Investigation of Computer-Simulated Visual Realism for Envisioning the Illusory Visual Effect of Installation Art Using Depth Reversal

Nan-Ching Tai*1 and Ting-Wei Yeh2

1Assistant Professor, Department of Interaction Design, National Taipei University of Technology, Taiwan
2Graduate Student, Department of Interaction Design, National Taipei University of Technology, Taiwan

Abstract

Depth reversal is the false perception whereby a receding or projecting spatial composition actually appears as the opposite of that composition. Such illusory effects are often forceful and have become a popular visual effect utilized in many site-specific installation artworks. However, the design approach most often employed is based on trial and error because the visual perception of depth-reversal illusion is often difficult to predict without actually seeing it in reality. Unfortunately, this approach demands extensive time and effort as well as increased material costs. Computer-aided design often provides a low-cost alternative for the design process; however, the feasibility of using a computer simulation in the design process depends upon the visual realism offered by the simulation. This study investigated the visual realism of a computer simulation with regard to envisioning the visual illusion of depth reversal. Perceptual studies were conducted to measure critical distances that occur when an observer experiences the visual perception of depth reversal in both physical and computer-simulated environments. The quantitative experimental results were used to establish the reliability of computer simulation for the design process of installation art that utilizes illusory visual effects of depth reversal from design ideation to exhibition planning.

Keywords: depth reversal; visual illusion; installation art; physically-based rendering; computer-aided design

1. Introduction

Depth reversal is the phenomenon of a visual experience of reversed depth perception. In general, it results from collective misleading depth cues that cause an illusory perception of receding or extruding geometry to appear as its opposite. One of the most studied examples of this is the hollow-mask illusion, in which a mask presented in its concave side is perceived as a normal convex face. It is generally agreed that depth reversal is caused by the processes of two competing visual phenomena, when the false percept derived from top-down stored knowledge overrules the veridical percept input from bottom-up perceived retinal signals (Gregory, 1997; Vlajnic et al., 2014).

Illusory perceptions are often so forceful that even if one is fully aware of the cause, one cannot avoid the perception. This is because top-down visual processing has its own systematic way of reaching its final interpretation, and that systematic way is often independent of the observer's cognitive awareness. As a result, the forceful illusion can be used as a design strategy in 2D graphic or 3D constructs, since the manipulation of the visual information presented and its resulting illusory visual effects can be anticipated. Applications of the illusory effect of depth reversal can also be found in many design fields ranging across different scales. One approach is to use an established principle, such as the hollow-mask illusion, to construct a similar installation. Another approach is to use the principle of false top-down visual processing to create an intentional visual illusion, such as "Afrum" designed by James Turrell (Govan et al., 2013). For the illusory visual experience of installation exhibits, the visual cue employed needs to be kept simple, but the methods used to present those visual cues can be innovative. For example, James Turrell used projecting lights on the intersections of adjacent walls, thus making the corner appear as an extruding cubic form.

Most art installations that exhibit a perception of depth reversal are site-specific and can only be experienced at the particular scene. This is because illusory visual perception is a complex process, and the design of such an exhibition requires consideration of how the installation is constructed; how it is displayed, and how it is to be viewed by the audience. As a result,
the trial-and-error design process, which relies on a designer's past experience and testing with a full-scale mock up, remains the most reliable method. However, this conventional method can be expensive in terms of both time and the cost of materials. In addition, the exhibition planning might be beyond the artist's control when the installation is to be incorporated in a joint exhibition.

Computer-Aided Design (CAD) has advanced the design process in many ways (Kalay, 2004). As it has allowed the design process to be incorporated as a pipeline process from ideation to realization, a feasible method of using computer simulation to visualize the illusory visual effect of an art installation can allow the designer to explore more possibilities and the curator to arrange the spatial planning of the exhibition to ensure that the intended visual experience occurs.

To develop and validate a computer simulation to simulate the illusory visual effect of depth reversal, it is important to establish an objective measurement of the visual effect. Hill and Bruce developed a quantitative method to measure the strength of the hollow-mask illusion (Hill and Bruce, 1993, 1994), a method that was later adopted by many others to investigate the influence of different parameters on the effect of the established visual illusion (Papathomas, 2002; Vlajnic et al., 2014). In this method, observers stand close enough in front of the installation to perceive the actual configuration, then gradually retreat until the percept switches to its opposite. The distance at which the switch occurs is termed the critical distance. The shorter the critical distance, the stronger the illusion presented by the installation. To measure how well an illusion can maintain its effect, on the other hand, the observer starts from far enough away to perceive the illusion, and gradually approaches until the percept switches. The critical distance percept at this point implies how well an illusion can maintain its effect.

In this study, the critical distance measured was used to compare the visual realism of the illusion exhibited in a computer-simulated art installation with that of the actual physical art installation. The goal of this study is to develop a computational framework that can envision the illusory effect of depth reversal, and thereby provide a practical computer-aided design method to assist in utilizing the illusory effect of depth reversal from design ideation to exhibition planning.

Three psychophysical experiments were conducted to evaluate the visual realism of the illusion exhibited in a computer-generated virtual environment. In all experiments, the physical installation was constructed and critical distances were measured in the real settings as a base-line reference. Computer simulations of the physical installations were created and displayed on an LED display. In the first experiment, sequential images were presented to volunteers to simulate viewing and moving forward and backward. In the second experiment, a static simulation was displayed on the screen, and the observers physically moved back and forth. In the final experiment, the observers moved physically, while the stereo image was displayed on a monitor. The critical distance measured in these three settings thus revealed the visual realism offered by different levels of simulation, from monocular stationary pictorial presentation, to monocular dynamic viewing of the computer simulation, and finally to stereo/binocular dynamic viewing of the computer simulation.

2. Method

The criteria used to construct a test installation to exhibit the illusion of depth reversal followed the underlying principle of using simple visual cues to favor false top-down visual processing. Two installations were used in this study. Fig.1.(a) illustrates the first installation, a truncated rectangular pyramid rotated 90 degrees. The top of the truncated rectangular pyramid measured 5 x 5 cm and its base measured 20 x 20 cm. The top square surface was painted black (C:93, M:88, Y:89, K:80). The four rings of the four sides measured 2, 4, 8 and 16 cm, and were painted in dark grey (C:78, M:73, Y:70, K:20), grey (C:65, M:56, Y:53, K:2), light grey (C:39, M:31, Y:29, K:0), and white (C:0, M:0, Y:0, K:0), respectively. When viewed in perspective, the constructed object appears to favor the visual perception of a rectangular hallway space such as those we encounter constantly in daily life, as illustrated in Fig.1.(b). Fig.2.(a) illustrates the second installation. A truncated triangular pyramid was created and rendered in a similar manner to the first; this was used for comparison with the first installation, to ascertain whether a more unfamiliar spatial experience such as that illustrated in Fig.2.(b) would affect the illusion.

![Fig.1. Installation to Favor the Depth Reversal of Visual Perception of a Familiar Rectangular Space](image-url)
There are many computer visualization tools available nowadays; however, each offers a different degree of visual realism. This study used a physically-based rendering program named RADIANCE. RADIANCE uses an unbiased rendering algorithm that allows the light to interact in the virtual environment as in the real physical world. RADIANCE can output a simulated scene in High Dynamic Range (HDR) image format with each pixel encompassing the luminance data of the simulated scene (Ward, 1998). The physical accuracy of RADIANCE has been validated (Mardaljevic, 2001), and it has been used in perceptual studies such as those investigating color perception and shape perception when the parametrical controls of experimental settings are difficult in the real environment (Boyaci, 2004; Fleming, 2004). For HDR scenes that have a dynamic luminance range beyond what the conventional display can show, the method of tone reproduction can be used to compress the luminance range to a level that is displayable (Reinhard et al., 2010). While many tone-reproduction methods are available, this study used photoreceptor tone reproduction as it is perceptually based (Reinhard and Devlin, 2005).

The scene parameters input in RADIANCE followed the physical setting as closely as possible. The surface materials, including the paint color on the physical model as well as on the walls and floor of the room in which the experiments were conducted, were measured using a Konica Minolta CM-2500D spectrophotometer. The measured values, including the secularity and surface color in Yxy format, could then be converted into RGB and input in RADIANCE to define the material properties.

For the illumination of the virtual scene, authors used an image-based lighting technique (Reinhard et al., 2010). The experiment was conducted in an interior space illuminated only with artificial light. Authors used a digital camera fitted with a circular fish-eye lens to generate a HDR light probe image. This light probe image captured the real-world illumination and was used in RADIANCE as the image-based lighting to ensure that the environmental lighting was consistent between the physical and virtual settings.

The computer simulation was created for display on a 46" LED display that supports 3D stereo display, located in the experiment room. Thus, the computer simulation was not intended to simulate the immersive virtual environment but was a replacement for the physical model in the scene. As a result, the camera setting in RADIANCE used an angle of view of 25 degrees, to simulate the near-peripheral field of view. The camera focused at the center of the surface of the truncated pyramid and was initially located 40 cm away from it. The intention was to create a display of a virtual model on a monitor with the same projection size and perspective distortion as the physical constructed model. The location of the camera was moved back to different locations to create sequential images that replicated the viewing experience of moving backward and forward.

Fig. 3. illustrates the comparisons of the computer simulation of the installation with the physical constructed models.

3. Experiment Design

Ten volunteers participated in each experiment. Their ages ranged from 26-37, and all had normal or corrected to normal vision. For the base-line reference test, the physical model was attached to the wall at eye level as the visual target. This was to be compared with the virtual target displayed with different degrees of visual realism. Each volunteer was encouraged to view
the model closely to ensure the perception of the actual extruding geometry, and then gradually moved back until he or she felt the percept switch. The researcher then recorded the distance, which was the critical distance of retreat, or "Dr." The measure "Dr" thus represents how strong the illusion was. Volunteers were also asked to start sufficiently far back that they could perceive the illusion and then gradually moved toward the visual target. When they perceived the switch, the researcher recorded the distance. This distance was called the critical distance of approach, or "Da." The Da represents how strongly the illusion could maintain its effect.

In each experiment, volunteers participated in 10 trials for each condition, both approaching and retreating. Thus, each volunteer participated in a total of 80 trials to measure the Dr and Da for both physical and simulated conditions of both the truncated rectangular and triangular pyramidal visual targets.

To interpret the experiment results, authors first compared the means of the measured Da and Dr of all trials between the physical and simulated conditions for each experiment setting. This was done to obtain a quick understanding of the difference in the measured critical distance under different conditions. However, as visual perception involves complex visual processing, the point at which the percept switch occurs might vary from person to person. The non-parametric Kolmogorov-Smirnov tests (KS-test) were thus performed to compare the distributed data sets between the same group of people under the physical and simulated conditions. If the result was significant (p<.05), meaning that the two distributed data sets were not related, the perceptual response from the simulated condition could not reflect the response from the physical condition. On the other hand, if the result was not significant (p>.05), then the two distributed data sets were related, implying that the perceptual response from the simulated environment could reflect the response from the actual setting.

4. Experiment Results and Analysis

3D modeling and rendering programs often use a single camera to simulate a scene, and thus simplify the visual representation to monocular vision. In the first experiment, authors tested the most readily available simulation method for visualizing the visual illusion of depth reversal. In each trial, participants used their dominant eyes to view the physical and simulated visual targets. In the physical setting, volunteers actually walked while observing a visual target. In the simulated setting, sequential images were generated with a camera setting of 1 cm apart, were presented to the volunteer, who could then use the mouse to control the displayed images to simulate movement in the virtual environment.

Table 1. shows the results of the first experiment. The error percentages of the average Dr between viewing of the physical and simulated visual targets were 17.6% and 12.7% respectively for the truncated rectangular and triangular pyramids. However, the error percentages were relatively high when viewing the target while approaching. The error percentage was 54.6% for viewing the visual target of the truncated rectangular pyramid; and 51.9% for viewing the visual target of the truncated triangular pyramid. One of the reasons for the high error percentage observed in the trial was that the sequential images presented in the computer simulation did not replicate the spatial experience of actually walking. There were a number of reasons for this: first, because walking can be performed in varying step increments, while the sequential images are set at a pre-determined fixed increment; second, the actual approach or retreat cannot be maintained in a strictly straight forward or backward direction; thus, dynamic viewing with a constantly changing viewing angle cannot be avoided. As a result, sequential images fall short of simulating the complex viewing experience of moving while observing a visual target, and contribute to the high error percentage.

Table 1. Comparison of the Average Measured Critical Distance for Experiment 1

|        | Dr (cm) | Error | Da (cm) | Error |
|--------|---------|-------|---------|-------|
| Rectangular |         |       |         |       |
| Physical | 68      | 17.6% | 227     | 54.6% |
| Simulated | 80      | 103   |         |       |
| Triangular |         |       |         |       |
| Physical | 79      | 12.7% | 212     |       |
| Simulated | 89      | 102   |         | 51.9% |

Experiment 2 repeated the same process as that performed in experiment 1. Instead of viewing the virtual visual target moving forward and backward through the sequential images displayed on the monitor, volunteers actually moved to approach and retreat from the stationary virtual model displayed on an LED monitor in the same way as when facing the physical model attached to the wall. The single simulation of the displayed virtual model is the initial setting that resembles the projection size and perspective distortion of the physical model. Table 2. shows the results: the error percentages of Dr between viewing the physical and simulated visual targets of the truncated rectangular and triangular pyramids were reduced to 8.9% and 4.3%, respectively. For Da, the error percentages were further reduced dramatically from 54.6% to 0.4% and from 51.9% to 1.7% for viewing the visual targets of the truncated rectangular and triangular pyramids. These experiment results suggest that it is difficult for the dynamic moving and viewing process used in computer simulation to be simulated using monocular viewing of a visual target to assess its illusory effect of depth reversal. However, the virtual model displayed on the computer display can provide a practical alternative that allows designers to gauge the critical distance of its physical construct.
Unless otherwise instructed, audiences naturally view art installations using both eyes. Experiment 3, therefore, examined the influence of stereovision on the visual realism offered by the computer simulation in terms of envisioning the illusory effect of depth reversal. The experiment procedure repeated that used in experiment 2. The computer simulation was used as a visual target in experiment 2 was also used in experiment 3. However, authors used the built-in 2D to 3D conversion feature available from the 46" Samsung LED display to display the image in stereo mode. The underlying principle of this 2D to 3D conversion is to create two separate distorted perspectives of the original image for the left and right eyes respectively, and to deliver each image to the corresponding eye through 3D active glasses to create a stereo viewing experience of the illusory 3D geometry.

Volunteers wore 3D glasses, using both eyes to perform the trials. Table 3 shows the results: the error percentage of Da between viewing the physical and simulated visual targets of the truncated rectangular and triangular pyramids increased from 0.4% to 12.3% and from 1.7% to 8.4%, respectively. For Dr, the error percentages increased from 4.3% to 4.9% for viewing the triangular pyramid, but increased greatly from 8.9% to 29.3% for viewing the visual target of the truncated rectangular pyramid. One possible reason for the dynamic increase in error percentage, particularly for the condition of viewing the visual target of the truncated rectangular pyramid, might be the more unpredictable percept switch when viewing a visual target that resembles a more familiar visual spatial experience.

Table 3. Comparison of the Average Measured Critical Distance for Experiment 3

|        | Dr (cm) | Error | Da (cm) | Error |
|--------|---------|-------|---------|-------|
| Rectangular | Physical | 188   | 29.3%   | 235   | 12.3% |
|         | Simulated | 133   | 206     |       |      |
| Triangular | Physical | 182   | 4.9%    | 225   | 8.4%  |
|         | Simulated | 173   | 206     |       |      |

5. Discussion

The average measured critical distance was averaged from a total of 100 trials in which 10 volunteers each participated 10 times. However, the distance at which the percept switched sometimes varied quite dramatically between individuals due to their respective visual processing based on prior knowledge, particularly for the visual target that was more successful in triggering a false perception with the composition of its misleading visual cues. As the visual target of the extruding truncated rectangular pyramid was to be falsely perceived as a receding rectangular space resembling the spatial experience of looking down a hallway, it was observed that the point at which the volunteers perceived the switch varied more from person to person. Comparing each volunteer's response may therefore reveal more insights into the experiment results.

Figs.4.(a) and 4(b) illustrate the measured critical distances of four conditions for both the rectangular and triangular visual targets for each individual for experiment 1. The Da for the physical truncated rectangular and triangular pyramid physical targets were significantly diverse compared to the Dr for each participant. In addition, the distributed data sets for the Da of both the rectangular and triangular pyramid targets did not appear to be concurrent between viewing of the physical and simulated targets. This observation is in agreement with the high error percentage in Table 1. The KS-test of each pair of data sets of the measured critical distances of the 10 participants between the physical and simulated targets also confirmed the above observation, that the two conditions, of rectangular approaching and triangular approaching, reached significant levels (p=.0021, p=.0149), while rectangular retreating and triangular retreating did not reach significant levels (p=.1641, p=.4175). This signifies that the perceptual judgment of depth reversal in the virtual environment can reflect the physical conditions in retreat viewing but not in approach viewing. Therefore, it is concluded that even the static representation of the presented image can reflect the visual appearance of the physical visual target, failing to simulate the dynamic interaction between moving and viewing will result in the simulation falling short of reflecting the visual realism necessary to perceive the illusory effect of depth reversal.

When the virtual model is set to be displayed only as a static visual target such as the physical one toward which the volunteer moves with monocular viewing, the computer simulation provides a reliable alternative. The data distributions of Dr and Da for both the truncated rectangular and triangular pyramids between the physical and virtual targets appear to be closely correlated, as shown in Figs.5.(a) and 5.(b). None of the KS-tests of Dr rectangular, Da rectangular, Dr triangular, or Da triangular reached significant levels (p=.7591, p=.9945, p=.8769, p=.9945), confirming that the percept switch of depth reversal for each volunteer between monocular viewing of the physical and virtual targets was correlated.

Despite increases in the error percentage in the retreat mode of viewing the rectangular pyramid, when the computer representation incorporates the stereo display, the data distributions remain correlated, as illustrated in Figs.6.(a) and 6.(b). That none of the KS-tests of Dr rectangular, Da rectangular, Dr triangular,
Fig. 4. Average of Measured Critical Distance for Individuals for Experiment 1 (Left: Truncated Rectangular Pyramid; Right: Truncated Triangular Pyramid)

Fig. 5. Average of Measured Critical Distance for Individuals for Experiment 2 (Left: Truncated Rectangular Pyramid; Right: Truncated Triangular Pyramid)

Fig. 6. Average of Measured Critical Distance for Individuals for Experiment 3 (Left: Truncated Rectangular Pyramid; Right: Truncated Triangular Pyramid)
The simulation for both the visual appearance of the illusion. However, with more careful preparation of processing to increase the effectiveness of the expected result, resulting in a favoring of the misleading visual realism and also reduces the visual cues, cannot avoid approximation, which compromises the illusion of depth reversal exhibited by a physical art installation. To predict the illusory effect for a physical art installation with monocular viewing, suggesting that the binocular disparity, which is important in contributing to 3D geometrical analysis, plays an important role in composing visual cues to create a visual illusion of depth reversal. This is evident as, excluding the parameter of viewing with binocular vision, the simulation methods employed in experiment 2 provided a fair degree of visual realism. However, as binocular viewing is the natural way to view art installations, the experiment 3 results provide a more useful indication of computer simulation use to envision a depth reversal illusion.

6. Conclusions
This study has presented an innovative investigation of the visual realism offered by computer simulations in regard to envisioning the illusory effect of depth reversal exhibited by a physical art installation. A complex visual illusion of depth reversal was examined through the quantitative measurement of critical distance, which is the location at which the audience perceived the switch in spatial composition of the observed visual target when approaching or retreating. The perceptual study conducted here employed a simple design of visual targets—a truncated rectangular pyramid and a truncated triangular pyramid—to be falsely perceived as rectangular and triangular receding hallways. Because the designs of the test visual targets were relatively simple, the error percentage derived from the experiment results should not be considered applicable to other situations. However, the experiment results of individuals’ response distributions do provide a good indication of the reliability of the tested computer simulation and display methods. The conventional single camera viewpoint, which rendered scenes with moving simulation as sequential images, did not provide perceptual realism to envision the illusion of depth reversal. To predict the illusory effect of depth reversal exhibited from the physical installation, it is suggested for a virtual simulation to be rendered as a stereo image, presented on a 1:1 scale, and for the illusory effect to be tested by viewing and actually moving. Furthermore, the critical distance measured is likely to be shorter than in reality. This is because, unfortunately, the simulated environment cannot avoid approximation, which compromises the visual realism and also reduces the visual cues, resulting in a favoring of the misleading visual processing to increase the effectiveness of the expected illusion. However, with more careful preparation of the simulation for both the visual appearance of the visual target and viewing interaction with the target, it might be possible to develop a computational environment that allows the visual illusion of depth reversal to be accurately envisioned. Nevertheless, this study concludes that when planning an exhibition to demonstrate depth reversal, designers or curators could use the computational framework presented in this paper to envision the existence of the illusory effect, but should plan a greater viewing distance to ensure the illusory effect can be experienced in a viewing area.

Acknowledgements
The authors would like to express their sincere appreciation to the volunteers who participated in this study.

References
1) Boyaci, H. (2004) Perceived surface color in binocularly viewed scenes with two light sources differing in chromaticity. Journal of Vision, 4 (9), 664–79. doi:10.1167/4.9.1.
2) Fleming, R. (2004) Specular reflections and the perception of shape. Journal of Vision 4 (9), 798–820. doi:10.1167/4.9.10.
3) Govan, M., Kim, C., Holzberr, F., Greene, A. and Krupp, E. (2013) James Turrell: A retrospective. 1st ed. Los Angeles, Munich, New York: Prestel USA.
4) Gregory, R. (1997) Knowledge in perception and illusion. Philosophical Transactions of the Royal Society B: Biological Sciences, 352 (1358), pp.1121-27.
5) Hill, H. and Bruce, V. (1993) Independent effects of lighting, orientation, and stereopsis on the hollow-face illusion. Perception, 22 (8), pp.887-97.
6) Hill, H. and Bruce, V. (1994) A comparison between the hollow-face and 'hollow-potato' illusions. Perception 23 (11), pp.1335-37.
7) Kalay, Y. (2004) Architecture’s new media: Principles, theories, and methods of computer-aided design. Cambridge, Massachusetts: MIT Press.
8) Mardaljevic, J. (2001) The BRE-IDMP dataset: A new benchmark for the validation of illuminance prediction techniques. Lighting Research and Technology, 33 (2), pp.117-34.
9) Papathomas, T. (2002) Experiments on the role of painted cues in Hughes's Reverspectives. Perception, 31 (5), pp.521-30.
10) Reinhard, E. and Devlin, K. (2005) Dynamic range reduction inspired by photoreceptor physiology. IEEE Transactions on Visualization and Computer Graphics, 11 (1), pp.13-24.
11) Reinhard, E., Heidrich, W., Debevec, P., Pattanaik, S., Ward, G. and Myszkowski, K. (2010) High dynamic range imaging: Acquisition, display, and image-based lighting. 2nd ed. Morgan Kaufmann.
12) Vlajnic, V., Papathomas, T., Keane, B., Zalokostas, A. and Silverstein, S. (2014) What's in a face? The role of depth undulations in three-dimensional depth-inversion illusions. Perception, 43 (5), pp.381-94.
13) Ward, G. and Shakespeare, R. (1998) Rendering with radiance: The art and science of lighting visualization. Morgan Kaufmann Publishers.