Application of Luminance Contrast in Architectural Design

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ABSTRACT

Enriching the spatial experience of an architectural space within its limited structural boundary is one of the goals in architectural design. The manipulation of physical configurations to create a misinterpretation of the depth cue has been found an effective way to create a false perception of the spatial depth in many architectural examples. Luminance contrast has been identified as effective visual information to create an illusory depth effect on a planar surface, and it can cue the relative distance in three-dimensional settings. However, the cause-and-effect relationship between the physical configuration, the luminance contrast, and the resulting spatial experience has not been established yet. In this study, psychophysical experiments were conducted to investigate the relationship between the architectural configuration of skylights, the scene luminance contrast rendered by the daylight that is admitted inside, and the effect on depth perception. Design principles of utilizing luminance contrast through daylighting to enrich the spatial experience of an architectural space were generalized to conclude this study.

Keywords: luminance contrast, space perception, design parameter, high dynamic range imagery.
DOI: 10.3722/cadaps.2013.953-963

1 INTRODUCTION

Visual illusion is a phenomenon in which the perception from a visual system is different from the physical reality [2] [7]. The illusion of depth, or of distance, in particular, refers to the discrepancy between the actual spatial configuration and its perceived third dimension [5]. The main cause of this type of illusion is the misinterpretation of the depth cue. Depth cues are visual information available from a scene that can be gathered by the human visual system to retrieve the lost third dimension of depth from two-dimensional retinal images [7]. Because the depth illusion can be controlled by the depth cue, manipulating physical configurations to create false perceptions of the depth cue has become a design strategy to enrich the spatial dimensions of an architectural space.

The pictorial depth cue, in general, can be either related to size or to tone. The cause-and-effect relationship of the size-related depth cue, such as the relative size, familiar size, or linear perspective on the perceived distance has been well established. As a result, their design applications are evident in the illusory spatial experience found in many early architectures such as the stage scenery of the Theatro Olimpico (designed by Vincenzo Scamozzi, 1585, Vicenza, Italy), and the hallway of the Galleria of Palazzo Spada (designed by Francesco Castelli detto il Borromini, 1653, Rome, Italy) [8][12].

Conversely, the tone-related depth cue of the luminance contrast has been proven to be effective in creating an illusory depth on a planar surface [6], and can cue the relative distance in three-dimensional layout [11]. However, the casual relation between the physical configuration, daylighting, and the effect on the spatial perception has yet to be established. Applications utilizing a window, courtyard, or skylight to introduce daylight to enrich spatial experience have thus remained experiential.

In this study, luminance contrast is proposed as a possible design parameter. The cause-and-effect relationship between the physical configuration, daylighting, luminance contrast, and depth perception of the spatial dimensions were examined through psychophysical experiments conducted in a perceptual realistic computer environment. Based on the results of these experiments, the principles of utilizing luminance contrast to enrich the spatial experience were generalized.

2 BACKGROUND

The effect of a particular depth cue on the perceived distance can be most effectively established by perceptual studies through psychophysical experiments. Figure 1 illustrates the setup of an experiment conducted by Blessing, Landauer, and Coltheart, which utilizes the false perspective to investigate the size-distance relationship [1]. The size at the viewing end and the texture pattern were manipulated for two pyramid-shaped viewing tunnels to create a false perspective of a shorter and a longer rectangular tunnel for tunnel A and tunnel B, respectively. The results demonstrated that physical manipulation based on the false perspective could affect the perceptual judgment of the perceived distance. Figure 2 further illustrates that the Galleria Spada has a physical manipulation similar to that of the tunnel B. Thus, the experimental result obtained by Blessing, Landauer, and Coltheart provides a theoretical foundation for the design strategy of utilizing false perspectives to amplify the perceived depth in the Galleria Spada.

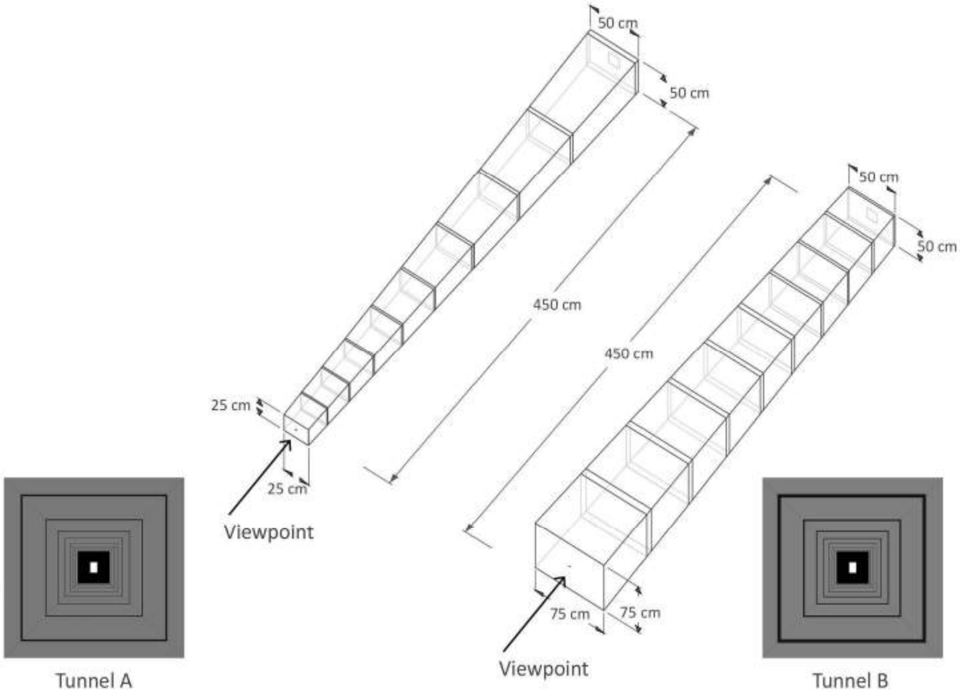


Fig. 1: Viewing tunnels for Blessing et al.'s experiment.

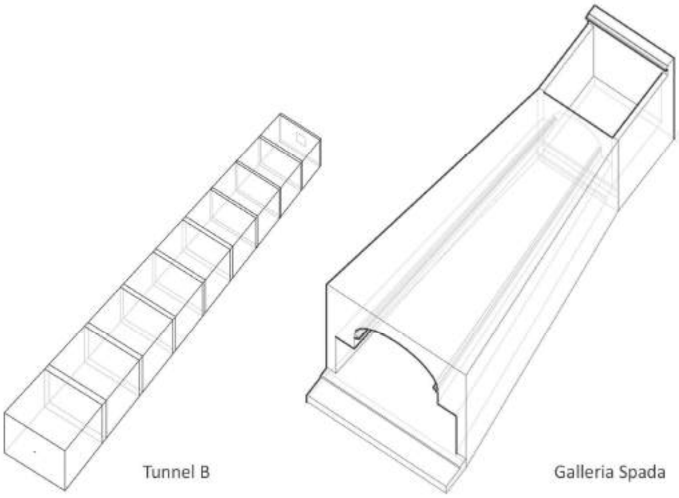


Fig. 2: Comparison of the configurations of tunnel B and the Galleria Spada.

The tone-related depth cue of atmospheric perspective has long been noticed and can be observed in early paintings in which distant objects were painted with a lower contrast than objects in the foreground [14]. O'Shea, Ono, and Blackburn conducted a perceptual study to investigate the depth effect of contrast [6]. As illustrated in figure 3, an identical pattern of a pair of dark and light squares on a planar surface would appear differently in depth with different backgrounds. The lower the contrast of the square against its background, the further away it appears to be. Tai and Inanici conducted a series of experiments using a perceptual realistic computer environment to investigate this effect in three-dimensional settings, and they concluded that the luminance contrast can be an effective cue to affect the perceptual judgment on depth [10] [11]. Figure 4 illustrates this effect; two identical visual targets appear to be at different distances with different luminance contrasts.

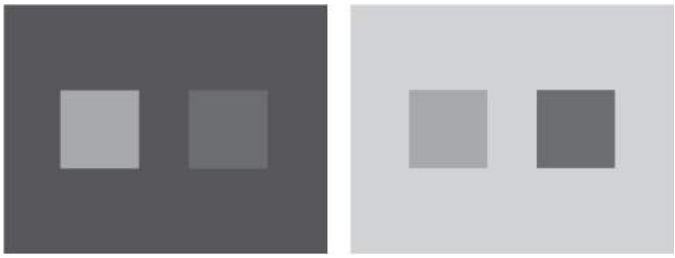


Fig. 3: Contrast effect on a planar surface: in each pair, the square with a higher contrast against its background appears to be closer than the one with the lower contrast.

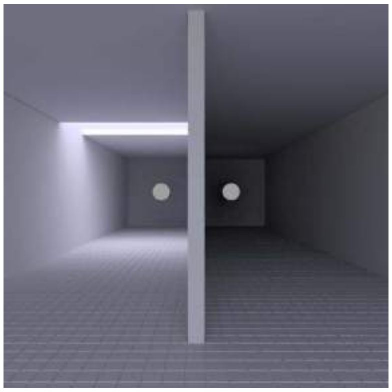


Fig. 4: Contrast effect in a three-dimensional built environment: the disk with a higher contrast against its background appears to be closer than the other identical disk located at the same distance.

Architectural configurations such as a window, courtyard, or skylight can introduce daylight to illuminate the interior. In many cases, it can also render the scene with a different pattern of the luminance contrast. Figures 5 and 6 illustrate the effect observed in the chapel of St. Ignatius, designed by Steven Holl, and in the AGO Art gallery of Ontario, designed by Frank Gehry. In both cases, the light introduced in the foreground reduces the luminance contrast between the visual target, a tree in the chapel and a sculpture in the gallery, and its background, and creates a sense of depth in the overall spatial perception. Figure 7 further illustrates the sequential scenes as one approaches the sculpture from the entrance through the courtyard in the AGO Art Gallery. The luminance contrast of the visual target against its background changes with changes in the illumination level of the viewing point, resulting in a rich spatial experience.

To utilize the luminance contrast as a design parameter, it is essential to compose a scene with a visual target along with architectural configuration to admit daylight, allowing the design to create a dynamic luminance contrast. In this study, psychophysical experiments were conducted to investigate the relationship between the configuration of the physical structure, the luminance contrast of the scene, and the perceived distance of the space. The intent is to generalize a design principle that can utilize the luminance contrast to enrich the spatial experience of an architectural space.

Fig. 5: View upon entering the St. Ignatius Chapel.

Fig. 6: View upon entering the AGO Art Gallery.

Fig. 7: Sequential scenes while approaching the sculpture at the AGO Art Gallery.

3 EXPERIMENTS

The experiments were conducted in a computer-generated environment. This alternative environment allows a precise parametric control of daylight, which changes constantly, and the flexibility to manipulate the architectural configuration to create different scene luminance contrasts. The experimental scenes were simulated by physically based lighting simulation program RADIANCE, and the output was in a high dynamic range (HDR) image format [13]. The HDR scenes were tone-mapped by a perceptually based photographic tone-mapping operator [9] to be displayed on a common display device. The visual realism of the final image in terms of studying the depth perception in relation to the lighting has been established in a previous study [10].

Figure 8 illustrates the architectural configuration set up of the experimental scenes. The hallway is comprised of four 6 m × 6 m × 4 m modules. The camera is set at a height of 1.6 m and it focuses on the center of the visual target. The visual target is a sphere with a radius of 30 cm, which floats 1.3 m above the ground. The initial position of the visual target is located at a distance of 15 m from the camera. Each module has a 2 m × 2 m skylight in the middle of the top ceiling. As illustrated in figure 9, the skylight can be open, half closed, or closed to admit different amounts of daylight into the space.

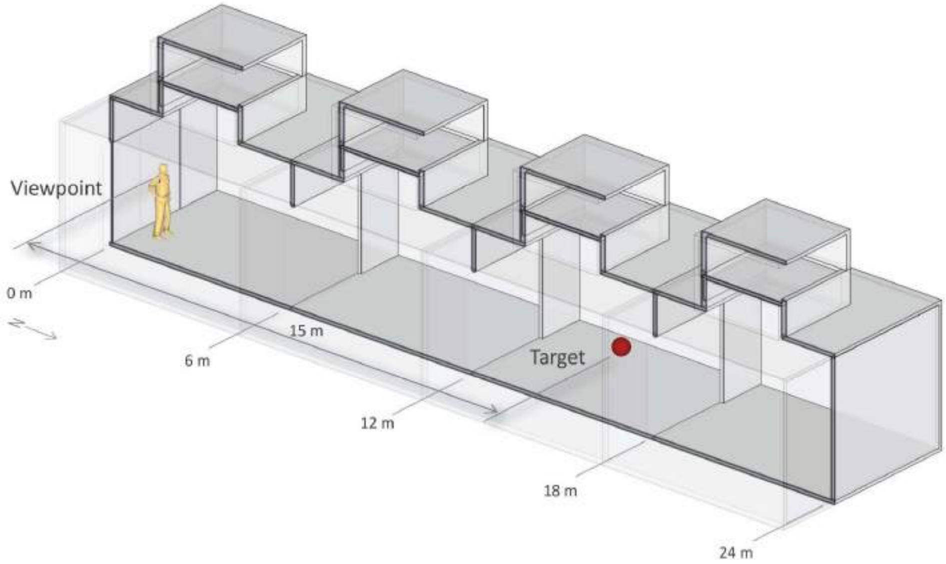


Fig. 8: The architectural configurations of the experimental scenes.

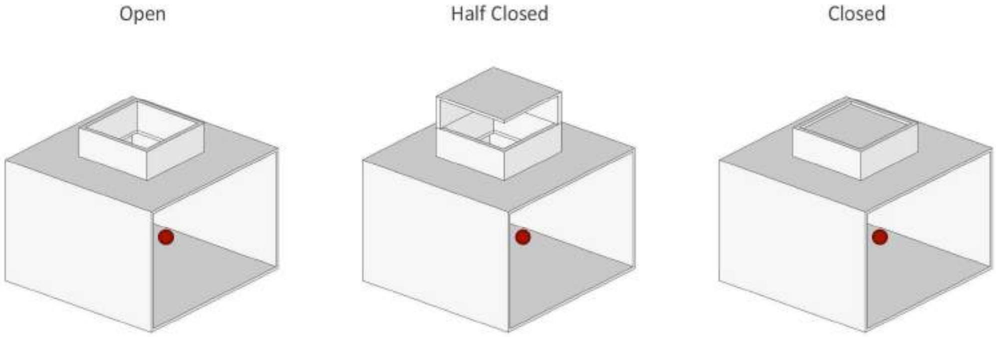
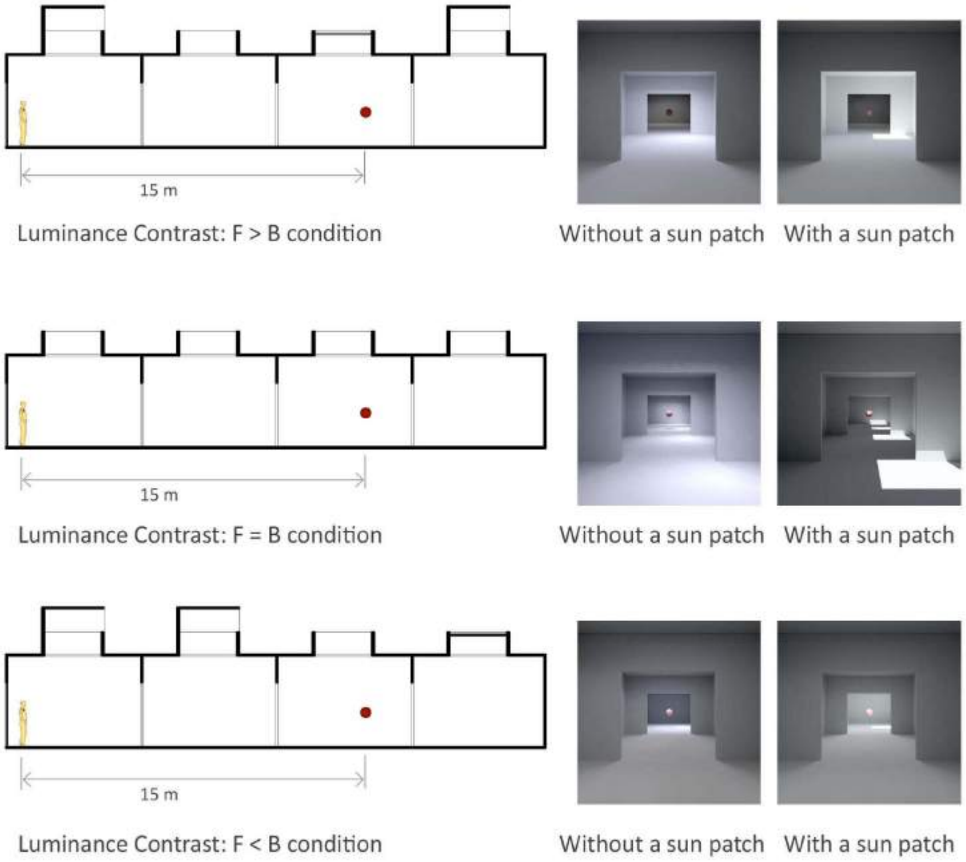


Fig. 9: Control of the skylight to create different scene luminance contrasts.

Figure 10 illustrates the test scenes in which the visual target is located 15 m away. The four skylights are controlled in different ways to create three conditions: luminance contrast between the visual target and the foreground is greater than (F > B), equal to (F = B), and lower than (F < B) the background. The rendering parameters such as the surface materials, location, date and time, and options of output quality were all kept constant in RADIANCE. The three skylight configurations were simulated under the same CIE sky models, defined by the International Commission on Illumination (Commission Internationale de l'Éclairage), located at latitude 25.1° and longitude 121.6°, with and without a sun patch to create two sets of test scenes.



Luminance Contrast: F > B condition
Without a sun patch
With a sun patch

Luminance Contrast: F = B condition
Without a sun patch
With a sun patch

Luminance Contrast: F < B condition
Without a sun patch
With a sun patch

Fig. 10: Test scenes.

Figure 11 illustrates a series of comparison scenes with the visual target located at varying distances, 12, 13, 14, 15, 16, 17, and 18 m, from the viewpoint under the same CIE sky model, without a sun patch. The skylights were all open to equalize the luminance contrast of the visual target between the foreground and the background.

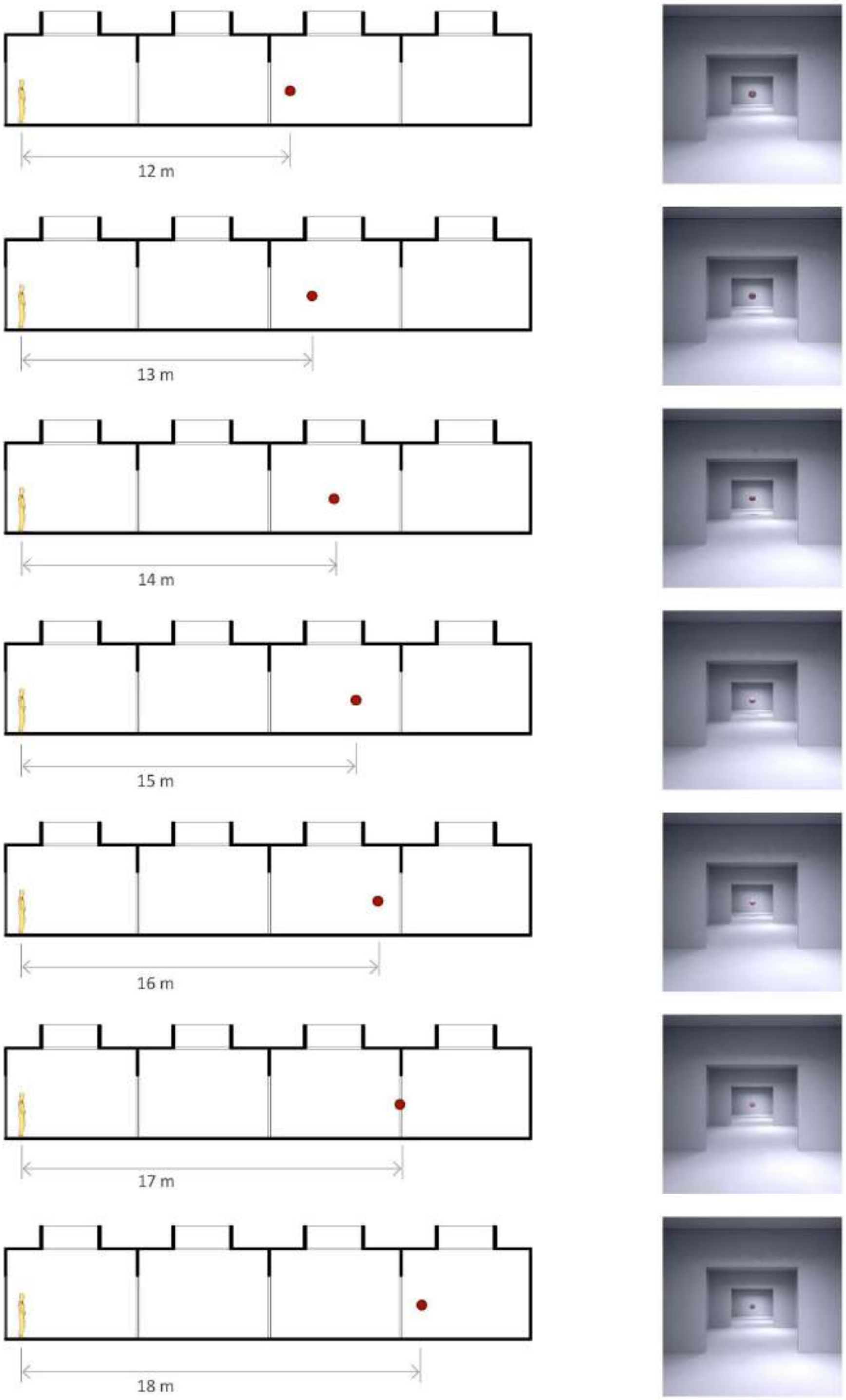


Fig. 11: Comparison scenes with the visual target located at a distance of 12, 13, 14, 15, 16, 17, and 18 m from the viewpoint.

The Method of Constant of Stimuli was used to measure the perceived distance of the visual target under different lighting conditions [4]. As illustrated in figure 12, the test scene was presented with a comparison scene simultaneously to a subject. The subject was required to report which target was perceived to be closer. Test scenes of different conditions were presented with 7 different comparison scenes 10 times in a random order. Each subject needed to make a total of 420 perceptual judgments. The concept of this method was to determine when the visual target was perceived to be equal in depth with the comparison target, and the actual location of the comparison target could be considered as the measured perceived distance for the test target.

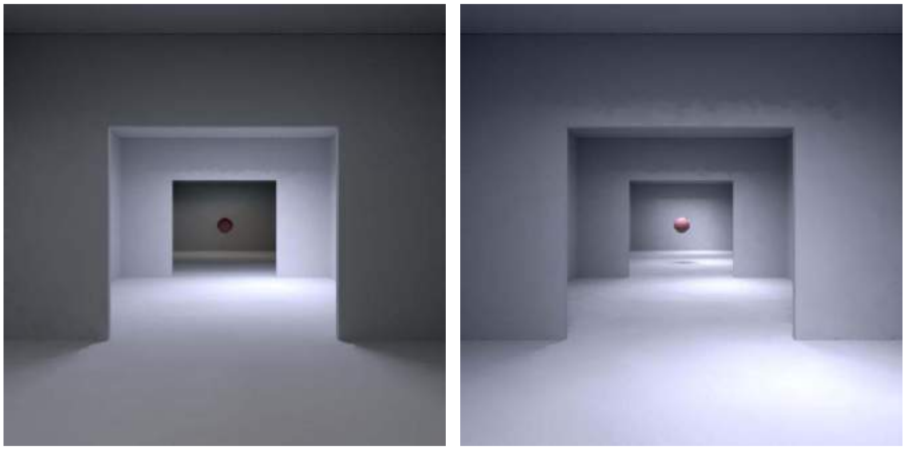


Fig. 12: An example of a test scene and one of the 7 comparison scenes presented in the experiment.

Eight subjects participated in this study. The subjects were between 20 and 38 years old, with normal or corrected to normal vision. The subjects were asked to sit in a dark room and view the image of the experimental scenes on a computer display at a comfortable angle and distance. The subjects were asked to make quick judgments of which visual target appeared to be closer. The subjects' responses were recorded as the number of times the visual target in the test scene was reported to be closer. The subjects first made judgments for the test scene set without a sun patch, and then repeated the same process for the test scene set with a sun patch.

Figure 13 illustrates the outcome of the Probit analysis of the experimental results of the three test scenes simulated with the CIE sky model without a sun patch. The y-axis represents the percentage of the visual target in the test scene when it is reported to be closer. The x-axis represents the actual locations of the comparison visual target. The intersection point of the 0.5 proportion line with the Probit regression curve is the point of subjective equality (PSE) [3], which represents the situation in which the two visual targets, from test and comparison scenes, are perceived to be equal in distance. As the visual target in the test scene is fixed at a distance of 15 m, the PSE is considered as its measured perceived distance under a uniform luminance condition. In figure 13, when the luminance contrast in the foreground equals the luminance contrast in the background (F = B condition), as in the comparison scenes, the PSE is 14.813 ± 0.079. When the background luminance is lower (F > B condition), the PSE increases to 16.192 ± 0.065. When the background luminance is greater (F < B condition), the PSE decreases to 14.469 ± 0.086. Figure 14 illustrates the Probit analysis of the experimental data of the test scenes simulated with the CIE sky model with a sun patch. The PSE is 14.796 ± 0.075, 15.678 ± 0.078, and 14.195 ± 0.088, respectively, for F = B, F > B, and F < B conditions.

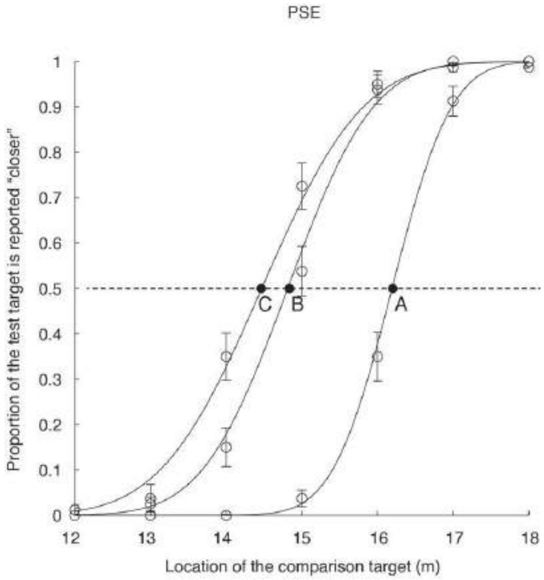


Fig. 13: Probit analysis for the CIE sky model without a sun patch, A is the PSE for the F > B condition, B is the PSE for the F = B condition, and C is the PSE for the F < B condition.

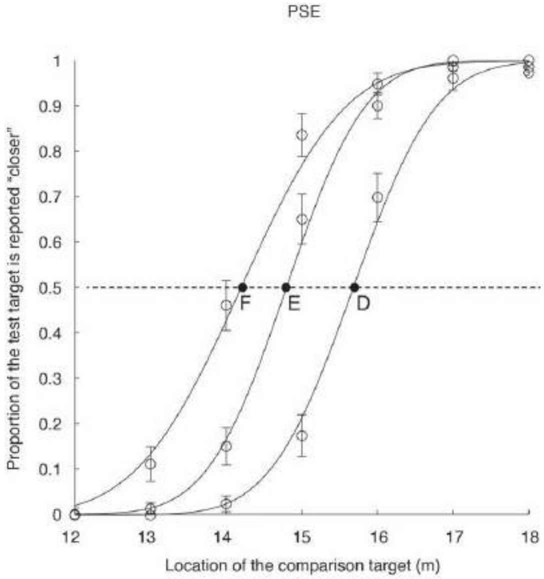


Fig. 14: Probit analysis for the CIE sky model with a sun patch, D is the PSE for the F > B condition, E is the PSE for the F = B condition, and F is the PSE for the F < B condition.

4 DISCUSSIONS

Two main questions asked in this perceptual study are, how can the luminance contrast be controlled through architectural configurations so that the spatial perception of a visual target in an architectural space changes, and whether the presence of a sun patch would affect the effect. The experimental results demonstrate that under different sky conditions, the luminance contrast of a scene, which is determined by the physical configuration, does affect the depth perception of the visual target in space. When the luminance contrast of the visual target was lower in the background as compared to the foreground, the perceived distance of the visual targets increased from 15 m to

15.678 m and 16.192 m respectively for sky conditions with and without the sun patch. Conversely, when the background luminance contrast was greater, the perceived distance decreased to 14.195 m with the sun patch and to 14.469 m without the sun patch.

The comparison scenes were simulated under sky conditions without a sun patch. The four skylights were kept open to ensure a uniform luminance contrast between the foreground and the background. In the six different test scenes, the F = B condition (without a sun patch) had an identical luminance distribution to the comparison scenes, and the perceived distance of the visual target (15 m away) was measured to be 14.813 m. However, when the sun patch was present, the luminance distribution was more complex due to the incoming sun angle, and the measured perceived distance of the visual target in the F = B condition remained close to 15 m and was 14.796 m. The measured perceived distance decreased significantly in both the F > B and F < B conditions with the sun patch compared to the same conditions without the sun patch.

Table 1 compares the measured perceived distances of the visual target in the F > B and F < B conditions against the measured perceived distance in the F = B condition, with and without application of the sun patch. The result given in the table demonstrates that when the luminance contrast against the background was lower, the perceived distance increased by 6% and 9.3% for sky conditions with and without the sun patch, respectively. Similarly, the perceived distance decreased by 4% and 2.3% with and without the sun patch, respectively, when the luminance contrast against the background was higher. It is thus concluded that lowering the luminance contrast against the background can effectively increase the perceived distance of the visual target in a space, and the effect is more pronounced when direct sunlight is avoided.

Luminance Contrast	F = B	F > B	F < B
Perceived distance of the visual target 15 m away under the CIE sky model without a sun patch	14.813 ± 0.079 m	16.192 ± 0.065 m	14.469 ± 0.086 m
% increase		9.3%	-2.3%
Perceived distance of the visual target 15 m away under the CIE sky model with a sun patch	14.796 ± 0.075 m	15.678 ± 0.078 m	14.195 ± 0.088 m
% increase		6.0%	-4.0%

Tab. 1: Comparisons of the relative perceived distances.

5 CONCLUSION

The light sources that can manipulate the luminance distribution within an architectural scene include daylight and artificial light. Instead of artificial light, the daylight was employed in this study for two reasons: one, as the daylight changes throughout the day, time, and sky conditions, it allows more dynamic scene luminance distribution and the resulting spatial experience; and two, introducing daylight into an architectural space requires a formal and structural configuration that is often determined in the early design process.

The objective of this study is to generalize a set of initial principles to configure the physical configuration to introduce daylight that renders the scene luminance contrast to enrich the spatial experience. Although the architectural configuration examined in this study is limited, the perceptual studies do demonstrate that by manipulating the physical configuration of skylights, one can control the daylight that is admitted inside to create the desired luminance contrast for the composed architectural scene. Because the study used a visual target in a space to measure the effect of the luminance contrast on depth perception, the general principle of utilizing luminance contrast as a design parameter is limited to the setting that has a visual target in a scene. The initial general principle utilizing the luminance contrast and a visual target to enrich the spatial experience of an architectural space can be concluded as below:

- Arrange a visual target to be in the center of a scene to direct the visual attention.
- To increase the depth perception of the visual target in a scene, configure the physical structure to manipulate the luminance contrast between the visual target and its background to be lower than the foreground.
- To ensure the effect, use diffused daylight to avoid a sharp shadow that results from direct sun light.

AKNOWLEDGEMENTS

This research was funded by the National Science Council in Taiwan, under the grant No: NSC 100-2218-E-032-002-. The author thanks the National Science Council for their support. The author also thanks the people who participated in the experiments and contributed to this study.

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