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Reproduction of Perceptual Translucency by Surface Texture in 3D printing

Kazuki Nagasawa [1*], Kamui Ono[1*], Wataru Arai[2], Norimichi Tsumura[1]

1) Graduate School of Science and Engineering, Chiba University, Chiba, Japan

2) MIMAKI ENGINEERING CO., LTD., Nagano 389-0512, Japan

**** The first and second authors are equally contributed in this paper.***

Abstract

We propose a method of reproducing perceptual translucency in three-dimensional printing. In contrast to most conventional methods, which reproduce the physical properties of translucency, we focus on the perceptual aspects of translucency. Humans are known to rely on simple cues to perceive translucency, and we develop a method of reproducing these cues using the gradation of surface textures. Textures are designed to reproduce the intensity distribution of the shading and thus provide a cue for the perception of translucency. In creating textures, we adopt computer graphics to develop an image-based optimization method. We validate the effectiveness of the method through subjective evaluation experiments using three-dimensionally printed objects. The results of the validation show that the proposed method using texture is effective in improving perceptual translucency.

1. Introduction

In the field of 3D printing, research on reproducing a translucent appearance has been conducted in line with the development of printing technology. Early studies reproduced spatially heterogeneous BSSRDFs by combining and stacking multiple translucent materials available for multi-material 3D printers or milling machines at spatially different thicknesses [2][3]. Taking a different approach, Papas et al. proposed a method of controlling sub-surface scattering using a mixture of transparent materials and pigments [4]. In recent years, Takatani et al. proposed a method using ultraviolet (UV) ink [5]. Their method reproduces arbitrary modulation transfer functions (MTFs) by layering an optimized amount of UV ink on top of materials such as wax or eraser rubber.

As described above, there have been many studies on translucent reproduction in 3D printing, whereas few works have focused on the perceptual aspect of translucency. We therefore propose a new method for reproducing translucency in 3D printing, focusing on the perceptual aspect of translucency. The idea is to reproduce the cues of human translucency perception using surface textures. Although the mechanism of translucency perception in the visual system is not fully understood, it has been suggested that it depends on several cues [1]. Moreover, various cues are commonly related to the surface brightness distribution [8][9]. We thus consider that it is possible to improve perceptual translucency using textures to represent patterns of surface brightness that are effective in translucency perception. In the present study, we considered two main translucent perceptual cues. The first was the high-frequency contrast in non-specular regions shown by Motoyoshi [8], who found that perceived translucency increases with decreasing high-frequency contrast in the non-specular region. The second was the covariance between the surface normal and shading shown by Marlow et al. [9]. In general, the shading intensity covaries with the normal direction of the surface; however, it has been reported that perceptual translucency improves when this covariance is lost.

In this paper, we propose a method of improving perceptual translucency by representing the above two main cues using surface textures. The first step is to create a texture based on the translucent perceptual cues using computer graphics technology. This process includes the calculation of light occlusion patterns and processing of the generated texture images. First, the method of ambient occlusion [10] is adopted to generate a texture that represents shading according to the degree of occlusion due to the object geometry. Next, image processing operations are implemented to represent the translucency perception cues. Finally, the generated textures are applied to the 3D printed object and the effectiveness of the method is validated in subjective evaluation experiments. This paper proposes a method based on the perceptual aspect of translucency; there have been few such methods proposed in the field of translucent reproduction in 3D printing. Furthermore, the study is unique in that it expresses translucency through texture only, even though internal scattering does not actually occur.

2. Related Work

2.2 Fabrication of Translucency

In the field of 3D printing, many studies have investigated the reproduction of translucent appearances. Our study aims to reproduce translucency in 3D printing, and we thus introduce related works in this field. In early works, various scattering behaviors were approximated by overlaying materials with different scattering properties [2] [3]. The scattering is calculated using Kubelka–Munk's multilayer scattering model, which assumes a horizontally semi-infinite media and is therefore not suitable for curved geometries. In addition, the range of BSSRDFs that can be represented is limited to the available materials. Meanwhile, Papas et al. proposed a method of controlling sub-surface scattering by mixing pigments with a transparent base material [4]. Their method realizes data-driven concentration optimization by measuring the scattering properties of mixed materials and creating a database; however, it is limited by the fact that materials are spatially homogeneous and the geometry is created using molds.

Takatani et al. reproduced an arbitrary MTF by layering UV-curable inks on translucent materials such as eraser rubber and wax [5]. They treated the spread of light as a translucency index, which is generally expressed by the point spread function obtained by measuring the intensity distribution of reflected light when a point light source irradiates an object. The MTF is related to the point spread function by the Fourier transform, and the MTF is employed because of its simplicity of measurement. This approach has the limitation that the MTFs that can be produced are not exhaustive, because few varieties of material are used in implementing the method.

There are studies that reproduce arbitrarily the line spread function using multilayered inks with optimized layouts, restricting the modeling object to human skin [12]. Nagasawa et al. proposed a method of reproducing the line spread function as an index of arbitrary skin tone and translucency by representing the epidermal and dermal layers, which are components of human skin, as thin layers of ink and varying the number of each type of layer (i.e., thickness). In this method, an encoder–decoder deep neural network is used to determine the optimal multilayer layout; however, the training data are created using patches actually fabricated by a 3D printer, which is costly. Nagasawa et al. thus developed a method of reproducing multilayer patches on a computer by simulating light scattering using a Monte Carlo method to generate training data [13]. Another approach reproduces the appearance of realistic skin by extracting a concentration map of pigment components from an image of human skin taken with an RGB camera and fabricating a multilayered structure that imitates actual skin [14].

Whereas the above studies focused on defining and reproducing a physical index of translucency, our study focuses on the perceptual aspects of translucency. As an example of a method based on the perceptual aspect of translucency, Brunton et al. proposed an end-to-end pipeline that reproduces color and translucency using the concept of translucent metamers [6]. They focused on the characteristics of human translucency perception and considered that the visual system does not solve inverse problems of light transport, such as estimating physical parameters [1]. To control for perceptual translucency, they used the index A, a perceptually uniform translucency scale. This is the scale proposed by Urban et al. [7] and derived in psychophysical experiments, and a set of isotropic materials are provided that cover this scale. By relating this index A to the A of the RGBA signal, which is a typical texture format, it is possible to change the translucency linearly in a perceptual manner. Their method changes the horizontal and vertical light transport by editing the voxel arrangement inside the object. Our method differs most from Brunton's method in that we use only surface textures to represent pseudo translucent perceptual cues and thus do not actually generate scattering phenomena.

3. Making Textures for Perceptual Translucency

The purpose of this study is to generate perceptual translucency by applying a surface texture that reproduces the cues of translucency perception. To achieve this, we design textures based on two types of cues. The first cue for translucency perception is the high-frequency contrast as proposed by Motoyoshi [8]. When humans observe an object, a phenomenon is observed whereby the perceived translucency increases as the contrast, especially at high frequencies in the non-specular region, decreases. This phenomenon is considered to be due to sub-surface scattering, a physical property of translucent objects. The light that reaches areas that would normally be in shadow reduces the contrast. In addition, this phenomenon more likely occurs in areas with detailed structure (having high spatial frequency) because of thinness allows light to penetrate easily. On the above basis, we consider that it is possible to represent translucency by pseudo-brightening areas with a high degree of occlusion and reproducing a reduction in contrast.

The second cue for translucency perception is the covariance between the surface normal and shading as proposed by Marlow et al. [9]. In general, a surface is brighter when its normal faces the light source, and the farther the normal is from the light source direction, the stronger the shading on the surface. It is observed that humans perceive translucency when the covariance between the normal direction and shading is lost for some reason. We therefore consider that translucency can be represented by losing covariance between the normal direction and shading.

Both of the above cues are related to the shading intensity distribution (i.e., brightness distribution) of the object's surface, and we consider that it is possible to reproduce the cues using textures.

3.1 Ambient Occlusion

As described previously, the objective of this study is to create textures that change the distribution of the apparent shade intensity. Shading results from the occlusion of light by the geometry. In addition, shading is greatly affected by changes in the lighting environment. Considering these two factors, a base texture is created using the method of ambient occlusion. This method calculates the intensity of shading according to the occlusion of ambient light by the geometry [10]. The target is ambient light, which is basically present in any lighting environment, and the system is thus highly robust against changes in the environment.

In this study, we use Blender [17], which is free modeling and rendering software with the method of ambient occlusion built in [18]. The results of applying the method of ambient occlusion are shown in Figure 1. The geometry of a dragon is imported from the Stanford 3D Scanning Repository [19]. It is seen that shading is added according to the degree of occlusion.

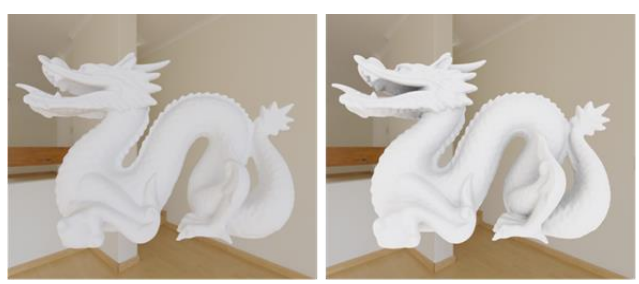


Figure 1. Natural shading added by applying the method of ambient occlusion.

3.2 Texture Processing

Adopting the above method, we create a texture that reproduces translucent perceptual cues by manipulating the ambient occlusion texture. There are three specific processes: gray-level inversion, gray-level range limitation, and gamma correction. To implement all three operations in a single operation, equation (1) is applied to all pixel values I in the texture image:

$$I' = R \times \left(\frac{255 - I}{255}\right)^{\frac{1}{\gamma}} + (255 - R), \quad (1)$$

where I' is the pixel value after processing, R is the number of gray levels (1–255), and γ is the gamma value in gamma correction. The effect of each operation is adjusted using R and γ as parameters.

We next describe the objectives of each operation. We first explain gray-level inversion. The luminance of the ambient occlusion texture is set so that the areas where ambient light is occluded are darker and the areas where it is not occluded are brighter. In contrast, our method aims to reduce or invert contrast by brightening the shaded area to make it appear as if there is sub-surface light transport. We therefore invert the gradations of the ambient occlusion texture to produce a texture that is lighter in the occluded areas and darker in the non-occluded areas. However, the large difference in brightness between the occluded and non-occluded areas may not be appropriate for reducing contrast. We therefore implement a gray-level range limitation.

In an ambient occlusion texture having an inverted gray level, the non-occluded areas are dark, and we thus restrict the gray-level range of the texture image to the high-luminance range. For example, if the number of shades R is set at 127, all pixels have pixel values within the range from 128 to 255. The gray-level range is adjusted according to the cues of translucency perception that are to be reproduced.

We finally explain the purpose of gamma correction. It has been shown that thin or detailed regions of a structure are important in translucency perception [16]. Therefore, it is necessary to have a large effect even in areas where the degree of occlusion is relatively small (i.e., thin and detailed areas). To achieve this, a gamma correction is applied to expand the effect of reducing shadows to areas with smaller occlusion. Figure 2 shows examples of textures created by varying the parameters R and γ. A texture image is shown on the right side of each panel and a rendered image with the texture applied is shown on the left side. It is seen that the parameters can be adjusted to generate textures with different characteristics.

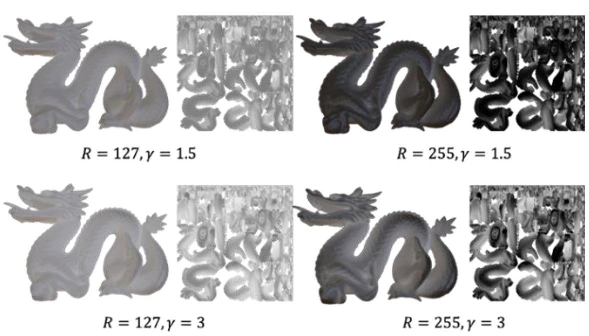


Figure 2. *Examples of textures with different parameter values. R is the number of gray levels (1–255) and γ is the gamma value used in gamma correction.*

3.3 Setting Parameters

Our method reproduces the two translucent perceptual cues mentioned previously. Accordingly, we define indexes with which to evaluate the applicability to each cue and determine the parameters R and γ. To enable image-based parameter optimization, we propose a method using rendered images of textured objects.

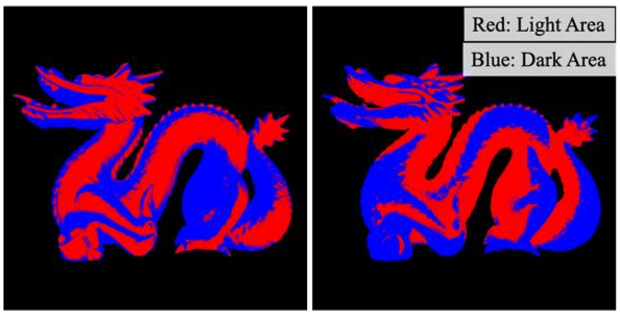
First, multiple combinations of the parameters R and γ are selected to generate a set of textures. The number of gray levels R is set at 63, 127, 191, and 255. The gamma value γ is set at several values between 0.5 and 3, which are known to be empirically valid, namely 0.5, 0.7, 1.0, 1.5, 2.0, 2.5, and 3.0. These parameters are combined to create 28 different rendered images. The number of parameter combinations is limited considering the cost of rendering. Rendering is performed using Blender [17]. For the lighting environment, Lebombo, a high-dynamic-range environment map of a room with sunlight, was obtained from Poly Haven [20] and used to represent a typical diffuse lighting environment. Examples of rendered images are shown to the left of each item in Figure 2.

The appropriate parameters are selected using the 28 images rendered using the method described above. We first discuss the first objective, contrast reduction. This objective is based on the observation that light penetrating the occluded area weakens the shading and the resulting reduction in contrast improves perceptual translucency [8]. The texture of the proposed method is designed to brighten the occluded areas and weaken the shading, and we thus select the parameter to maximize this effect. For calculating the contrast, we use the Michelson contrast expressed by

$$C = \frac{I_{max} - I_{min}}{I_{max} + I_{min}}, \quad (2)$$

where I_{max} is the maximum pixel value and I_{min} is the minimum pixel value in the image. The calculation method follows the literature [8] by calculating the contrast in multiple spatial frequency sub-bands and averaging the results. Sub-band images are generated by applying a Gaussian band-pass filter with a bandwidth of 20 in the frequency space. Nine sub-band images are created, and the contrast is calculated for a total of 10 images including the original image. Here, a mask is applied to extract only the object region from the rendered image. In this process, the sub-band image has a high-contrast boundary between the object and background owing to the effect of the band-pass filter, and the mask is therefore blurred to eliminate this effect. Finally, the contrast is calculated for the object regions in the 10 obtained images, and the parameter with the smallest average contrast is determined as the optimal parameter. In this paper, the texture whose parameters are determined by this index is referred to as texture 1.

We next discuss the second objective, limiting covariance between the surface normal and shading. This objective is based on the observation that translucency is perceived when the covariance between the direction of the surface normal and shading is lost [9]. The normal direction and shading intensity generally covary in the opaque case (without texture). Therefore, adjusting the texture so that the distribution of the shading intensity is different from that in the opaque case would improve perceptual translucency. Accordingly, the difference in the intensity pattern of the shading from the opaque case is used as an indicator. The calculation method of this indicator is described below. First, considering the encoding of the distribution of shading on the surface, we define light and dark areas. In the case of an opaque object, the non-occluded area is bright, and the occluded area is dark; we thus consider these as light and dark areas, respectively. In a rendered image, the median pixel value in the object region of the image is used as a boundary with which to divide pixels into light and dark areas. The pattern of shading encoded by the above process is shown in Figure 3. The index is calculated by comparing the number of pixels with different signs relative to the rendered image without texture (Figure 3(a)). The parameters having the largest value for this index are selected as being optimal. In this paper, the texture whose parameters are determined by this index is referred to as texture 2.



(a) Without Texture **(b) With Texture**

Figure 3. *Overview of encoding shading patterns. The light and dark areas, which are divided by the median of luminance on the surface, are respectively shown in red and blue. It is seen that the pattern differs greatly depending on the presence or absence of texture.*

4. Experiment

This section describes the validation of our method for representing perceptual translucency with textures. Textures created using the method described in the previous section were applied to an object for fabrication using a 3D printer. We validated the effectiveness of our method by conducting a subjective evaluation experiment on the perceptual translucency of the fabricated samples.

4.1 Fabrication of Samples

We used four geometries, namely a dragon, bunny, Buddha, and armadillo, taken from the Stanford 3D Scanning Repository [19]. For each geometry, we created a texture whose parameters were determined using the two indexes described in the previous section. In addition to these eight samples, non-textured samples were fabricated to validate the effect of the texture. The bulk was fabricated entirely with 100% white ink and was physically opaque. The 3D printer used in this experiment was a Mimaki Engineering 3DUJ-553 [11]. Figure 4 shows the fabricated samples.

Figure 4. *Fabricated samples. For each geometry, from left to right, the order is without texture, with texture 1, and with texture 2.*

4.2 Experimental Design

In validating the effectiveness of the proposed method, a subjective evaluation experiment was conducted to evaluate the translucency of each sample. In preparing for the experiment, we determined the definition and scale of translucency, the lighting environment, and the observation environment. The following is a description of each item.

We first discuss issues in considering definitions and scales of translucency. In the field of translucency perception, the term translucency is regarded as having no clear definition [1]. Commonly used psychophysical scaling methods, such as the adoption of magnitude estimation and rank order, are not appropriate in this case because of this ambiguity in the definition of translucency. Instead, many studies adopt matching tasks involving computer graphics [15] [16]. Although it would have been preferable to conduct a matching task in the present experiment, it is difficult to adjust parameters in real time in an experimental setting using real objects, making it impossible to perform the task. Therefore, in this experiment, we established our own definition and scale of translucency and held a session to explain them to participants before the evaluation task. We referred to the relationship between scattering and transparency described in the literature [6] and defined translucency as an index determined by the relationship between horizontal and vertical light transport. When an object changes from opaque to transparent, it is known that the horizontal and vertical light transport changes as shown in Figure 5. The horizontal light transport (i.e., spread of light due to sub-surface scattering) does not change monotonically, and it is thus combined with the vertical (transmission) to uniquely define the degree of translucency as shown in Figure 5 Considering the balance between task difficulty and granularity, we designed a seven-level evaluation task as indicated by the circles in the figure.

The following is a description of the lighting environment. In the present experiment, four lighting environments were prepared as shown in Figure 6. We prepared multiple environments because it is known that the lighting direction affects the perception of translucency [1]. The first environment was of fluorescent light. The method of ambient occlusion is expected to be highly effective under such diffused illumination because it takes ambient light into account. The second environment was of artificial sunlight. Such lighting is commonly used in psychophysical experiments, and the booth used in the present experiment had top lighting. The third and fourth environments were of front and back lighting with illumination from light-emitting diodes. On the basis that back lighting enhances translucent perceptual cues more than front lighting in studies of translucency perception [15] [16], we used front and back lighting environments.

We finally describe the observation conditions. We conducted the experiment by observing the whole object and by observing a local area of the object. This was done knowing that important information as cues for translucency perception is enriched on edges, in thin areas, and in detailed shapes [16]. All the local areas had thin or detailed structure.

Experiments were performed under a total of eight conditions combining the lighting environments and observation conditions. The 12 samples described in the previous section were targets of observation. The objects were placed in a lighting booth at an observation distance of 60 cm. There were 10 participants, specifically nine males and one female in their twenties.

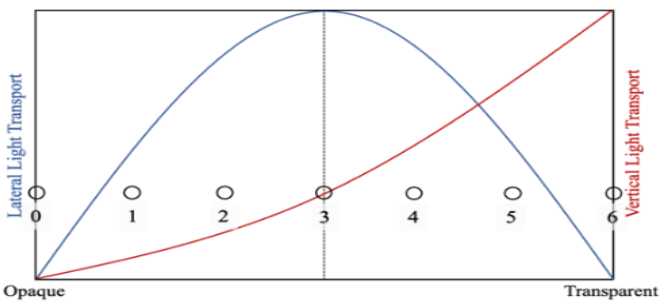


Figure 5. *Concept of the translucency scale in the experiment. The scale has seven levels, as indicated by the circles.*

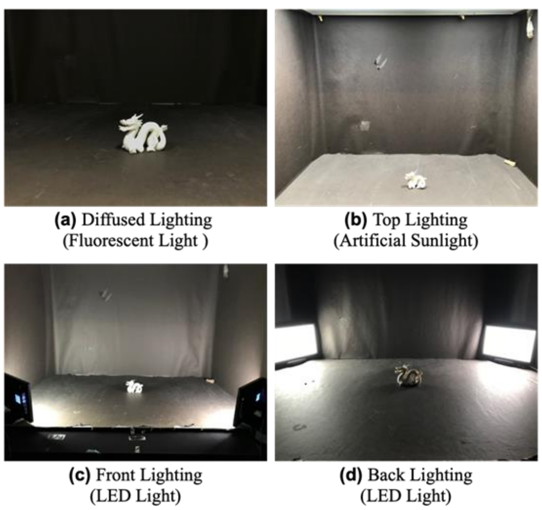


Figure 6. *Four lighting environments in the experiment.*

4.3 Results

Table 1 gives the average evaluation values across participants for each experimental condition. The evaluation values are given as the difference from the value for the sample that has no texture and positive values are presented in red. Under most conditions, at least one of the textures has the effect of increasing perceptual translucency. This indicates that the representation of translucency by texture is effective; however, the representation lacks robustness against the observation environment.

Table 2 compares the results for the observation areas. Each evaluation value is the average for each lighting environment and texture type. For geometries other than the bunny, it is seen that the observation of local areas with thin and detailed structures has higher perceptual translucency than the observation of the whole. We consider that the reason for the higher evaluation value for the observation of the whole bunny is that the thinness and complexity of the local area are lower in the case of the bunny.

Table 3 compares the results for lighting environments. Each evaluation value is the average of the observation areas and texture types. It is seen that the lighting environment providing the highest perceptual translucency is different for each geometry. The effectiveness of our method is thus affected greatly by the interaction between the geometry and lighting environment.

4.4 Discussion

We discuss the conditions for which there were particularly high and low evaluations of translucency. Figure 7(a) shows an image of the dragon object with texture 1 taken under the condition of front lighting. Note that this image was captured by a camera and therefore differs from the image perceived by human vision. Under this lighting condition, the evaluation value is particularly high in the whole-object observation. We consider that the effect of contrast reduction by texture 1 was appreciable under this lighting condition. Some of the participants who perceived high translucency also perceived a wet appearance. The possibility of a correlation between wetness and translucency is suggested and will be the subject of future research. Figure7(b) shows an image of the Buddha object with texture 2 taken under the condition of front lighting. Under this lighting condition, the evaluation value is particularly high in the whole-object observation. This is because the extreme brightening by texture 2 is concentrated in areas with detailed structure. There are thus many cues for translucency perception under this condition. Finally, Figure 7(c) shows an image of the Buddha object with texture 2 taken under the condition of diffused lighting. Under this lighting condition, the texture reduces the perceptual translucency in the whole-object observation. Most of the participants commented that the object appeared to have black paint on it, and it is thus assumed that this lighting condition caused the texture to be perceived as paint rather than as shadows.

Our method assumes that texture creation targeting ambient light is robust against changes in lighting conditions. However, the results were found to depend strongly on the object geometry and lighting.

Figure 7. *Examples of conditions with particularly high/low evaluation values of translucency: (a), (b) examples of a high evaluation value, and (c) an example of a low evaluation value.*

5. Conclusions and Future Works

We proposed a method of representing perceptual translucency in 3D printing using textures. We focused on the cues by which humans perceive translucency and enhanced perceptual translucency by reproducing the cues through surface textures. The textures were designed to reproduce translucent perceptual cues relating to the distribution of the shading intensity. We proposed an image-based method using computer graphics for optimizing the parameters used in texture creation. Subjective evaluation experiments were conducted to validate the effectiveness of this method, and the results showed that the method had a certain effect in improving perceptual translucency. Specifically, either or both textures improved translucency in 29 of 32 conditions.

Our method is based on the method of ambient occlusion and thus considers only ambient light and not other lighting environments. As a result, the perceived translucency was greatly affected by the lighting environment. Therefore, as future work, it is necessary to develop a method for designing textures that considers the target lighting environment. Here, it is noted that our method is more suitable for a particular lighting environment.

Although the present study focused on reproducing perceptual translucency, we suggest the possibility of expressing a unique appearance that changes depending on the angle of view and lighting environment by combining our texture with conventional methods of altering scattering characteristics.

Table 1. Mean evaluation values of the particpants (relative to the non-textured sample)

Lighting Environment	Diffused	Diffused	Top	Top	Front	Front	Back	Back
Observation Area	Whole	Local	Whole	Local	Whole	Local	Whole	Local
dragon(Texture1)	-0.1	0.2	0.8	1.3	1.3	0.2	-1.6	-0.3
dragon(Texture2)	0.1	-0.7	-0.6	0.3	0.4	-1.2	-0.5	-0.3
bunny(Texture1)	0.7	0	0.3	1.3	0.9	-1	-0.8	0.2
bunny(Texture2)	0.7	0.6	-1.6	1.2	-0.4	-0.3	0.1	-0.9
buddha(Texture1)	-1	0.7	0.8	-1	-0.2	0.4	0.4	1.2
buddha(Texture2)	-1.2	0.2	1.9	0.2	2	0.9	-1.4	1.7
armadillo(Texture1)	1.3	0.8	-0.5	0.4	-0.4	1	0.3	0.1
armadillo(Texture2)	-0.1	0.5	1.7	0	1.4	1	-1	1.1

Table 2. Comparison of evaluation values for observation areas

	Whole	Local
dragon	1.23	1.26
bunny	1.44	1.42
buddha	1.36	1.61
armadillo	1.30	1.61

Table 3. Comparison of evaluation values for lighting environments

	Diffused	Top	Front	Back
dragon	0.92	1.25	1.47	1.35
bunny	1.33	1.55	1.37	1.47
buddha	1.38	1.42	1.57	1.57
armadillo	1.77	1.42	1.60	1.03

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