method for modeling regression of binary responses. They are used to fit a cumulative distribution to each data set. The intersection points of each curve with the 50% proportion line are taken as the point of subjective equality (PSE). The PSE represents when the right and left disks are perceived equal in depth. The result demonstrates that in the "no skylight" condition, the two disks were perceived equal when the two disks were configured at the same locations ($\text{PSE} = 0.03 \pm 0.01$). In the "skylight at left" condition, the PSE shifted to left, the two disks were perceived equal in depth when the right disk was actually 1.8 feet away than the left disk ($\text{PSE} = -1.84 \pm 0.11$). In the "skylight at right" condition, the PSE shifted to right, the two disks were perceived equal in depth when the right disk was actually 2 feet closer than the left disk ($\text{PSE} = 2.12 \pm 0.11$).

3.2. EXPERIMENT 2

In the second experiment, the location of the left disk is fixated at 40' away from the viewpoint and it is referred as the standard disk. The location of the right disk is varied to create 9 different scenes (located 36', 37', 38', 39', 40', 41', 42', 43' and 44' away from the viewpoint). Right disk is referred as the comparison disk. The objective of the second experiment is to investigate whether the directional properties of light source impact the resultant pictorial cue. The variation of disk locations were rendered with three different lighting conditions of "no skylight", "skylight at left" and "window at left" to generate a total of 27 scenes. To avoid getting the lighting effect only on the left hallway, the 27 scenes were flipped horizontally to create another set of mirrored images.

The images were tone-mapped by Photographic TMO. Each image was presented 5 times to each subject in a random order. A different group of eight

subjects participated in this study. Subjects were aged between 21 to 36, had normal or corrected-to-normal vision. Participant's responses were recorded as the number of times that the standard disk is reported closer.

3.2.1. Results and Analysis

The results of the experiment demonstrate that the perceived distance of the standard disk is increased around 4% with the presence of the lighting pattern introduced by a skylight or window (figure 2b). In the “no skylight” condition, the two disks were perceived equal in depth when the two disks were configured at the same locations (PSE = 40.14 ± 0.09). In “skylight at left” condition, the PSE is 41.81 ± 0.11 , and the perceived distance of the standard disk was increased 4.5%. In “window at left” condition, the PSE is 41.66 ± 0.11 , and the perceived distance of the standard disk was increased 4.2%.

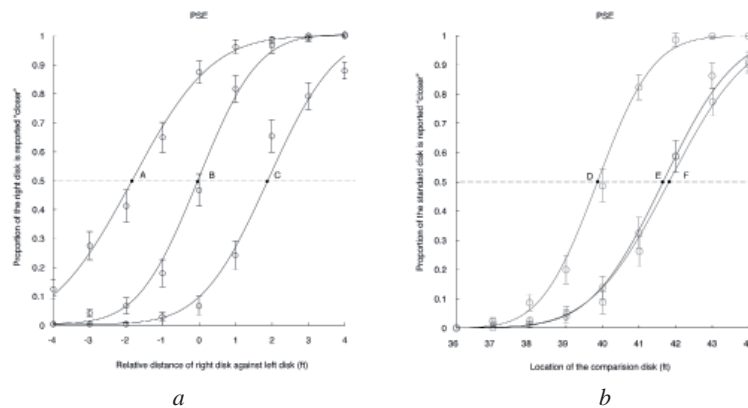


Figure 2. Probit analysis for experiments 1(a) and 2 (b): A is PSE with “skylight at left”; B is with “no skylight”; C is with “skylight at right”; D is with “no skylight”; E is with “window at left”; F is with “skylight at left” conditions.

4. Discussion

In size–distance relationship, perceived size of an object is derived from its perceived distance in a three-dimensional layout. Therefore, the perceived size can be considered as a source of depth cue. Experiment results from the “no skylight” conditions of both experiments demonstrate this size–distance relationship. The fact that PSE are 0.03 (expected value is 0) and 40.14 (expected value is 40) respectively indicate that subjects were able to judge accurately the relative distance between the two disks based on the pictorial cue dominated by the size perspective. The PSE has significantly shifted when the additional lighting pattern was presented. In the first experiment, the PSE shifted to left in the “skylight at left” condition, and shifted to right in the

“skylight at right” condition.

Figure 3 illustrates the false colour studies of the original high dynamic range scenes with disks configured at the same locations under different lighting conditions. The luminance contrast of the two disks and their backgrounds were identical in the base cases (“no skylight” condition). However, the luminance contrast between the disk and its background was reduced when the hallway was illuminated by additional skylight (“skylight at right” and “skylight at left” conditions). In each instance, the perceived distance was increased. These results are in agreement with O’Shea et al. study (1983), which argued that the higher the luminance contrast, the closer the target appears to be. The additional skylight reduces the luminance contrast between the disk and its background, and therefore, increases its perceived distance. Results from the second experiment support this analysis, as well. Although the luminance distributions between the experimental scenes were quite different in scenes with skylight and window, the contrast between the standard disk and its background remained similar. The subjects reported similar perceived distances of the standard disks. Therefore, it is concluded that the effect of scene based lighting patterns on the depth perception is dependent on luminance contrast of the visual target and its immediate background. The lower the contrast, the farther away the target appears.

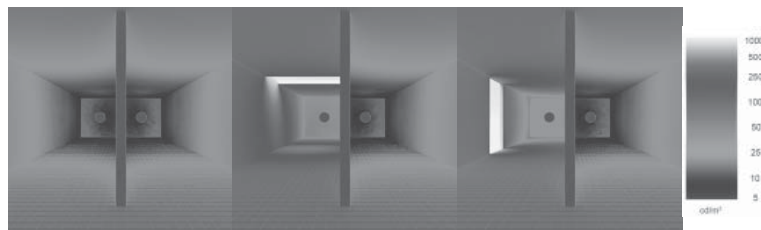


Figure 3. False colour studies of experimental scenes (left: “no skylight” condition; middle: “skylight at left” condition; right: “window at left” condition).

5. Conclusion

Architectural design process is often mediated on two-dimensional representation systems and envisioned three-dimensionally in the pictorial space. Pictorial cues have been used by architects as powerful representation and design tools to visualise and enhance the spatial qualities of architectural space. The Galleria Spada (designed by Francesco Borromini, 1635) is a significant example that utilised the pictorial cue of linear perspective to increase the perceived spatial depth (figure 4a). The height and size of each column, and the spacing between them are decreased gradually as they recede into space. Along with the convergent inclination of the ceiling and tile patterns, a distorted linear perspective is laid out for the entrance view to amplify the

perceived depth of the space. Lin's family garden (designed by Kuan-Cao Hsieh, 1853) is another example (figure 4b), in which the application of the pictorial cue of size perspective can be observed. Bridges were constructed at reduced size, barely allowing one person to walk through. When viewed from the pavilion, the homogenous texture of water provides no further contextual depth information. The observers mistakenly perceive the bridges at normal size, which in return exaggerates the distance between the two bridges and amplifies the overall spatial depth. These examples illustrate that navigation can be guided with planned circulation, and the points of observation can be restricted by framed openings in architectural spaces (figure 4c). Manipulation of physical settings can exaggerate the pictorial cue for expected scenes, and therefore affect the spatial experience of the architectural spaces.

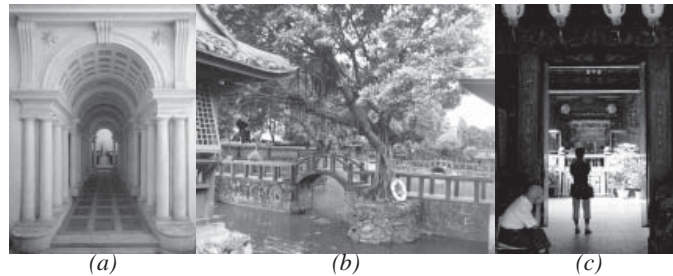


Figure 4. Applications of pictorial cues in architectural designs (a: Galleria Spada; b: Lin's Family Garden; c: Tien-Ho Temple).

Pictorial spaces generated with physically based rendering tools and perceptually based tone mapping techniques allow architect to understand the relation of the architectural structure, resultant lighting distribution and perception of spatial depth. Our study demonstrates that scene based lighting patterns affect the perceived distance. Lighting schemes introduced to render scenes with different luminance contrasts can alter depth perception as the occupant explores the space. As a result, the effect of the lighting as pictorial cue can enrich the spatial experience.

The computational framework utilised in this paper offers a powerful tool for architects to simulate the perceived qualities of built environments. It provides a flexible environment where representational and analytical approaches are employed to envision the visual qualities of built environments, and to improve the design decisions.

Acknowledgements

The authors would like to thank Dr. John Palmer at the University of Washington, Department of Psychology for his suggestions and discussions on conducting the experiment. The authors also thank the students and staff of the College of Built Environments at the University of Washington who have participated in the experiments.

References

- Boyaci, H., Maloney, T. and Hersh, S.: 2003, The effect of perceived surface orientation on perceived surface albedo in binocularly viewed scenes, *Journal of vision*, **3**(8), 541–553.
- Cadik, M., Wimmer, M., Neumann, L., and Artusi, A.: 2008, Evaluation of HDR tone mapping methods using essential perceptual attributes, *Computer and graphics*, **32**(3), 35–44.
- Delahunt, P., and Brainard, H.: 2004, Color constancy under changes in reflected illumination, *Journal of vision*, **4**(9), 764–778.
- Doerschner, K., Boyaci, H., and Maloney, T.: 2004, Human observers compensate for secondary illumination originating in nearby chromatic surfaces, *Journal of vision*, **4**(2), 92–105.
- Ferwerda, J.A.: 2001, Elements of early vision for computer graphics, *IEEE computer graphics and applications*, **21**(5), 22–33.
- Fleming, R. W., Torralba, A. and Adelson, E. H.: 2004, Specular reflections and the perception of shape, *Journal of vision*, **4**(9), 798–820.
- Gescheider, G. A.: 1984, *Psychophysics: method, theory, and application*, Hillsdale: Lawrence Erlbaum Associates, Inc.
- Greenberg, D. P., Torrance, K. E., Shirley, P., Arvo, J., Ferwerda, J. A., Pattanaik, S., Lafortune, E., Walter, B., Foo, S. C. and Trumbore, B.: 1997, A framework for realistic image synthesis, *ACM SIGGRAPH proceedings of the 24th annual conference on computer graphics and interactive techniques*, 477–494.
- Hubona, S.G.: 2000, The relative contributions of stereo, lighting, and background scenes in promoting 3D depth visualization, *ACM transactions on computer–human interaction*, **6**(3), 214–242.
- Holway, A. H. and Boring, E. G.: 1941, Determinants of apparent visual size with distance variant, *American journal of psychology*, **54**(1), 21–37.
- Kuang, J., Liu, C., Johnson, G. and Fairchild, M.: 2006, Evaluation of HDR image rendering algorithms using real-world scenes, *International congress of imaging science*, **4**(2), 1–27.
- Mardaljevic, J.: 2001, The BRE-IDMP dataset: a new benchmark for the validation of illuminance prediction techniques, *Lighting research and technology*, **33**(2), 117–136.
- Meng, J. C. and Sedgwick, H. A.: 2001, Distance perception mediated through nested contact relations among surfaces, *Perception and psychophysics*, **63**(1), 1–15.
- O’Shea, R. P., Blackburn, S. G., and Ono, H.: 1994, Contrast as a depth cue, *Vision research*, **34**, 1595–1604.
- Ramanarayanan, G., Ferwerda, J., Walter, B. and Bala, K.: 2007, Visual equivalence: towards a new standard for image fidelity, *ACM transactions on graphics*, **26**(3).
- Reinhard, E. and Devlin, K.: 2005, Dynamic range reduction inspired by photoreceptor physiology, *IEEE transactions on visualization and computer graphics*, **11**(1), 13–24.
- Reinhard E., Stark, M., Shirley, P., and Ferwerda, J.: 2002, Photographic tone reproduction for digital images, *ACM transactions on graphics*, **21**(3), 267–276.
- Ruppertberg, I. and Bloj, M.: 2006, Rendering complex scenes for psychophysics using RADIANCE: how accurate can you get? *Journal of optical society of America*, **23**(4), 759–768.
- Schwartz, B. J. and Spering, G.: 1983, Luminance controls the perceived 3D structure of dynamic 2D displays, *Bulletin of the psychonomic society*, **21**, 456–458.
- Spencer, G., Shirley, P., Zimmerman, K., and Greenberg, D. P.: 1995, Physically-based glare effects for digital images, *SIGGRAPH 95 conference proceedings*, 325–334.
- Tai, N. and Inanici, M.: 2009, Depth perception in real and pictorial spaces: A computational framework to represent and simulate the built environment, *CAADRIA 2009, Yunlin*, 543–552.
- Ward, G. and Shakespeare, R.: 1997, *Rendering with Radiance*, Morgan Kaufman Publisher, San Francisco.