



## Luminance Contrast as Depth Cue: Investigation and Design Applications

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### ABSTRACT

It is known that contrast can be an effective depth cue on planar displays. However, previous studies do not provide enough information on the impact of luminance contrast and luminance distribution patterns on perceived distances in three-dimensional built spaces. This research investigates the role of luminance contrast and luminance distribution patterns on space perception of three-dimensional layouts. Three experiments were conducted to study the impact of the following parameters on depth perception: 1) investigation of different lighting apertures, 2) lighting distribution patterns, and 3) luminance contrast as a depth cue. It is concluded that the luminance contrast of a target against its surround is an effective depth cue that can increase or decrease the perceived distance of a visual target in a built space. The application of this depth cue is demonstrated through an architectural design example.

**Keywords:** depth cue, luminance contrast, high dynamic range imagery.

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### 1 INTRODUCTION

Pictorial depth cues can be categorized as size-related and tone-related. Size-related cues (such as relative size, familiar size, linear perspective, and texture gradient) are identified by sharp luminance variations along the boundaries of objects (i.e., edge detection). Since edge detection is relatively simple and abstract visual information, reproduction of such cues does not require high levels of visual realism. Effects of various size-related pictorial cues on space perception in physical environments have been thus studied and well understood using psychophysics over the past 50 years. Although most studies investigated the contribution of a particular pictorial cue on gauging correct dimensions, some studies reveal an ability to manipulate the pictorial cue to exaggerate or diminish the perceived distances.

Blessing et al. [1] utilized false perspective to investigate the relationship between perceived size and perceived distance. Sinai et al. [21] demonstrated the influence of terrain on accurate judgment of distance and concluded that the presence of texture gradient influences the judgment of the perceived distance. Galleria Spada, designed by Francesco Borromini (1653), is an interesting early example in a built environment that demonstrates the application of above size-related depth cues to enhance the spatial experience. From the entrance point of view, a false linear perspective is laid out to exaggerate the perceived distance of the hallway. The height and size of each column as well as the spacing between them are decreased gradually toward the end of the hallway. Along with the distorted patterns of ceilings and tiles, the sense of depth is greatly amplified.

Tone-related cues are inferred from luminance distributions in a scene. Shading and atmospheric perspective are two of the pictorial depth cues that relate to tonal values. The rendering technique *Chiaroscuro* was used by Renaissance painters to create the contrast of light and shadow on canvas. However, this technique was mainly used to describe the 3D shape and form of objects, rather than to cue the overall spatial depth. Atmospheric perspective refers to distant objects that tend to appear more muted than closer objects. This pictorial cue can be observed in natural scenes and has been widely used in paintings to enhance the illustration of great depth. It has also been promoted in a study of depth effect of luminance contrast where Oñeña et al. [15] attribute the pictorial depth information provided by luminance contrast to the pictorial cue of atmospheric perspective. Palmer et al. [16] utilize the contrast cue to enhance 2D displays of air traffic control. However, both the investigation [by Oñeña et al. 1994] and the application [by Palmer et al. 2008] of contrast pictorial cue studies use abstract 2D presentation techniques and do not adequately address the complexities of lighting distributions in 3D built environments. Tai and Inanici [22] investigated this effect in a 3D context and concluded that lighting distributions can affect the perceptual judgment of a visual target's perceived distance. However, lighting distributions in a scene determine the lighting patterns in the environment as well as the luminance contrast between the visual target and its background. In this study, computational methods were employed to individually analyze the lighting patterns and the luminance contrast; and particular contributions from each component were investigated through psychophysical experiments.

## 2 METHODOLOGY

Lighting in architectural spaces is dynamic in character. Temporal dynamics in daylighting is attributed to the movement of the sun and the changing sky conditions. Such variations present challenges to conduct parametric psychophysical studies in daylight scenes. Computational approaches allow stability for parametric control (i.e., enable a fixed daylight scene during experimentation) that is otherwise impossible to achieve in physical experimental scenes.

### 2.1 Image Generation and Display

Physically based rendering uses mathematical models to simulate the complex physical processes to generate digital images that mimic the physical world with reasonable accuracy. The RADIANCE Lighting Simulation and Rendering System [24] [25] is a physically based rendering tool that has been validated with quantitative studies [14].

The High Dynamic Range (HDR) pixel values output by the RADIANCE rendering system correspond to the physical quantity of luminance [25]. However, computational accuracy does not guarantee a visual display of the real-world scene. Limited dynamic range, spatial resolution, and color gamut of the display devices are technical limitations that restrict a displayed image for psychophysical experiments. The total human visual range from starlight to sunlight is 14 logarithmic

units, and span 4 logarithmic units at once. The conventional display devices limit the luminance range to a dynamic range of only 2 logarithmic units [18], and thus, it is not possible to display the full range of luminance values contained in HDR images.

Perception based tone-mapping algorithms have been developed to compress HDR images into a display range such that they depict faithful visual appearances of scenes. It is beyond the purpose of this paper to provide a complete survey of the available tone-mapping algorithms. However, it was necessary to identify an appropriate tone-mapping algorithm that can compress HDR data into the display range while preserving the overall contrast and the detail visibility. Previous studies have compared various tone-mapping operators with each other [6], with HDR images displayed on an HDR display device [13], and with real scenes [4] [11] [27]. Although those studies cannot conclude a single operator that performs the best for all types of scenes, the Photographic tone-mapping operator [19] has been identified as a viable solution as it can consistently provide good results in those perceptual studies. In this respect, it is important to note that we are using physically based lighting simulation software to start with physically accurate quantitative data (which is not possible to display in any display device in absolute photometric units) and use this data to derive a perceptually based image display.

The RADIANCE Lighting Simulation and Rendering System was used to simulate experimental scenes for investigating visual perception of lightness [3] [8], color [2] [5] [26], shape [9] [12], and depth [22] [23]. The accuracy and appropriateness of using RADIANCE to generate experimental scenes for perceptual studies have been previously demonstrated by Ruppertsberg and Bloj [20], and it was concluded that there is no other rendering package that can provide better physical realism than RADIANCE.

The experimental scenes used in this study are generated by RADIANCE and tone-mapped by Photographic tone-mapping operator. Since this research provides an insight into the impact of luminance contrast on perceived distance, it is important that the employed tone mapping procedure does not alter the contrast ratios between the target and its background in a way that would impact the results (when the physically based HDR images are compressed into displayable ranges). The luminance contrast of the HDR scenes and the tone-mapped images is found to be consistent in the studied scenes ( $r^2 = 0.95$ ).

## 2.2 Experiment Setup

The geometry comprises an elongated space (20m by 70m by 10m) that is divided into two equal hallways (Fig. 1). The images are generated as the observer is facing the front end. The rear end behind the observer is open and allows daylight to enter the interior space. The two hallways are surrounded by walls on three sides, and additional daylight from side lighting or top lighting is incorporated when different architectural configurations were tested in the experiment. Wall, floor, and ceiling materials have diffuse reflectivities of 65%, 55%, and 70%, respectively. The camera viewpoint is set at a normal eye level toward the center of the elongated space. An identical floating luminous disk (12m in radius) is located at the perceived center of each hallway as a visual target. The disk emits an equal energy white light of 200 cd/m<sup>2</sup>. One of the hallways serves as a test scene while the other is the reference. Surface materials and disk luminance were kept constant for all the rendered scenes.

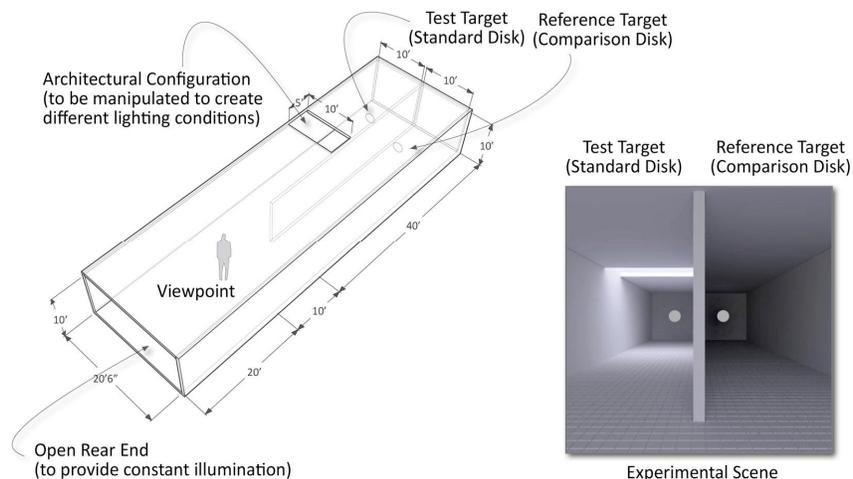


Fig. 1: Generic experiment setup.

The experiments were carried out with two major groups of variables: the relative distance between the two identical disks and the different lighting conditions between the left and right hallways introduced by the manipulated architectural configurations of skylight or a window. For each particular condition, different configurations of disk locations between the test target (standard disk) and the reference target (comparison disk) were rendered (Fig. 2).

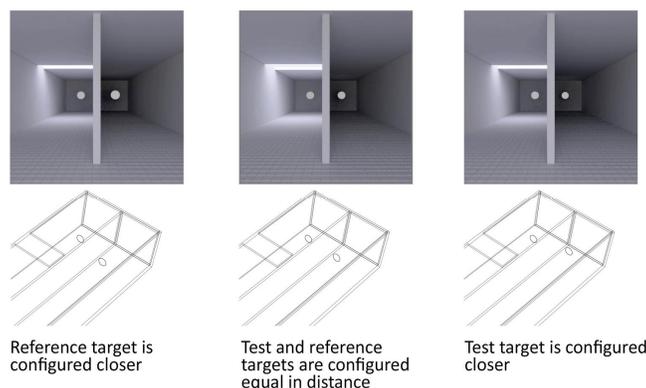


Fig. 2: Scenes with different configuration of visual targets under the same lighting condition.

The method of constant stimuli was utilized to measure the perceived distance of the test target. The standard stimulus (test scene) and comparison stimulus (reference scene) were presented to subjects simultaneously. Subjects were asked to report the visual target that appeared to be closer. The design of the binary responses allows intuitive responses from subjects, and the data can be analyzed using probit regression models [7] to derive psychometric functions, as illustrated in Fig. 3. The intersection point of the 0.5 line and the regression curve is the point of subjective equality (PSE). It represents when the value of the comparison stimulus is subjectively perceived to be equal to the standard stimulus [10].

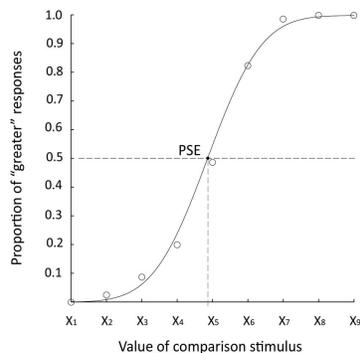


Fig. 3: A typical psychometric function fitted with a probit regression curve.

### 3 EXPERIMENTS

A series of psychophysical experiments were conducted to examine the interrelationship of the architectural configuration, scene-based lighting distribution patterns, and the depth perception of space. By comparing the subjects' reports with the actual configuration of targets' locations under different lighting conditions, the effect of lighting distribution patterns on depth perception are studied. In the first experiment, the effect of the different lighting apertures on depth perception is compared. In the second experiment, different luminance distribution patterns resulting from different configurations of skylight are investigated. In the third experiment, the impact of luminance distribution patterns and luminance contrast are separated using image-editing capabilities of a computational tool. The individual contributions of the luminance patterns and luminance contrast on space perception are studied.

#### 3.1 Experiment 1: Investigation of Different Lighting Apertures

There are two objectives in the first experiment. The first is to investigate whether the position of the lighting aperture impacts the perception of depth. As the window and skylight are the two common strategies to introduce daylight into architectural space, three experimental setups were tested: in "no skylight" condition, the scene is illuminated by daylight admitted from the open rear end; in "skylight at left" condition, an additional 5m x 10m skylight is installed 24m away from the viewpoint on the left hallway; and in "window at left" condition, a 5m x 10m window was installed 24m away from the viewpoint replacing the skylight. Fig. 4 illustrates these three conditions. It is important to note that a vertical glazing (window) provides different luminance distributions compared to a horizontal glazing (skylight) as the incidence angle of the solar rays change considerably between these two orientations.

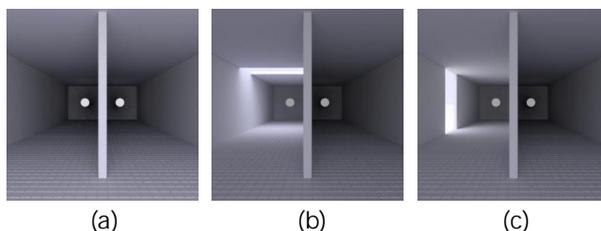


Fig. 4: Scenes with left and right disks configured at same locations under different lighting conditions for experiment 1: (a) "no skylight" condition, (b) "skylight at left" condition, and (c) "window at left" condition.

The second objective of this experiment is to quantify the effect of the luminance distribution patterns on perceived spatial depth. The left disk is referred to as the standard disk and its location is fixated at 40 ft away from the viewpoint. The location of the right disk is varied to 36 ft, 37 ft, 38 ft, 39 ft, 40 ft, 41 ft, 42 ft, 43 ft, and 44 ft away from the viewpoint to generate nine different scenes. The right disk is referred to as the comparison disk. The nine different configurations 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 the lighting effect to appear always on the left hallway, scenes were flipped horizontally to create another set of mirrored images.

The HDR scenes were rendered with a resolution of 700 by 700 dpi and tone-mapped with Photographic tone-mapping operator. Each image was presented five times to each subject in a random order (each combination of the locations of the standard and comparison disks was thus presented 10 times in total per lighting condition). Eight subjects participated in this study. Subjects were aged between 21 and 36, with normal or corrected-to-normal vision. The number of times that the standard disk is reported closer was recorded from each subject.

### 3.1.1 Results and Analysis

The results of probit analysis illustrated in Fig. 5 demonstrate that when additional lighting pattern is presented, the perceived distance of the standard disk increases by about 4%. In the "no skylight" condition, the two disks were reported to be perceived equal in depth when they were actually about the same distance away ( $PSE = 40.14 \pm 0.09$ ). In "skylight at left" condition, the PSE is measured as  $41.81 \pm 0.11$  and the perceived distance of the standard disk increased by 4.5%. In the "window at left" condition, the PSE was measured as  $41.66 \pm 0.11$ , so the perceived distance of the standard disk increased by 4.2%. As the difference in the PSE between the "skylight at left" and "window at left" conditions is insignificant, the results suggest that the orientation of lighting apertures in this architectural setting has minimal impact on depth perception.

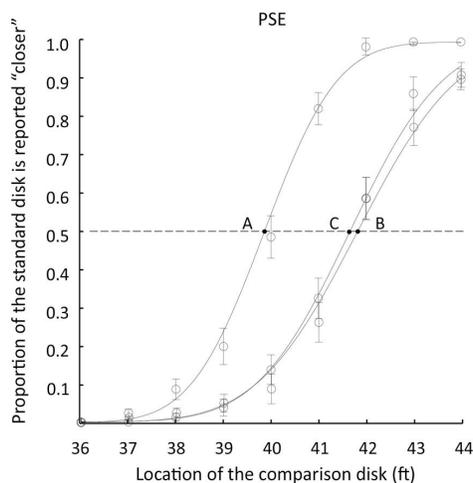


Fig. 5: Probit analysis for experiment 1: A is PSE with "no skylight" condition, B is PSE with "skylight at left" condition, and C is PSE with "window at left" condition.

### 3.2 Experiment 2: Lighting Distribution Patterns as a Depth Cue

A sky condition with sun patches not only increases the overall dynamic range of the scene but also introduces sharp lighting patches that can be used to cue the distance. The objective of the second experiment is to further investigate the impact of the different patterns of lighting distribution on depth perception. The 3D structure of the generic experiment setup was manipulated to create repetitive lighting patches (Fig. 6). Three different configurations of single skylight, two skylights, and three skylights were rendered with two different sky conditions of intermediate sky with and without sun patches. A total of six different scenarios were generated: single skylight (1sky), single skylight with sun patches (1skyS), two skylights (2sky), two skylights with sun patches (2skyS), three skylights (3sky), and three skylights with sun patches (3skyS). The location of the left disk remained fixed at 40° away from the viewpoint, and the location of the right disk is varied to 34°, 36°, 38°, 40°, 42°, 44°, and 46°. A total of 42 scenes were rendered, and a mirrored set was created. Each of the seven combinations of disk locations of standard and reference disks under different lighting condition was presented to a subject 10 times in a random order. A different group of eight subjects participated in the experiments. Subjects were aged between 21 and 36 with normal or corrected-to-normal vision. The number of times that the standard disk is reported closer was recorded from each subject under each condition.

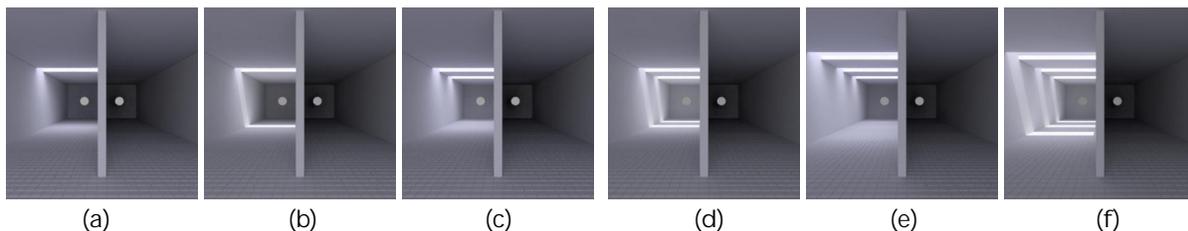


Fig. 6: Scenes with left and right disks configured at the same locations under different lighting conditions for experiment 2: (a) single skylight, (b) single skylight with sun patches, (c) two skylights, (d) two skylights with sun patches, (e) three skylights, and (f) three skylights with sun patches.

#### 3.2.1 Results and Analysis

The experiment results are illustrated in Fig. 7. The results of probit regression analysis demonstrate that the PSE for conditions 1sky, 1skyS, 2sky, 2skyS, 3sky, and 3skyS all shifted to the right and the perceived distance of the standard disk increased from 40 feet to  $41.43 \pm 0.13$ ,  $42.15 \pm 0.14$ ,  $42.44 \pm 0.13$ ,  $43.38 \pm 0.17$ ,  $42.45 \pm 0.16$ , and  $43.11 \pm 0.14$  feet, respectively.

Fig. 8(a) illustrates the relationship between the number of skylights and the PSE. In three conditions under the intermediate sky without sun patches, the PSE increases as the number of skylights increases. However, the increase of PSE from one skylight to two skylights is much greater than that from two skylights to three skylights. In the intermediate sky with sun patches, the PSE increases significantly from one skylight to two skylights but slightly decreases from two skylights to three skylights. Fig. 8(b) presents the luminance contrast of the left disk and its background as well as the contrast ratio between the left disk and the right disk for three skylight configurations. Both the left luminance contrast and the contrast ratio decrease significantly from the one skylight configuration to two skylights; however, the numerical change is relatively low when the two skylights configuration is modified to three skylights. The experiment is interpreted such that the impact of the number of skylights on depth perception depends upon on the resultant luminance contrast between the target and its background.

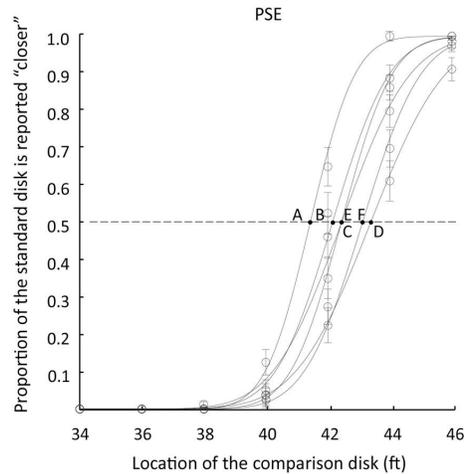


Fig. 7: Probit analysis for experiment 2: A is PSE with [single skylight] condition, B is PSE with [single skylight with sun patches] condition, C is PSE with [two skylights] condition, D is PSE with [two skylights with sun patches] condition, E is PSE with [three skylights] condition, and F is PSE with [three skylights with sun patches] condition.

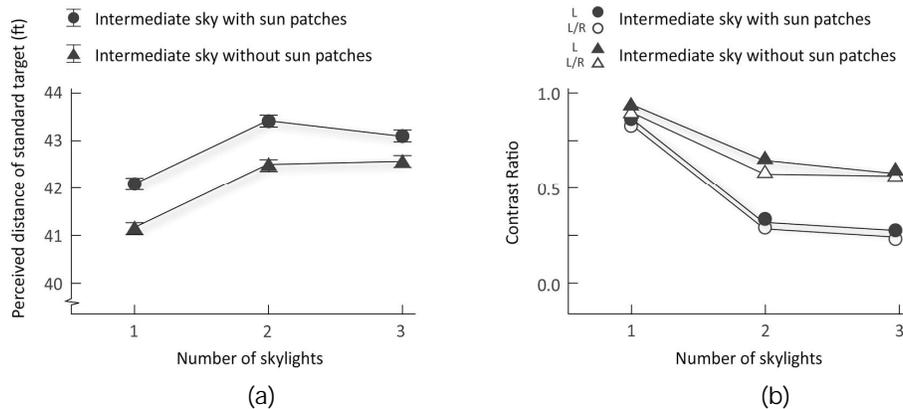


Fig. 8: (a) PSE with different skylight configurations, and (b) Contrast ratio with different skylight configurations.

### 3.3 Experiment 3: Luminance Contrast as a Depth Cue

The luminance distribution in a scene determines the lighting patterns in the environment and the luminance contrast between the target and its background. However, the results from the first two experiments do not clarify the individual contributions from each component on depth perception. The objective of the third experiment is to study the particular effect of lighting patterns and luminance contrast on the perception of spatial depth.

Image editing methods were used to isolate the lighting patterns and the luminance contrast. The rendered scenes of single skylight (1sky), single skylight with sun patches (1skyS), and three skylights with sun patches (3skyS) from the second experiment are adopted and edited by an image processing program to create six different setups (Fig. 9). In Fig. 9(a), (b), and (c), the square portion of the target and the back wall from the left hallway are edited to equalize the luminance contrast of the target and its background between the left and the right hallways, leaving the lighting patterns in the

environment as the only variable in this set. In Fig. 9(d), (e), and (f), the presence of the skylight and its resulting lighting patterns were removed, allowing the luminance contrast between the disk and its background as the only variable in this set. Different group of eight subjects with normal or corrected-to-normal vision, aged between 21 and 36, participated in the experiments. The procedure and data recording of the experiment remains the same.

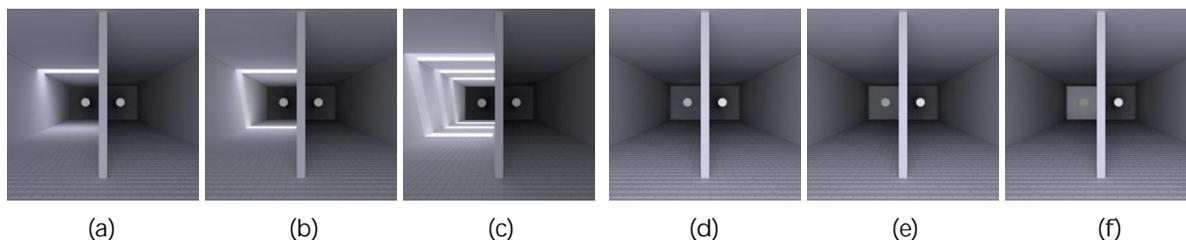


Fig. 9: Experimental scenes with left and right disks configured at the same locations under different conditions for experiment 3: (a) Single skylight with lighting patterns variable, (b) Single skylight with sun patches and lighting patterns variable, (c) Three skylights with sun patches and lighting patterns variable, (d) Single skylight with contrast variable, (e) Single skylight with sun patches and contrast variable, and (f) Three skylights with sun patches and contrast variable.

### 3.3.1 Results and Analysis

The experiment results are illustrated in Fig. 10. For setups that investigate the effect of lighting distribution patterns, the PSE values shifted slightly to the right. The perceived distance of the standard disk was increased from 40 feet to  $40.44 \pm 0.15$ ,  $40.55 \pm 0.15$ , and  $40.32 \pm 0.16$  feet for single skylight, single skylight with sun patches, and three skylights with sun patches, respectively. For setups that investigate the luminance contrast, the PSE results were shifted significantly to the right and the perceived distance of the standard disk was increased from 40 feet to  $42.55 \pm 0.15$ ,  $42.93 \pm 0.17$ , and  $44.28 \pm 0.17$  feet for single skylight, single skylight with sun patches, and three skylights with sun patches, respectively.

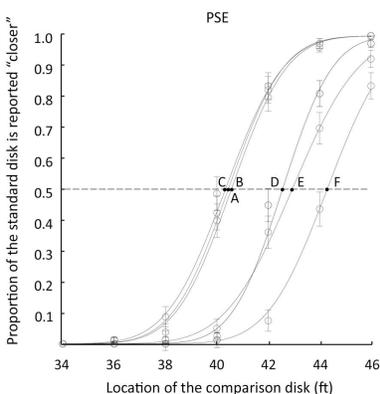


Fig. 10: Probit analysis for experiment 3: A is PSE with [single skylight with lighting patterns variable] condition, B is PSE with [single skylight with sun patches and lighting patterns variable] condition, C is PSE with [three skylights with sun patches and lighting patterns variable] condition, D is PSE with [single skylight with contrast variable] condition, E is PSE with [single skylight with sun patches and contrast variable] condition, and F is PSE with [three skylights with sun patches and contrast variable] condition.

contrast variable condition, and F is PSE with three skylights with sun patches and contrast variable condition.

#### 4 DISCUSSION

Size-related pictorial cues are kept identical between the two hallways in each experiment scene under different lighting conditions with the exception of the distance of the two visual targets. The subjects are instructed that the actual sizes of the visual targets are the same. The perceived size of the visual targets thus indicates their perceived distance. The direct comparison between the left and right visual targets allows subjects to make quick and intuitive judgments and reveal the impact of the additional lighting distributions on the perceptual judgment of depth.

The results from the no skylight condition in the first experiment demonstrate that size cues provide enough contextual information for subjects to correctly judge the perceived distances of the visual targets. Results from conditions with additional lighting distribution consistently demonstrate that subjects overestimate the distance of visual targets. Results of the third experiment further demonstrate that effect is mainly caused by the luminance contrast between the visual target and its immediate background. This effect is illustrated in Fig. 11. The lower the contrast between the visual target and background, the farther it appears to be.

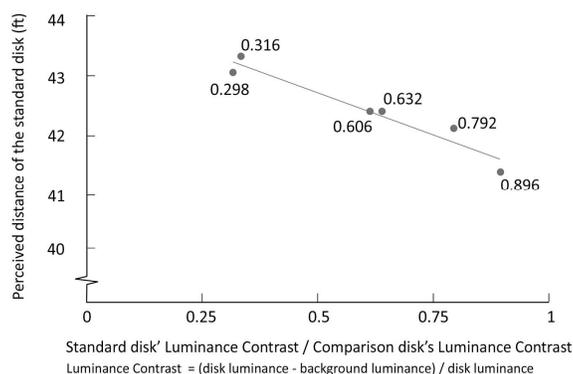


Fig. 11: Luminance contrast ratio and perceived distance (Experiment 2).

Studies on space perception are often concerned with how human visual systems can correctly perceive objects' locations in a three-dimensional layout. It is generally agreed that it is the integration of multiple cues to allow our visual system to accurately interpret depth [17]. This is also true for depth perception in a pictorial space as many pictorial cues, particularly the size-related pictorial cues, are interrelated such that they cannot be distinguished from one another. However, tone-related pictorial cues, such as atmospheric perspective and luminance contrast, can work independently from size-related pictorial cues to affect perceived distances. Fig. 12 illustrates the study conducted by O'Keefe et al. [15] to investigate the competing effects between the pictorial cues of size and luminance contrast. The luminance values of the dark and light squares are kept constant throughout the experiment. The background luminance values were varied to create three conditions. In the lighter background, the contrast ratio of the darker square and its background is higher than the ratio of the lighter square and its background; in the Mid condition, they are equal; and in the darker background, the situation is vice versa. Throughout the experiment, the size of the lighter square remained the same but the size of the darker square was varied from trial to trial.

The solid line in Fig. 12 illustrates the result for the **Mid** condition. The two squares displayed on the computer monitor are equal in depth to the observer. The probability of **the dark square being reported closer** increases as its size increases. A similar trend can be observed in the results for both light and dark backgrounds represented by the dotted line and dashed line, respectively, in Fig. 12. However, the fact that the dotted line of the light background condition shifted up and the dashed line of the darker background shifted down indicates that high contrasts between the dark square and its background increase the probability of it being reported closer, while lower contrasts decrease this probability. Therefore, the pictorial cue of luminance contrast is an effective cue that can increase or decrease the depth cue introduced by size perspective.

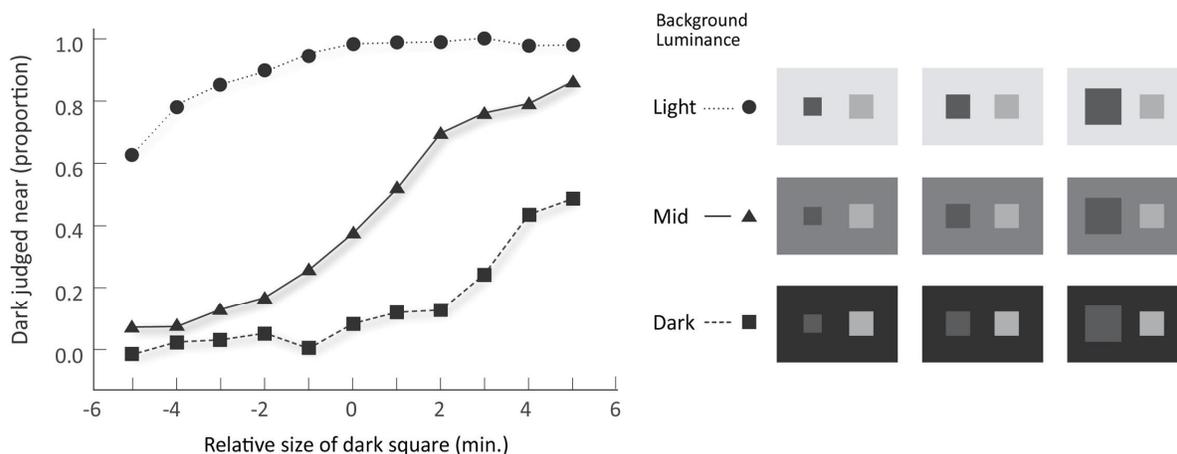


Fig. 12: Experiment results from Ono, Blackburn, and Ono experiment on the competing effects of the pictorial cues of size and luminance contrast. (Reproduce after Ono et al. [15]).

Comparisons between the visual targets measured perceived distances of the **single skylight**, **single skylight with sun patches**, and **three skylights with sun patch** conditions in the second experiment and the same conditions with the lighting patterns removed in the third experiment further attest to the competing effects of size and contrast cues in a 3D environment (Fig. 13). Perceived distances increased when the lighting patterns were absent, suggesting that lighting patterns allow size perspective to recover the correct spatial depth in 3D scenes and minimize the effect of the luminance contrast that exaggerates the perception of the spatial depth.

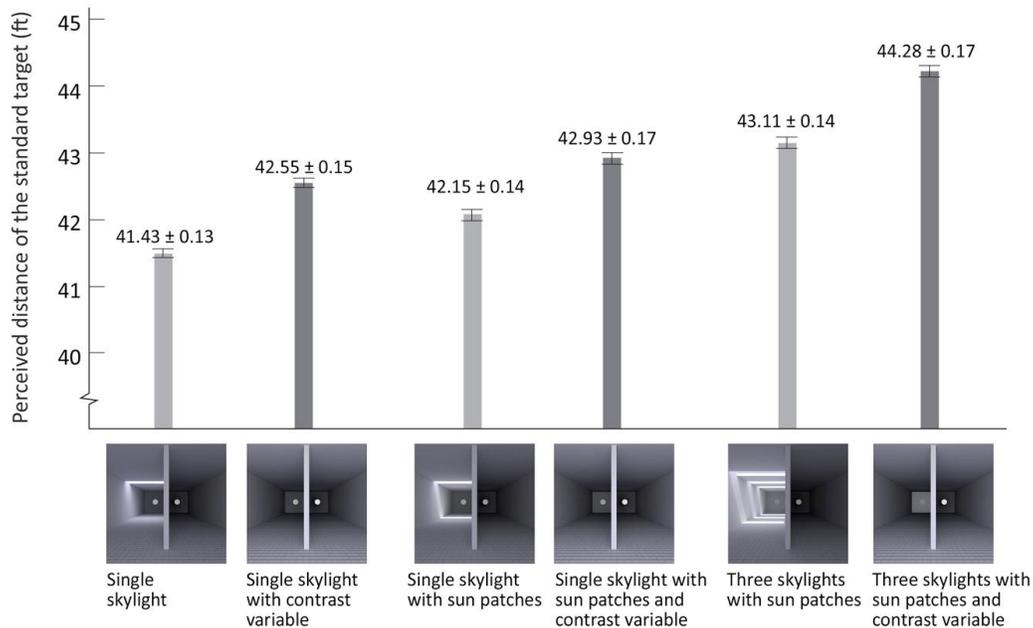


Fig. 13: Effect of lighting patterns and luminance contrast on perceived distance.

## 5 CONCLUSIONS

This study demonstrates the effect of luminance contrast on depth perception in 3D layouts. It is concluded that the pictorial cue of luminance contrast is an effective cue that can increase or decrease the spatial depth introduced by the size-related cue. Although the quantitative depth effect of luminance contrast of a target and its background is relatively small (range around 4%), the perceptual impact is significant as it allows the designers to consciously alter luminance distribution patterns over time or from one scene to another to create dynamic environments.

The size-related cues in a scene are often determined by the geometric relations within the physical configuration. Views from a particular point can be relatively static, especially when the geometrical composition of the physical structure is designed to create a particular intended effect. Luminance distributions can vary over time due to variations in daylight admittance. As a result, design strategies for daylighting can allow one scene to be perceived differently in spatial depth. Applications in architecture can be observed in the Chapel of St. Ignatius in Seattle (designed by Steven Holl, 1994-1997), which exhibits rich spatial qualities shaped by dynamic lighting variations. Fig. 14(a) illustrates the view upon entry and demonstrates the influence of luminance contrast on spatial depth. The framed tree serves as a visual target in this view and is rendered with a light and dark pattern by the side lighting that creates a sense of deepness. Fig. 14(b) and (c) demonstrate simulations of the same view under different lighting conditions. In Fig. 14(c), the side window is covered, removing the side lighting from the scene and increasing the luminance contrast between the tree and its background. As the increased contrast diminishes the perceived distance, the visual target of the framed tree in Fig. 14(c) appears to be closer than that in Fig. 14(b). On the other hand, daylighting introduced in the foreground by the side window reduces the luminance contrast between the framed tree and its immediate background in Fig. 14(b) and effectively increases the overall spatial depth.

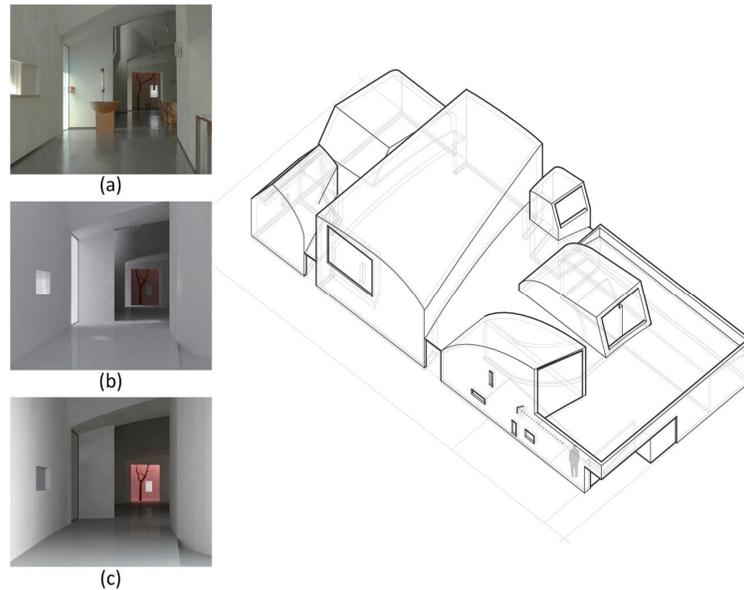


Fig. 14: Chapel of St. Ignatius: (a) entrance view, (b) computer simulation of entrance view with the window light, and (c) computer simulation of entrance view without the window light.

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