Space Perception and Luminance Contrast: Investigation and Design Applications through Perceptually Based Computer Simulations

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Abstract

Pictorial cues are the visual information gathered from 3D scenes; and they provide depth perception in the physical world. Pictorial cues are also used to create the illusion of depth on planar media. Planar media are a common platform for architects to visually examine the spatial qualities of their designs. Therefore, knowledge of pictorial cues can be used as a design strategy to enrich the spatial experience. In this paper, luminance contrast is proposed as an effective depth cue and design strategy. Lighting based perceptual studies are challenged by the dynamics of the luminous environments in physical experimental settings. Computer simulation allows the study of lighting variability throughout the day and year in a systematic manner. This paper utilizes a computational framework to simulate perceptual reality. Psychophysical experiments are conducted in this alternative environment. 3D scenes and the resulting 2D imagery are utilized to investigate the impact of lighting patterns and luminance contrast on depth perception. The results of the study demonstrate that luminance variations within a space impacts the perceived distance as much as they impact the luminance contrast between the task and the background. Application of this pictorial cue is demonstrated through architectural and urban design examples.

1. INTRODUCTION

The human visual system processes three-dimensional (3D) physical environments based on the two-dimensional (2D) images projected on to retinae [Palmer 2000]. Conversely, the process and products of 2D representation systems are used to design and develop 3D un-built proposals, and to provide instructions for constructing the projects [Ching 1998]. Pictorial cues gathered from the physical world supplement the 2D retinal images with additional visual information to perceive the spatial depth. These pictorial cues are also used to create the illusion of depth on planar media. Therefore, knowledge of pictorial depth cues has been used to enrich spatial experience within given structural boundaries. However, the ability to examine the spatial quality from design alternatives is limited by the perceptual realism offered by the representation media.

Although visual perception is a complex process that is yet to be fully understood, it is generally agreed that the visual system has two distinct functions: i) identification (i.e. color perception, object and face recognition) and ii) localization (i.e. perception of motion, spatial relation and depth). The localization system is insensitive to color and responds only to luminance differences [Ferwerda 2001; Livingstone 2002].

In space perception, edge detection provides conceptually meaningful visual information, and facilitates the understanding of the geometrical properties of the 3D scene. The geometrical properties are governed by size-distance relationships, i.e., the perceived size of an object is derived from its perceived distance, and supplemented with the pictorial cues of size perspective that include relative size, familiar size, linear perspective and texture gradient.

Reproduction of depth cues based on detected edges is straightforward and does not require high levels of perceptual realism. Therefore, it is relatively easy to demonstrate the effect (Figure 1). In Figure 1a, three cylinders located in the hallway have exactly the same projected size. However, the pictorial cues of cylinders' relative size, convergent lines, and foreshortening of texture pattern inform the viewer that the three cylinders are located at different locations. The further the cylinder is located, the larger it appears. In Figure 1b, the effect of the pictorial cue of shadow is illustrated. The three cylinders are floating at the same distance from the viewer, and the presence and the length of the shadows inform their vertical positions. The cylinders appear the same size.

Lighting has been identified as a pictorial depth cue. However, its application is often limited to the resultant shadow to locate the objects in a 3D context. Schwartz and Sperling [1983] promoted perceived luminance as a pictorial depth cue. O'Shea, Blackburn and Ono [1994] further pointed out that target with higher luminance contrast would

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appear closer on a 2D setting. Authors [Tai and Inanici 2009a] previously investigated this effect in a 3D context. In a computer-simulated environment, physical structures were manipulated to introduce different lighting conditions in an architectural scene. Effect of luminance distributions on depth perception was studied through psychophysical experiments. It was concluded that lighting distributions can affect the perceived distance of the visual target. Figures 1c and 1d illustrate this effect in the hallway illusion. With the introduction of additional lighting, the perceived distance of the farthest cylinder in Figure 1d is increased in comparison to the same configuration in Figure 1c.

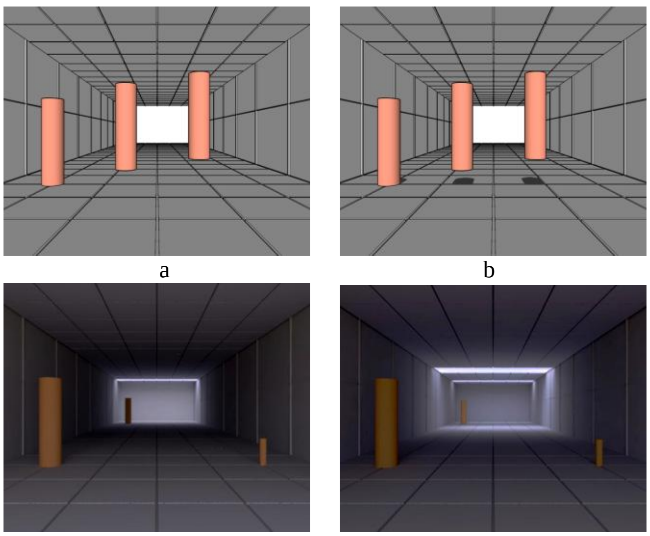


Figure 1. Hallway illusion illustrating a) the size-distance relationship, b) the pictorial cue of shadow, c) and d) the pictorial cue of luminance distributions

Luminance distributions in a scene determine the lighting patterns around the visual target, and the luminance contrast between the target and its background. The objective of this research is to study the individual contributions of lighting patterns and luminance contrast on depth perception. This study extends the research framework previously developed [Tai and Inanici 2009a and 2009b] by taking advantages of two-dimensional nature of the computer imagery. The lighting patterns and luminance contrast were isolated using computational methods. Psychophysical experiments were conducted to investigate the particular contribution from each component.

2. METHOD

Using computer simulations to demonstrate and study depth perception is not a new approach. Meng and Sedgwick [2001] used a computer environment to manipulate the presence of shadows in their research to investigate its impact on depth perception. Determining the hard shadows of objects in a computer environment is a fairly simple mathematical calculation that is based on the geometric relationship of the object, light source and the viewer. Photorealistic rendering methods used in Meng and Sedgwick's study provided the necessary realism of representing forms and casted shadows. However, the study of lighting distribution and the investigation of its impact on depth perception require a representation that matches the intended perceptual reality.

The Radiance lighting simulation and visualization system is a physically based rendering program that models the light transport and material properties based on their governing physical equations [Ward and Shakespeare 1997]. The rendered image is a luminance map that encompasses numerically accurate lighting data [Mardaljevic 2001; Ruppertberg and Bloj 2006]. Current display devices cannot display high dynamic range lighting information that is simulated through physically based rendering tools. Tone mapping operators were developed to compress the full range of lighting data that can be processed by human visual system (14 logarithmic units in cd/m^2 from starlight to sunlight) to the range of conventional display devices (2 logarithmic units). Using appropriate tone mapping operators, physically accurate, high dynamic range images can be displayed as low dynamic range perceptually realistic scenes on conventional display devices. Physically and perceptually accurate images have previously been utilized in experimental studies to investigate various aspects of lightness, color, shape, and depth on visual perception [Boyaci et al. 2003; Doerschner et al. 2004; Delahunt and Brainard 2004; Fleming et al. 2004; Tai and Inanici 2009b].

Experimental scenes used in this study were generated by the Radiance lighting simulation and visualization system and tone mapped by the Photographic tone mapping operator [Reinhard et al. 2002]. The Photographic tone mapping operator was selected based on the research that compared perception between physical scenes and tone mapped imagery [Cadik 2008].

3. PSYCHOPHYSICAL EXPERIMENTS

The effect of a pictorial depth cue is often studied through psychophysical experiments. Psychophysics is a field that investigates the relation of psychological sensation and physical stimuli [Gescheider 1984]. In general, subjects are asked to judge the perceived distance of the visual targets from the test and reference scenes. By comparing the measured differences, the effect of a depth cue controlled in the experimental scenes can be systematically studied.

The method of constant stimuli is employed in our study to measure depth perception. In this method, both the standard stimulus and comparison stimulus are presented to the subjects simultaneously. While the standard stimulus remains constant, the comparison stimulus changes from trial to trial. Subjects' responses are recorded based on their response to the varied stimuli. In this method, the comparison stimulus usually has five, seven or nine values, separated by equal distances in physical scale. The comparison stimulus is varied such that variation of greatest magnitude is almost always perceived greater than the standard stimulus, and the least magnitude is perceived less than the standard stimulus. Pairs of standard stimulus and comparisons are presented in a random order; and subjects are asked to determine which stimulus produces a greater magnitude of sensation [Gescheider 1984]. The design of the binary responses allows the data to be analyzed with probit regression models to derive psychometric functions, as illustrated in Figure 2. The 0.5 point in the regression model is called the point of subjective equality (PSE). It represents the value of comparison stimulus that is subjectively perceived equal to the standard stimulus. In other words, at the point of subjective equality, measured sensory perception is equal to the physical stimuli [Finney 1971].

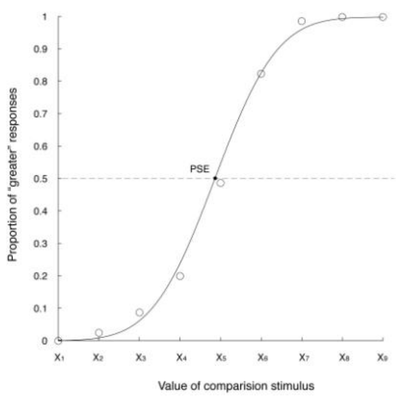


Figure 2. Typical psychometric function fitted with Probit regression curve [Gescheider 1984]

3.1. Experiment Design

As the size perspective is a dominant depth cue for the space perception of physical space, it is essential to ensure that the size-distance relationship can be observed effectively in the computer-generated pictorial space. The authors [Tai and Inanici, 2009b] previously conducted a computer based study to reproduce a classic experiment [Holway and Boring 1941] that investigates the size-distance relationship in a physical environment. In the Holway and Boring experiment, circular disks are used as visual targets. By acquiring similar results in a computer generated study in comparison to the original one, it is demonstrated that the utilized computational framework is a reliable alternative environment to study depth perception.

The use of circular disks as visual targets is also adopted for the current study. Figure 3 illustrates the setup, where architectural configurations are modified to study the impact of lighting distributions on spatial depth. The test and reference scenes are presented simultaneously. One of the hallways serves as a test scene and the other as a reference scene. A different lighting condition is introduced into one of the hallways. For each particular condition, seven images were generated. In each of these images, the test target (standard disk) remains constant at a fixed distance, while the reference target (comparison disk) is rendered at one of the seven different locations (Figure 4). Subjects are asked to report which visual target is closer. The underlying concept of the experiment design is to identify when the test and reference targets are perceived equal in depth. By comparing the perceived distance and its actual location, the effect of lighting distribution on depth perception can be revealed.

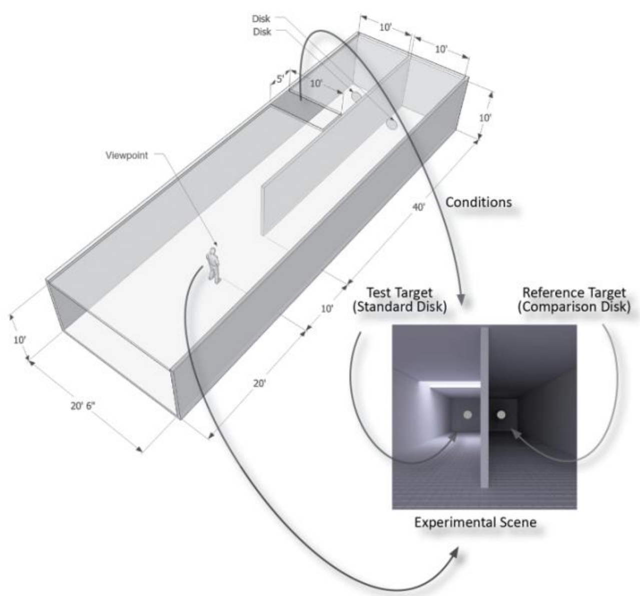


Figure 3. Experimental setup

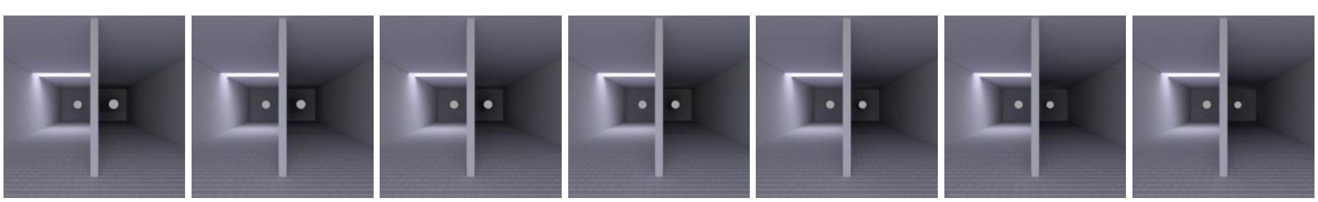


Figure 4. Experimental scenes with different configurations of visual targets under the same lighting condition

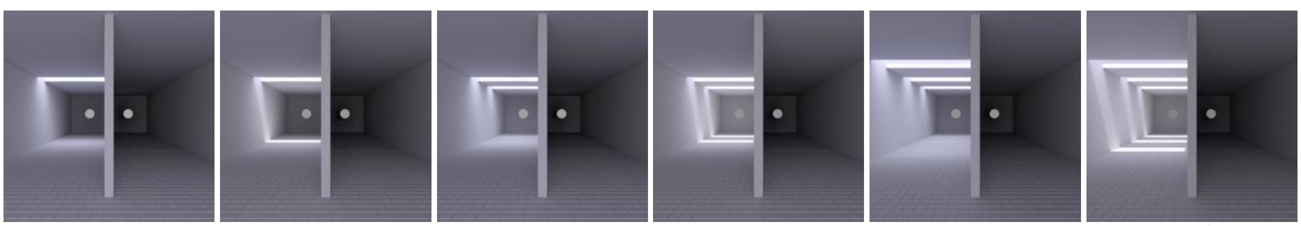
Two experiments are conducted in this study. In the first experiment, the setup is manipulated to create different lighting conditions (Figure 5). Each scene is illuminated with the daylighting admitted from the rear end of the corridor. Three different configurations are rendered (single skylight, two skylights and three skylights) with the two different sky conditions (intermediate sky with / without sun patch) to generate total of six different setups: single skylight (1sky), single skylight with sun patch (1skyS), two skylights (2sky), two skylights with sun patch (2skyS), three skylights (3sky), and three skylights with sun patch (3skyS).

The second experiment is conducted to investigate the individual contributions of the lighting patterns around the visual target and the luminance contrast between the target and its immediate background. The renderings of single skylight (1sky), single skylight with sun patch (1skyS) and three skylights with sun patch (3skyS) from the first experiment are adopted, and image processing techniques are used to generate six different setups as shown in Figure 6. In Figures 6a, 6b, and 6c, the portion of the disk and the back wall are edited so that the luminance contrast of the disk and its background are identical between the right and left corridors. This set equalizes the luminance contrast between the target and its background, leaving lighting distribution patterns as the variable. In Figure 6d, 6e, and 6f, the presence of the skylight and the resulting lighting distribution patterns surrounding the disk were removed. The luminance contrast between the disk and its background is the only variable between the right and left hallways of each scene.

3.2. Procedure

In all conditions, 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 7 different alternatives (located 34', 36', 38', 40', 42', 44' and 46' away from the viewpoint). The right disk is referred as the comparison disk. Various disk locations are simulated under twelve different lighting conditions. To avoid lighting effect always coming from one side (i.e. left hallway), the rendered scenes were flipped horizontally to create another set.

Images were displayed on the center of a LCD display in a dark room. Eight subjects participated in each experiment. Subjects were aged between 21 and 36, had normal or corrected-to-normal vision. They were given enough time to adapt to the dark environment. They sat in front of the display at a normal viewing distance and angle. They were instructed that in each scene there were two identical disks floating at the center of left and right hallways; and were asked to provide a quick response. In each session, images were shown in a random order ten times. Participant's responses were recorded as the number of times that the standard disk is reported closer.



a b c d e f

Figure 5. Experimental scenes with right and left disks configured at same locations under different conditions for experiment 1: (a) Single skylight; (b) Single skylight with sun patch; (c) Two skylights; (d) Two skylights with sun patch; (e) Three skylights; (f) Three skylights with sun patch.

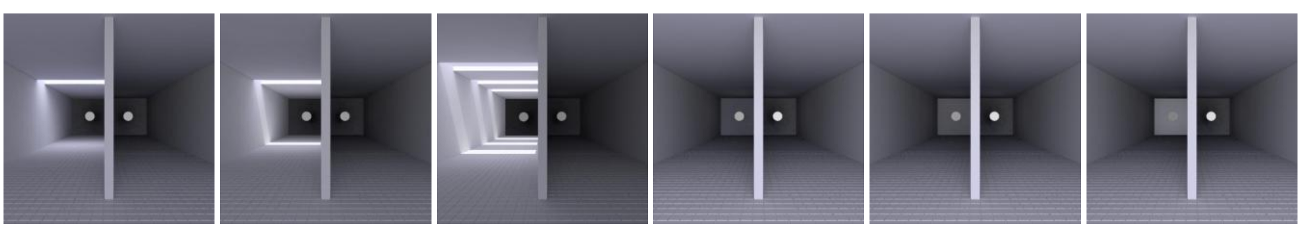


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Figure 6. Experimental scenes with right and left disks configured at same locations under different conditions for experiment 2. Contrast between disk and the background is equal, variable is the luminance distribution patterns in the hallway: (a) Single skylight; (b) Single skylight with sun patch; (c) Three skylight with sun patch. Lighting distribution patterns are eliminated; variable is the luminance contrast between the disk and background: (d) Single skylight; (e) Single skylight with sun patch; (f) Three skylight with sun patch.

3.3. Results and Analysis

The experiment results are illustrated in Figures 7a and b for experiments 1 and 2, respectively. Subjects' responses are plotted as the proportion of scenes on which the standard disk is reported "closer" as a function of the comparison disk's location. The probit regression curve is fitted to each data set. The intersection points of each curve with the 50% proportion line are taken as the PSE. The PSE represents when the right and left disks are perceived equal in depth. In other words, it is the measurement of the perceived distance of the standard disk. In experiment 1, the perceived distance of standard disk was increased from 40 feet to 41.432 ± 0.125 (5a), 42.150 ± 0.141 (5b), 42.438 ± 0.133 (5c), 43.377 ± 0.165 (5d), 42.445 ± 0.156 (5e) and 43.109 ± 0.143 (5f) feet, respectively. In experiment 2, the perceived distance of the standard disk of the setups shown in Figure 6a, 6b, 6c was increased slightly from 40 feet to 40.440 ± 0.154 (6a), 40.554 ± 0.154 (6b) and 40.324 ± 0.158 (6c) feet respectively. For setups shown in Figure 6d, 6e, 6f, the perceived distance of the disk was increased from 40 feet to 42.547 ± 0.146 (6d), 42.926 ± 0.171 (6e) and 44.284 ± 0.166 (6f) feet respectively.

The results indicate that luminance contrast significantly increases the perceived distance of the visual target. 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 on a 2D context. Our study demonstrates that the same effect can be observed in 3D environments. In the experimental setup, daylighting introduced by the skylight increases the overall dynamic range of the luminance distribution; as a result, it decreases the luminance contrast between the visual target and its immediate background. Thus, it increases the perceived distance of the visual target and the overall spatial depth of the hallway.

Figure 8 further illustrates the impact of the luminance contrast on perceived distance. The dashed line represents the ratio of the luminance contrasts from original HDR images, and the straight line represents the same ratio from the tone mapped images. It is important to note that tone mapping conserved the contrast within the scenes. In both cases, the perceived distance increases as the ratio decreases.

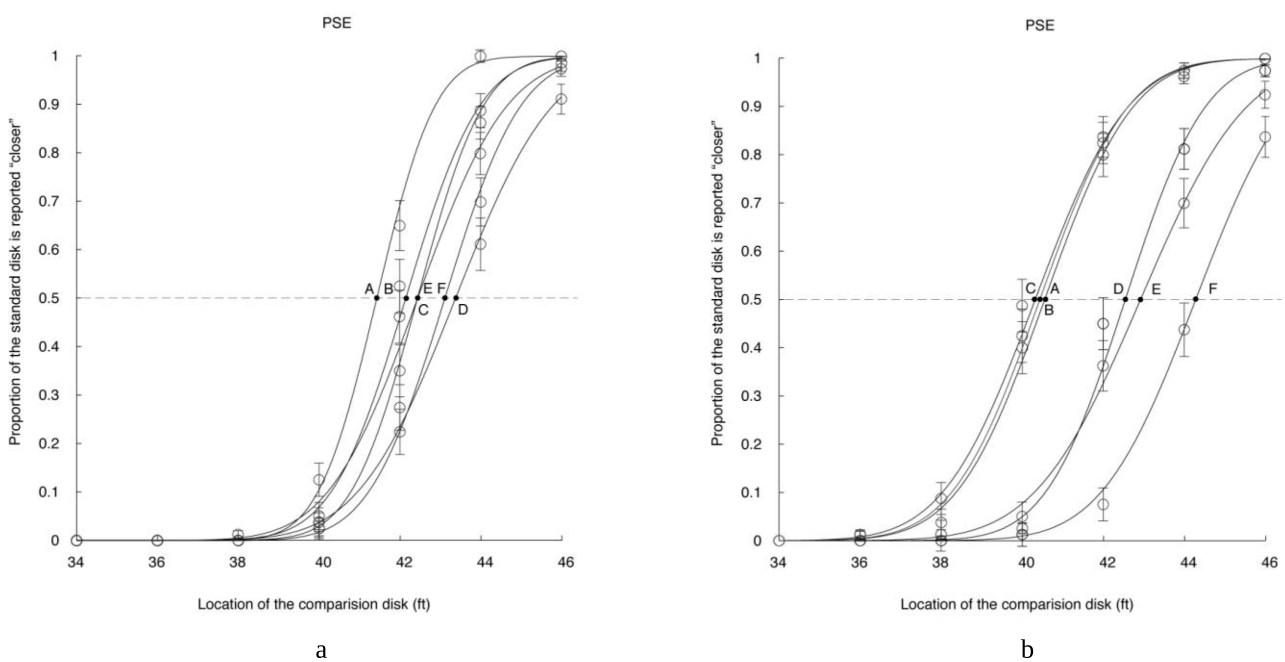

Figure 7. Probit analysis. (a) PSE is given for A "single skylight", B "single skylight with sun patch", C "two skylights", D "two skylights with sun patch", E "three skylights", F "three skylights with sun patch". (b) PSE is given for A "single skylight with distribution variable", B "single skylight with sun patch and distribution variable", C "three skylights with sun patch and distribution variable", D "single skylight with contrast variable", E "single skylight with sun patch and contrast variable", F "three skylights with sun patch and contrast variable".

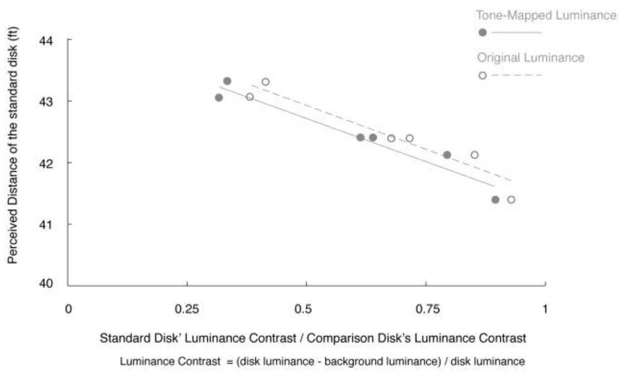

Figure 8. Impact of luminance contrast ratio on perceived distance

The results of the experiment also indicate that lighting patterns alone has insignificant effect on increasing the perceived distance of the visual target. Comparison between the measured perceived distances between the conditions shown in 5b (single skylight with sun patch: 42.150 ± 0.141 ft.), 5f (three skylight with sun patch: 43.109 ± 0.143 ft.) and the same conditions with the sun patch removed shown in Figure 6e (42.926 ± 0.171 ft.), 6f (44.284 ± 0.166 ft.), suggests that subjects tend to overestimate the perceived distance of the visual target when the lighting patterns are absent. A possible interpretation is that the patterns of sun patches provide pictorial cue of linear perspective to correctly judge the depth. This effect is a compounding factor. A further study is planned to study the impact of luminance distribution patterns that impact other pictorial cues such as the linear perspective.

4. DISCUSSIONS & APPLICATIONS

Computer simulations with appropriate algorithms can provide pictorial representations with adequate realism to study the perceptual qualities of a space. In this study, we have demonstrated its utilization to identify the effect of the luminance contrast on spatial depth in an experimental setting. Two examples are discussed to demonstrate the application of research findings in architectural design and urban planning problems.

Figure 9 illustrates a planning conflict between street expansion and the preservation of a vernacular Taiwanese temple. In the route of ritual ceremony in a vernacular Taiwanese temple, three particular scenes are expected to be perceived as part of the spatial experience (Figure 9b, c, d). Each scene is a composed perspective view rendered with repeated patterns of light and dark. However, the light pattern distributions in particular scene are not intended to faithfully inform the visitor about the actual distance of the temple at each viewpoint. Instead, it is intended to exaggerate the sense of depth [Tai 2003].

The three scenes presented in Figure 9b, c, d have similar lighting distribution patterns investigated in this study. In the first view, the visual target of the deity is rendered with repeated patterns of light and dark, similar to the two skylights setup in the first experiment. In the second view, a single skylight pattern is experienced. In the last standpoint, skylight is not visible. According to the experiment results, the spatial depth is exaggerated in the first two views, but the factor of exaggeration is removed in the last scene. As a result, the “sense of the depth” is created by repeating lighting patterns in earlier scenes. Conversely, the “sense of depth removal” pulls the visitor away from the physical site context into the ritual realm as one continues to move from one scene to the other in a very short walk.

The spatial experience in the temple is a result of the daylighting scheme introduced through the courtyard. Unfortunately, the front hall and courtyard of the temple were demolished to accommodate the growing traffic, leaving only the main hall preserved at its original location. The demolished parts eliminated the scenes that provide the repeated patterns of light and dark. If the resultant luminance contrast introduced by the courtyard has been recognized as the factor that enriches the spatial depth and its value as an integral part of a vernacular temple’s spatial experience, the decision may have been made differently for this planning conflict.

The research findings can also be applied as design parameter. The chapel of St. Ignatius in Seattle (designed by Steven Holl) is known for its rich lighting variation and spatial qualities (Figure 10). The spatial dimension in the chapel is enriched by dynamic lighting distributions. Figure 10b illustrates the very first view upon entry, and demonstrates the utilization of luminance contrast to enrich the spatial depth. Figures 10c and 10d demonstrate a simulation of the chapel with a tree that is framed by an opening at the end of the space. The tree serves as a visual target. In this view, daylight coming from the side renders the framed picture of tree with patterns of light and dark, and creates a sense of ‘deepness’. Comparison of the computer simulations in Figure 10c and 10d demonstrate the effect of luminance contrast on spatial depth. In Figure 10d the side window is covered, and therefore, the side lighting is removed from the scene. The luminance contrast between the tree and its background is increased. The increased contrast diminishes the perceived distance. As a result, the visual target (tree) in Figure 10d appears to be closer than Figure 10c. Conversely, brightness in the foreground reduces the luminance contrast between the visual target and its immediate background in Figure 10c, and thus increases the overall spatial depth.

a b c d

Figure 9. Planning conflict between the street expansion and the perseveration of a historical temple, a: outside view of the main hall; b and c: the eliminated views that demonstrate the sense of deepness; d: the surviving view of the main hall

a b c d

Figure 10. Chapel of St Ignatius. a: exterior view; b: interior view; c: computer rendering of entrance view with the side window; d: computer rendering of entrance view without the window light

5. CONCLUSIONS

This research demonstrates the utilization of a simulation approach to study the perception of spatial depth in pictorial spaces. This approach is useful as a methodology for studying space perception and for evaluating the perceptual qualities of spaces throughout the design phases. The contributions of this study can be summarized at practical and theoretical levels:

1) At the practical level, luminance contrast is identified as an effective pictorial cue. Occupants navigate built environments through a planned circulation, resulting in sequential experience of one scene after another. Careful manipulation of the physical configuration can create scenes with intended lighting distributions and luminance contrasts that can enrich the spatial experience of built environments.

2) Luminance variations within a space impacts the perceived distance as much as they impact the luminance contrast between the target and the background. However, a further study is planned to study the impact of luminance distribution patterns on other pictorial cues such as linear perspective.

3) In the theoretical level, physically and perceptually accurate simulation techniques bridge the gap between perceptual qualities of built environments (physical space) and their representation in pictorial spaces. The perceptually accurate simulations provide an alternative environment that offers flexibility and precise parameter control of scene components for 3D scenes and the resulting 2D imagery.

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