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Computational Investigation of the Effect of Luminance Contrast on Depth Perception in Physical and Simulated Scenes

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ABSTRACT

Luminance distribution of a scene results from the complex interaction of physical construction, light, and visual perception from the point of observation. Perceptual studies using computer-generated environments for accurate variable control have been conducted to perform psychophysical experiments to investigate the cause-and-effect relationship between luminance contrast and its effect on depth perception. The effect of luminance contrast on the perceived distance of a visual target in an architectural scene has been identified through perceptual studies utilizing the pictorial environment generated using the related high dynamic range (HDR) imaging digital technologies. In this study, psychophysical experiments were conducted to investigate the effect of luminance contrast on depth perception in physical and computer-simulated scenes. Experimental scenes were generated using the HDR image of a physical model, and through computer simulations of the same physical model on which image-based lighting techniques were applied in the lighting simulation program RADIANCE. The objectives of this study are to compare the effect of luminance contrast in the physical scenes to that in the computer-simulated scenes; and to verify the reliability of applying luminance contrast in architectural designs through computer-aided design processes using HDR-related technologies.

Keywords: high dynamic range imaging, luminance contrast, image-based lighting, depth perception, computer-aided design.

1. INTRODUCTION

The development of high dynamic range (HDR) imaging and its related technologies has advanced the visual realism of digital representation to physical accuracy. Both the existing and imaginary scenes can be recorded and simulated in an HDR format that encompasses the complete dynamic luminance range of the scene it represents using related technologies of HDR photography, and the lighting simulation program RADIANCE [8,12]. Perceptual-based tone-mapping techniques were developed to compress the dynamic range of HDR images to enable viewing them on a common display device's displayable range based on the light processing technique used by the visual system [8]. As a result, the visual realism of digital representation generated by HDR-related technologies has advanced from physical accuracy to perceptual realism, and it provides a possible alternative environment to conduct a perceptual study that is restricted by the physical environment.

Prior studies conducted psychophysical experiments using computer images generated by HDR-related technologies to investigate the effect of luminance distribution of a scene on depth perception [9]. The principles of using luminance contrast to enrich spatial experience in architectural design were generalized and verified using the same computational environment [10,11]. Although the visual realism of the used HDR technologies and their outputs have been previously established in terms of lighting simulation and depth perception [9], the visual realism of digital representation of experimental settings used in previous perceptual studies is yet to be verified using stimulated physical scenes. In this study, experimental scenes were generated using HDR images of the physical model, as well as the computer simulation of the same physical model with the image-based lighting technique applied through RADIANCE. There are two objectives of this study. First, to compare the effect of luminance contrast in the physical scenes with that in the computer-simulated scenes, and second, to verify the reliability of the application of luminance contrast in architectural design through the computer-aided design process using pictorial environments generated by HDR-related technologies.

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2. BACKGROUND

The core concept of the HDR image is to extend the range of values a pixel can store. The standard 24-bit images use 8 bits for each R, G, and B channels, limiting the total range from 0 to 16.7 million. The RGBE file format, which was first introduced with the physically based lighting simulation program RADIANCE, uses additional 8 bits as a shared exponent for each of the R, G, B channels, allowing a 10^{-38}–10^{38} range per pixel [8]. As a result, the HDR image that uses the RGBE format enables the digital image to store the complete range of luminance data available from a real scene.

There are two techniques to generate an HDR scene. The first is to use RADIANCE to simulate a scene that can be either real or imaginary. The second is known as HDR photography, which uses the multiple exposure images captured by a digital camera from the same scene and combines them into a single HDR image [2]. This method facilitates practical and accurate recording of the dynamic range of luminance distribution of an existing scene. Many software programs have been developed for the post processing procedure to derive the complete range of luminance data from the sequential images, each of which contains a portion of the complete luminance range. Among these software, Photosphere allows the generated HDR scene to be calibrated with the measured luminance data of the real surface by a luminance meter, thus providing a validated accuracy in terms of scene-based luminance distribution [5].

HDR photography permits the luminance distribution of an existing scene to be recorded and stored in a digital image. It can also be used to record the lighting of a real environment using a circular fisheye lens, and it provides the physical accuracy for the application of image-based lighting [8]. The hemispherical HDR image can be mapped onto Skydome through RADIANCE. As a result, the light source in the RADIANCE-simulated scene can be the captured lighting environment of the real scene. RADIANCE also allows the surface material properties to be assigned based on the optical properties measured by the spectrometer off the real surface. Along with the unbiased light transport calculation, known as Monte Carlo ray tracing, the final output obtained from RADIANCE, which uses HDR photography for image-based lighting, can generate a fairly accurate simulation of the real scene [12].

3. EXPERIMENTAL DESIGN

The HDR-related technologies of HDR photography and physically based lighting simulation using image-based lighting were used to generate the experimental scenes. Figure 1 illustrates the physical model. It comprised four 60 cm × 60 cm × 40 cm modules. Each module was composed of plywood and internally covered using gray cardboards. At the center

Fig. 1: Physical configurations to generate experimental scenes (left: *Even* condition; right: *Contrast* condition).

of each module was a 25 cm × 25 cm opening. Two interior luminance distributions of *Even* and *Contrast* were generated by controlling the four openings as all open; and as half open, open, closed, and half open, respectively. A 4-cm-diameter ping-pong ball was spray-painted red, and left hanging in the space 15 cm above the ground as a visual target. For the test scenes, the visual target was located 150 cm away from the viewpoint; both the conditions of *Even* and *Contrast* were used to generate two test scenes with different interior luminance distributions. For comparison scenes, the luminance distribution condition was controlled as *Even*; the visual target was placed at seven different locations ranging from 120 cm to 180 cm away from the viewpoint to create seven comparison scenes. Each of the test and comparison scenes was recorded with multiple exposures by a CANON Mark 5D III digital camera with a 50-mm

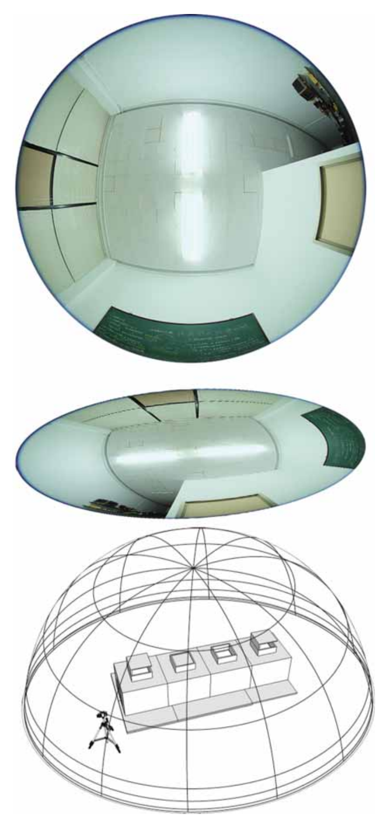

Fig. 2: Setting of image-based lighting.

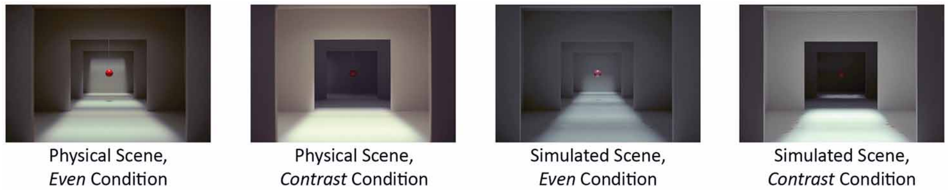

Fig. 3: Test scenes (visual targets located 150 cm away from the viewpoint).

lens and the images were assembled by Photosphere with the calibration of the luminance measurement to generate HDR images [8]. The HDR images were further tone-mapped by the Photographic tone-mapping operator into JPG images [7]. The Photographic tone-mapping operator is a tone-mapping operator that performs better in many perpetual aspects in different validation studies [1,6].

The experimental setting was configured using a 3D modeling program and simulated using RADIANCE. The material properties of the visual target and interior finish were measured using a spectrometer. An HDR photo of the environment where the physical model was placed was captured using a CANNON Mark 5D III camera with a Sigma 8-mm circular fish-eye lens. The HDR image was used as the light source in RADIANCE, as illustrated in Figure 2. The same settings of the test and comparison scenes were rendered through RADIANCE and tone-mapped using the Photographic tone-mapping operator into the JPG format. Figures 3 and 4 illustrate the test and comparison scenes for the physical and computer-simulated scenes.

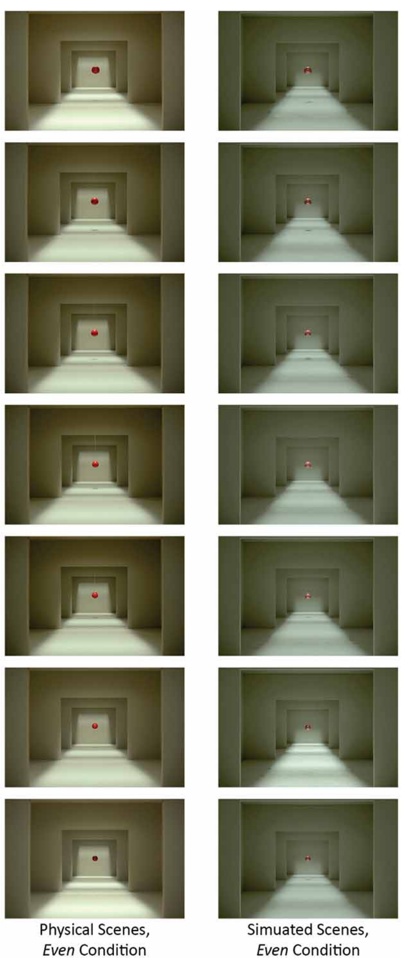

Fig. 4: Comparison scenes (visual targets located at a distance of 120, 130, 140, 150, 160, 170, and 180 cm from the viewpoint).

The perceived distance of the visual target was measured using the constant stimuli method [4]. Each of the test scenes was paired with one of the seven comparison scenes to be presented to the subjects. The subjects were required to inform the researcher on the visual target that he or she perceives to be closer. Both the test scenes under the luminance distribution conditions of *Even* and *Contrast* were presented with seven different comparison scenes ten times in a random order. The experiment was repeated twice with the experimental scene set of the physical model and computer simulation.

Ten subjects participated in the experiment. Each of them had normal vision, with or without glasses. The subjects were asked to sit in a research lab in which only electrical lighting was used to maintain a constant lighting environment for every trial. The experimental scenes were displayed on a 15-in laptop screen. The subjects were first instructed about the experimental procedure, and a total of 280 perceptual judgments were obtained.

4. EXPERIMENTAL RESULTS

Probit analysis was used to derive the measured perceived distances of the visual targets in the four test scenes from the trial results [3]. As illustrated in Figure 5, Probit analysis derives a regression curve from the binary responses from the participants in the experiment. The y-axis represents the proportion that the test target is reported closer, the x-axis represents the actual locations of the comparison targets. The point where the 0.5 proportion line intersects the progression curve is the point of subjective equality (PSE) that represents the condition where the subject cannot judge whether the test or comparison target is perceived to be closer. The corresponding location on the x-axis of the comparison target is thus considered as the measured perceived distance of the visual target in the test scene. The results

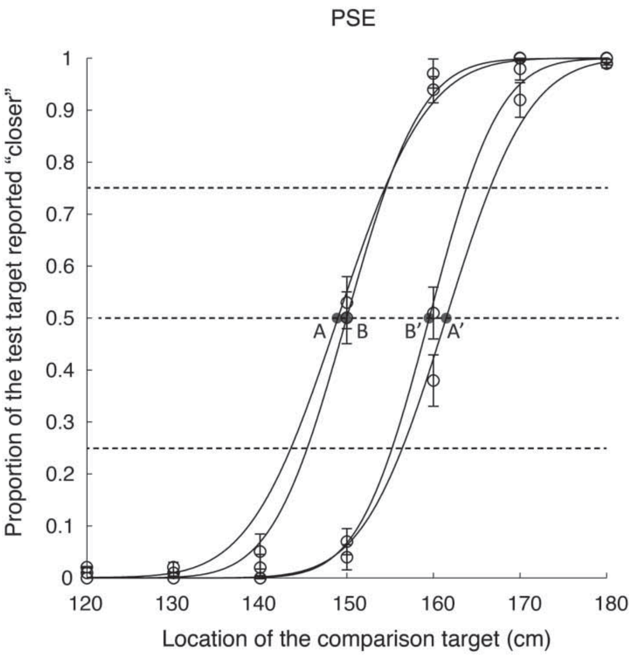

Fig. 5: Probit analysis of the experimental results: A and B are the PSEs under the *Even* condition for the physical and simulated scenes, respectively; A' and B' are the PSEs under the *Contrast* condition for the physical and simulated scenes, respectively.

demonstrate that the measured perceived distances of the visual targets located 150 cm away in the test scenes under the *Even* condition for the physical and simulated scenes are 149.00 ± 0.07 and 149.98 ± 0.62 cm, respectively. In contrast, under the *Contrast* condition, both distances increased to 161.46 ± 0.65 and 159.51 ± 0.60 cm for the physical and simulated scenes, respectively.

5. DISCUSSIONS

Figure 6 compares the physical accuracy of the physical and simulated experimental scenes. Figure 6 (a) shows the false color studies of the HDR image captured and used for image-based lighting in RADIANCE. Figure 6 (b) shows an HDR scene generated through RADIANCE with a camera pointing upward with the view type set as hemispherical and view angles as 180° in both horizontal and vertical directions. The comparison of the false color studies demonstrates the accurate application of the image-based lighting setting in the simulation process. Figures 6 (c) and (d), on the other hand, compare the test scenes between the physical and the simulated scenes under the *Contrast* condition. As indicated in the false color studies, although the luminance values do not completely match, the distributions remain similar. The contrasts of the three layers of the walls around the visual targets also remain similar.

For perceptual equality, Table 1 summarizes the experimental results. Under the *Even* condition, the luminance distributions are identical between the test and comparison scenes. In both the physical and simulated scenes, the measured perceived distances are approximately equal to the actual location of 150 cm, as 149.00 ± 0.07 cm and 149.98 ± 0.62 cm,

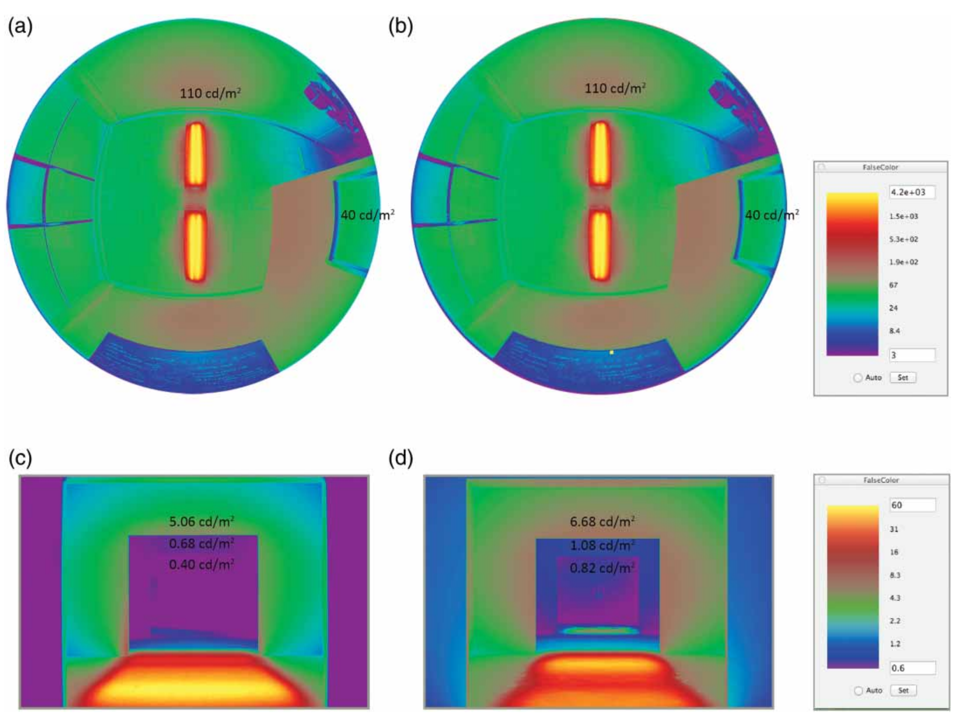

Fig. 6: Comparison of the physical accuracy between the physical and the simulated scenes.

Luminance Distribution	Even	Contrast	% Increase
Perceived distance of the visual target 150 cm away in physical scene	149.00 ± 0.07 cm	161.46 ± 0.65 cm	8.36%
Perceived distance of the visual target 150 cm away in simulated scene	149.98 ± 0.62 cm	159.51 ± 0.60 cm	6.36%

Tab. 1: Comparison of the effect of luminance contrast on the perceived distance in the physical and simulated scenes.

D-threshold	Even	Contrast
Physical scene	5.42 ± 0.39	5.06 ± 0.38
Simulated scene	4.54 ± 0.36	4.29 ± 0.36

Tab. 2: Comparison of the D-thresholds.

respectively. On the other hand, under the *Contrast* condition, the measured perceived distances of the visual targets in the test scenes both increased by 8.36% to 161.46 ± 0.65 cm, and 6.36% to 159.51 ± 0.60 cm, respectively. It is thus concluded that the luminance contrast is an effective depth cue that can affect the perceptual judgment of the perceived distance of a visual target in both the physical and computer-simulated scenes.

Table 2 further compares the D-thresholds of the Probit analysis of the four test scenes. The D-threshold indicates the slope of the regression curve derived by the Probit analysis [4]. It is the average of the intersection points of the regression curve with the 0.25 and 0.75 proportion lines to the PSE. The smaller D-threshold thus indicates the steeper curve and implies a more determined perceptual judgment. As summarized in Table 2, the D-thresholds decreased under both *Even* and *Contrast* conditions from the results derived from the physical scenes to the results derived from the simulated scenes. One possible interpretation is that the experimental scenes generated by the computer simulation process can be precisely controlled through the numerical inputs, while manipulations of the physical settings to generate HDR photographed scenes are prone to induce errors. As a result, the numerical control offered by the computer simulation process provides a more practical and relatively easy method to generate the experimental scenes in order to control experimental variables.

6. CONCLUSIONS

There are two objectives of this study. The first is to investigate the effect of luminance contrast on depth perception in the physical and simulated scenes. The

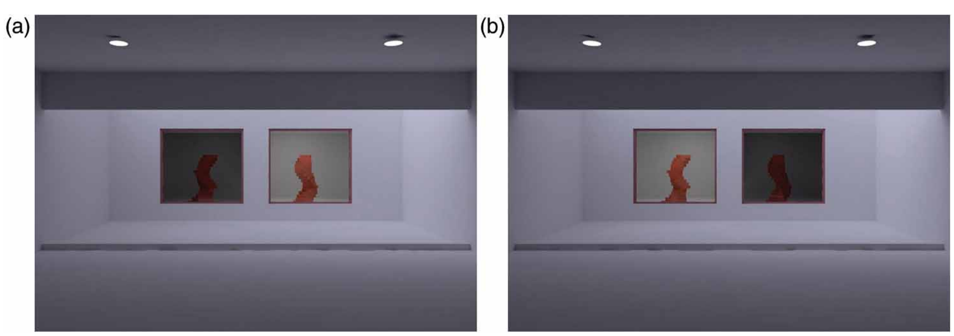

Fig. 7: Digital simulations of a gallery scene with different lighting control.

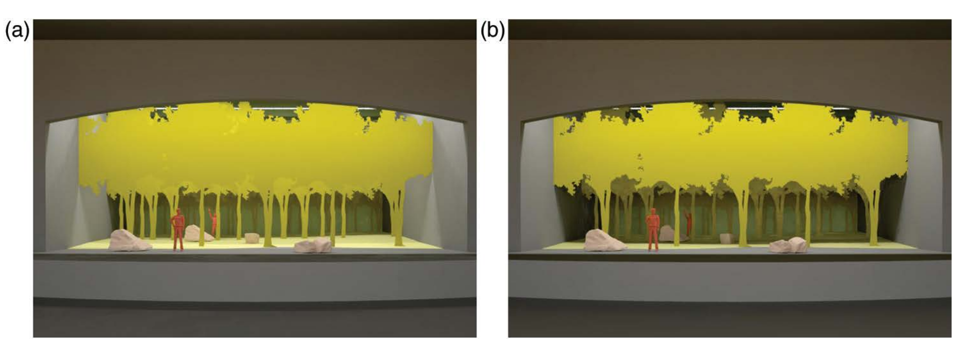

Fig. 8: Digital simulations of a stage scene with different lighting control.

second is to validate the visual realism offered by digital simulation using the HDR-related technologies to envision the depth effect resulting from luminance contrast. The results of the perceptual study demonstrate that luminance contrast is an effective parameter that can increase the perceived distance of the visual targets in a scene. In a particular setting of this study, the visual targets in both the physical and simulated scenes were increased by approximately 8.36% and 6.36%, respectively. In addition, the measured perceived distance of the visual target in a computer-simulated scene implies a more determined perceptual judgment. This study thus concludes that the computer-generated environment generated using the HDR-related technologies can provide necessary visual realism to study and envision the effect of luminance contrast on depth perception; and this alternative pictorial environment requires much less effort to generate experimental scenes with precise variable control.

Figures 7 and 8 illustrate two possible applications. As shown in Figure 7, the two displayed sculptures are located at the same distance. By controlling the illumination of each sculpture, the difference in the luminance contrast of each of the sculptures against its background and foreground can create a different perception of their perceived distances. This example illustrates that changes in lighting can alter the relative perceived distances of static objects. As shown in Figure 8, a stage scene is composed of three layers of trees to create a foreground, middle-ground, and background. As shown in Figures 8 (a) and (b), the lighting is manipulated to reduce the luminance contrast of the middle-ground; as a result, the middle-ground is perceived to be closer to the foreground as shown in Figure 8 (a); however, it recedes more into the background as shown in Figure 8 (b). Along with the depth cue of occlusion, the waving person, who is partially behind a tree in the middle-ground, is thus perceived to be farther away from the standing person in the foreground as shown in Figure 8 (b) rather than in 8 (a). This example illustrates that lighting control can be used in a more dynamic setting to enrich spatial perception.

In summary, as lighting can be more easily manipulated than the constructed setting, luminance contrast can be used as an effective design strategy to enrich the spatial perception of a three-dimensional scene. With the availability of a perceptual realistic computer-generated pictorial environment to envision, this design strategy can be incorporated into the computer-aided design process.

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