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Investigation on light effect on spatial illusion resulting from forced perspective

Nan-Ching Tai

National Taipei University of Technology, Taiwan

ABSTRACT

Linear perspective is a drawing system that can transform geometry from conceptual form to perceptual, and thus it is an essential tool for designers to predict the spatial perception of proposed construction designs. Linear perspective is also identified as an effective pictorial depth cue that can provide the visual information necessary to retrieve the three-dimensional sense of depth from both the two-dimensional retinal images and drawn pictures. As a result, linear perspective has been used as an effective design strategy to create forced perspectives that can exaggerate the depth perception of architectural scenes. Light has also been observed to influence the perceptual judgment of depth in an architectural scene. Luminance contrast has been proven through perceptual studies conducted using the perceptually realistic computer-generated environment to be an effective depth cue that can create illusory depth effects. In this study, the interrelationship of the size and tone-related depth cues of forced perspective and luminance contrast, respectively, are investigated in a three-dimensional setting. The Colonnade Spada architectural space was designed based on forced perspective to create illusory depth. The original design has a series of skylights that no longer exist. For this study, the Colonnade Spada (with and without skylights) was simulated in a digital environment. Psychophysical experiments were conducted to investigate whether the luminance contrast introduced by the skylights would affect the illusory depth effect created by the distorted structural configuration caused by forced perspective.

KEYWORDS
Forced perspective; light; depth perception; spatial illusion

1. Introduction

Two-dimensional drawings have been used to mediate the process of architectural design. The conceptual layout of the architectural structure can be manipulated in multi-view drawings, and the resulting spatial experience of the architectural scene can be envisioned through perspective drawings. Linear perspective refers to the mathematical drafting method that can transform multiple two-dimensional conceptual representations into one perceptual view as seen from a single eye [4]. The geometrical relationship governed by the linear perspective not only allows architects to predict how the proposed conceptual layout would appear at a particular viewpoint, but it also allows them to manipulate the conceptual configuration to create an intentional, illusory space perception. This design strategy is called "forced perspective," and many examples can be observed in Renaissance architecture. One such example is the Colonnade Spada designed by Francesco Borromini in 1632 and located in the Palazzo Spada in Rome, Italy. As illustrated in Fig. 1, the architectural components and their layout in the Colonnade Spada were distorted and manipulated to create a forced perspective, looking from the entrance of the gallery and towards the statue at the end of the hallway. This trapezoidal space was designed to appear as a rectangular space that is twice as deep as the trapezoidal space [1]. The Colonnade Spada is composed of four sets of arches, with a certain distance or gap between arches. The ceilings over these gaps are very plain when compared with the coffered ceiling of the arches, which suggests that these gaps could have been originally designed to be skylights. However, the existing Colonnade Spada does not have any skylight between the arches, thereby preventing daylight interaction with the architectural interior, and leaving the contribution of light on the illusory depth effect unexplored.

Lighting distribution (or luminance contrast) has been identified as an effective cue that can alter the perceived distance of a visual target in space. The lower the contrast of the target against its background than against the foreground, the farther it appears to be [17]. However, studies have also demonstrated that this illusory depth effect that results from the lighting contrast is more effective with diffused light because direct sun patches provide additional visual information that helps retrieve actual distance [18]. In this study, perceptual studies are conducted

CONTACT Nan-Ching Tai nctai@ntut.edu.tw

Figure 1. Colonnade Spada: (a) view from the front, and (b) view from the side.

to investigate two items: the first is the effectiveness of the Colonnade Spada forced perspective in creating intentional illusory depth; and the second is whether the presence of skylights would decrease or increase the illusory depth effect of the Colonnade.

2. Background

Depth perception is a process where we use our sensory modalities to perceive the three-dimensional spatial layout we encounter [9] [11]. Vision often provides the most immediate and reliable perception of depth, and therefore, visual depth cues are the factors investigated the most when studying depth perception. Pictorial depth cues refer to the collective visual information that can be used to retrieve the three-dimensional understanding of the space from the two-dimensional retinal images. It is termed "pictorial cue" because such visual information can also be used to create the illusory third dimension of depth on two-dimensional drawings [11] [15]. Because drawing is the most common platform for representing architectural design, pictorial depth cues have been utilized as effective design strategies for enriching the spatial experience.

Pictorial depth cues include several size-related cues: relative size, familiar size, linear perspective, and texture gradient. These cues can be integrated with linear perspective and are associated with the geometry of the spatial environment. On the other hand, shading, atmospheric perspective, and contrast are tone-related pictorial depth cues, all of which are associated with the lighting distribution reflected by the environment geometry. The cause-and-effect relationships of the size-related depth cues on depth perception have been established through extensive perceptual studies. However, the causal relationship between the tone-related depth cues and depth perception is not well known because of the difficulty in controlling the lighting conditions required for conducting systematic, experimental investigation.

Recent developments of High Dynamic Range (HDR) imaging-related digital technologies have advanced the visual realism of computer simulations [12]. Physically based lighting simulation programs, such as RADIANCE, have been used to generate experimental scenes that can serve as alternative environments when conducting psychophysical experiments on various aspects of visual perception [2] [6] [20]. Tai [16] developed a computational framework that uses tone-mapped images of the HDR scene generated by RADIANCE in order to investigate depth perception. When RADIANCE was used to repeat a classic experiment conducted in a physical setting, the results acquired were similar to the results of the classic experiment, thereby establishing the reliability of computer simulation as an alternative environment for conducting experimental investigation related to depth perception. This computational framework further incorporates the autostereoscopic display technology in order to integrate binocular disparity in the visual display. The results of perceptual studies on the autostereoscopic display technology indicated that subjects can have a more reliable perceptual judgment when incorporating binocular disparity in the visual display [19]. The current study adopted the recently established computational framework to generate experimental scenes for the perceptual study. This computational, alternative environment allows for the manipulation of the architectural configuration (which is one of the variables investigated), while generating series of experimental scenes that can be parametrically controlled for the experiment design.

3. Methodology

Studies on depth perception often require conducting psychophysical experiments to measure the perceived distances of visual targets in controlled experiment scenes. Comparisons between the measured perceived distance of the visual target and its actual distance can reveal the depth effect of the variable being controlled in the experiment. The most common method for measuring the perceived distance is visual matching, wherein subjects are asked to adjust the location of a visual target in a reference scene to match the perceived distance of the same visual target in a test scene. However, this method usually requires the reference and test scenes to have the exact same configuration of the environment. Because one of the variables manipulated in this study is the architectural configuration itself, the test and reference scenes have different geometrical forms and shapes, and thus conventional visual matching may not be an appropriate approach for revealing the effect of the controlled variables.

According to the size-distance invariance hypothesis, the perceived size of an object can be derived from its perceived distance. Therefore, size has been proposed as an alternative measurement in visual matching to study depth perception [8]. Fig. 2 illustrates the experiment setup of this study. The Colonnade Spada was modeled in a digital environment in two different ways: one is the existing trapezoidal configuration of the gallery, whereas the other is the rectangular configuration derived from reversing the forced perspective of the trapezoidal configuration. At the far end of both configurations is a courtyard; a sphere that serves as the visual target for the experiment appears to float within the courtyard approximately 150 cm above the floor. The figure of a person standing at the front end of the configuration and looking towards the visual target represents the point of the observation. Such observation point is 3.3 cm from the edge of the entrance step stone. The distance between the observer and the visual target in the rectangular configuration of the Colonnade is twice the distance between the observer and the target in the trapezoidal configuration.

The second variable investigated in this study is the presence of skylights, specifically, how the lighting pattern and distribution introduced by a series of skylights would affect the illusory depth effect created by the forced perspective. The existing trapezoidal configuration of the Colonnade Spada is set to have two conditions: one with skylights and the other without. Fig. 3 shows the three scenes perceived from the observer's viewpoint: the rectangular configuration (without skylight) of the Colonnade, the existing trapezoidal configuration without skylight, and the existing trapezoidal configuration with skylight. The visual target is 50 cm in diameter in the rectangular configuration, but 25 cm diameter in the trapezoidal ones. Because the visual target in the rectangular configuration is twice as far as the visual target in the trapezoidal configuration, the size of the visual target is doubled so that the visual targets between the three scenes have the same apparent size.

4. Experiment design

Three sets of experiments were developed to explore the effects of geometrical configuration and lighting

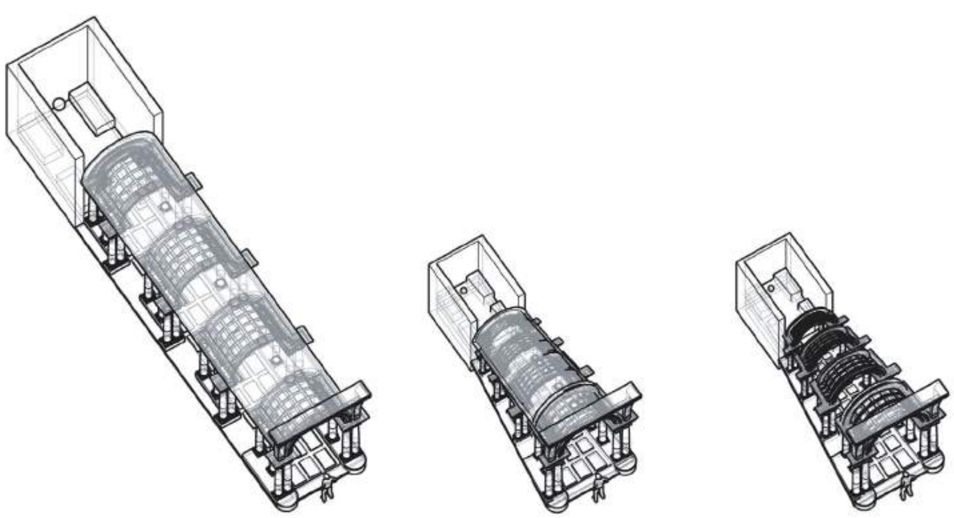

Figure 2. Architectural configurations generated for experiment scenes.

Figure 3. Experiment scenes as perceived from observer's viewpoint.

condition on perceived distance. The first is a comparison between a fixed-size (50 cm) visual target in the trapezoidal configuration (without skylights) and nine levels of the visual target size in the rectangular configuration. This comparison is designed to explore the illusory perspective depth effect that results from distorted geometrical construction. The scene with a fixed-size target in a trapezoidal configuration without skylights is set as the test scene, whereas scenes with variable-size targets in the rectangular configuration are the reference scenes. The second experiment is a comparison between a fixed-size (50 cm) visual target in the trapezoidal configuration (with skylights) and nine levels of the visual target size in the rectangular configuration. Unlike the first experiment, this is intended to explore the influence of lighting patterns (introduced by the presence of skylights) on the illusory depth effect. The scene with fixed-size target in the trapezoidal configuration with skylights is defined as the test scene, and the scenes with variable-size target in the rectangular configuration are the reference scenes. The third experiment is a comparison between a fixed-size (50 cm) visual target in the rectangular configuration, and nine levels of the visual target size also in the rectangular configuration. This last experiment serves as the baseline with which the first two experiments are compared. The scene with a fixed-size target is the test scene, and the scenes with variable-size targets are the reference scenes.

Using the size of the visual target as the controlled variable, the nine levels of the visual target size are derived from reducing and increasing the size of the original 50 cm target at 5% intervals, such that the size ranges of the visual targets are as follows: 40 cm, 42.5 cm, 45 cm, 47.5 cm, 50 cm, 52.5 cm, 55 cm, 57.5 cm, and 60 cm. The scenes that contain one of these visual targets (the rectangular configuration) are paired with a scene that has a fixed-size target to determine which size value is perceived as equal to the fixed-size target. By measuring the change in size, the change in distance can then be measured.

The three experiment scenes were rendered with a physically based lighting simulation program (RADIANCE) that can output images in the HDR image format to show physically accurate lighting distribution in the scene [10] [14]. The HDR images were tone-mapped using the photographic tone-mapping operator in order to display them on a typical computer monitor (which can only display a low dynamic range) [13]. To provide the perceptual realism that reflects binocular vision, two tone-mapped, slightly different images of the same scene (one showing the field of vision of the left eye, and the other that of the right eye) were combined to generate stereoscopic experiment scenes saved in the JPEG Stereoscopic (JPS) image format.

Employing a within-subject design, ten subjects (six females and four males) volunteered to participate in the psychophysical experiment. The volunteers were between the ages of 20 and 42, and each had normal or corrected-to-normal vision. The experiment was set in a campus research lab illuminated by electrical lighting. The experiment scenes were displayed on a 15.6″ Toshiba Satellite P850 laptop capable of displaying autostereoscopic scenes in a JPS image format. After the volunteer was seated with a comfortable view of the display, the experimenter explained the procedure and administered a short practice test before the official trial.

The experimental tasks used to measure perceptual sensibility ranged from description, rating, to forced choice; each method requires different levels of response time, and each provides different degrees of certainty [3]. For depth perception studies with reduced-cue conditions, two-dimensional representations of three-dimensional scenes are commonly used as stimuli, and forced choice is the preferred experimental task. Forced choice requires less effort for the subjects when they make perceptual judgments, allowing them to focus on the stimuli and provide more intuitive responses.

By employing the method of constant stimuli, the observers were asked to report which visual target in the pair of experiment scenes was bigger (forced

Figure 4. Test and reference scene pairs for the experiments.

choice). Each of the 27 pairs of experiment scenes (nine experiment scenes for each set of experiments) were presented to the observers ten times in randomized sequence. Each observer made ten perceptual judgments for each test and reference scene pair for a total of 270 perceptual judgments for the entire trial. The binary responses from the observers were recorded; the data from all ten subjects were collected and processed to determine the number of times (out of 100 perceptual judgments) that a reference scene visual target was perceived as bigger than the test scene visual target.

Figure 4 shows an array of the paired experimental scenes for the three experiments: each of the three columns has a pair of experiment scenes. The image on the left side of each pair is the scene with a fixed-size visual target, whereas the image on the right side is the scene with variable-size visual targets. Each row, meanwhile, shows the nine levels or sizes of the variable-size visual targets. Whereas Fig. 4 shows that all test scenes are on the left, this was not the case during the experiment. The location of the test and reference scenes was randomized, such that the test scene could be on the left or right (and the same for the reference scenes).

5. Results and discussions

The data collected from the psychophysical experiments are analyzed using Probit analysis, a regression model usually applied to analyze binary responses, such as the data acquired in this study. Fig. 5 shows the psychometric functions obtained for the three experiments. Functions A, B, and C represent the data for the rectangular configuration without skylights, trapezoidal configuration without skylights, and trapezoidal configuration with skylights, respectively. With visual inspection, functions A and B are much closer to each other than function C, which shifted considerably to the left of functions A and B.

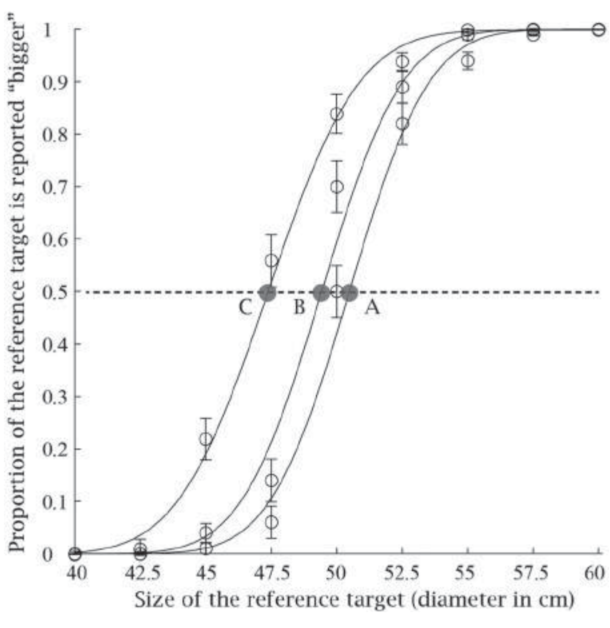

Figure 5. Psychometric functions for rectangular configuration without skylights (A), trapezoidal configuration without skylights (B), and trapezoidal configuration with skylights (C).

The horizontal dashed line in Fig. 5 is the difference threshold, and where the psychometric function intersects with this line is the Point of Subjective Equality (PSE). PSE represents the physical value of the variable-size visual target that is perceptually equal to the fixed-size visual target [5] [7]. PSE values for the rectangular configuration without skylights, trapezoidal configuration without skylights, and trapezoidal configuration with skylights are 50.479 ± 0.182 cm, 49.421 ± 0.184 cm, and 47.379 ± 0.194 cm, respectively.

With the size-distance invariance hypothesis, the change in perceived size of the visual target can be translated to a change in perceived distance. Assuming that the illusory depth effect of the trapezoidal configuration (without skylights) works to full effect, the perceived size of the visual target in that configuration should appear twice as large as the visual target in the rectangular configuration (which is twice as deep).

The measured perceived size decreases approximately 2.1% from the "Rectangular configuration without skylights" condition to the "Trapezoidal configuration without skylights." According to size-distance invariance hypothesis, the perceived distance of the visual target in the "Trapezoidal configuration without skylights" condition is 2.1% shorter in depth compared with the "Rectangular configuration without skylights." However, the measured perceived size of the visual target in the "Trapezoidal configuration with skylights" condition decreases 4.1% compared with the condition of the "Trapezoidal configuration without skylights." This suggests that additional skylights may further reduce the depth effect of the forced perspective.

6. Conclusion

Two factors were investigated in the experiment design: the depth effect of the forced perspective from a distorted geometrical layout, and the influence of light (introduced by the presence of skylights in the scene) on the intended illusory depth effect. The experiment results showed that the depth effect of the forced perspective founders 2.1% short of its fully working scenario, and the additional light patterns introduced by skylights further reduce the illusory depth effect by 4.1%.

One possible reason for the quantitative results being so small is the lack of visual realism; dynamic viewing was absent from the presented static experiment scenes. Although the computational framework generated experiment scenes in this study that reflected the perceptual reality of the static pictorial depth cues and binocular vision, it did not address the motion parallax that provides us with further visual information for retrieving the actual depth perception. Therefore, the influence of the motion parallax could be a reason for the experiment results not reflecting a more-reduced illusory depth effect experienced from on-site observation of the Colonnade Spada.

This study demonstrated the use of computer simulation for investigating the variable depth effect that is difficult to manipulate in a real setting. Computer simulation was used to generate the experiment scenes because it allows for easy and precise replication, as well as modification, of the geometrical configuration. The complex architectural details of the Colonnade Spada would be difficult and expensive to reproduce (whether full scale or at a smaller scale) for an experiment such as this, and thus computer simulations can be quite cost-effective without sacrificing detail or accuracy. However, because this study employed an indirect method for measuring the perceived distance by measuring the perceived size, the findings can only account for possible trend interpretation. For a more precise quantitative effect, future simulations may have to incorporate motion parallax in the experiment design.

Furthermore, daylight quality varies through time, and thus the simulations in this study cannot account for all sky conditions. Therefore, this study cannot fully conclude the quantitative depth effect of the forced perspective that results from the trapezoidal configuration and the presence of skylights in Colonnade Spada. However, an interesting finding from the experiment results is that additional visual information (such as sharp sun patches) can reduce the depth effect of the forced perspective, suggesting that the presence of skylights can make the illusory depth effect more unpredictable.

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ORCID

Nan-Ching Tai http://orcid.org/0000-0001-6656-3285

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