Toon-shading - Perception of glossiness

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Aiming for grade A.
Github, with the source code:
`https://github.com/malinjam/DH2323-Toon-Shader`
Blog:
`https://malinjam.github.io/DH2323-Toon-Shader/index.html`

1 Abstract

Toon-shading is a popular rendering technique known for its ability to produce cartoon-style visuals. When employing stylized shading methods, striking a balance between artistic expression and visual clarity becomes crucial. Glossiness plays a significant role in rendering textures as it provides essential information about a material's surface properties. Therefore, the perceived glossiness of a toon-shader becomes crucial for maintaining clarity in rendering various objects. This study aims to examine and compare the perceived glossiness of painted cardboard, rolled brass, and lightly brushed aluminium when rendered on both regular and irregular 3D objects using a toon-shader. An online survey is utilized as the primary means to gather perceptual data and insights regarding the rendering of these materials. The study found that the majority of participants perceived the gloss on an irregular object as more glossy than on a regular object.

2 Introduction

There are many different ways to render objects and people graphically. Rendering in computer graphics refers to the process of generating an image using software programs from a model. Shading is one of the key aspects that must be decided when rendering, and there are many different styles that highlight different aspects of the image. However, the choice of shader is not only an artistic choice but also a practical one. There are many aspects of clarity that may be affected by the choice of shader, Vangorp's 2009 paper [12] investigated numerous things, one of them being how the perception of Ward model glossiness changes depending on the object rendered. This study aims to conduct a similar investigation, specifically examining the commonly used toon/cel-shading technique.

2.1 Glossiness

For the purposes of this study, glossiness is defined as a visual property that describes the smoothness or shininess of a surface. It refers to the ability of a material to produce specular highlights or concentrated reflections. Surfaces with high glossiness appear shiny and reflective, like a polished mirror, while surfaces with low glossiness appear dull and diffuse, like a matte surface.

2.2 Toon-shading

Toon-shading is a non-photorealistic rendering technique that gives a mesh a cartoonish appearance, resembling a hand-drawn illustration in the final render. This technique has long been employed in the animation industry and is also prevalent in video games. Traditional toon-shading determines the color of an area based on the orientation of a 1D texture relative to a light source, extending the Lambertian shading model, which assumes that light is evenly scattered in all directions upon hitting a surface, with no preferential reflection or refraction. This means that the surface appears equally bright from any viewing angle, regardless of the position of the light source. This approach accurately renders every surface location, enabling the shader to capture even small shape features. However, toon-shading is view-independent, which means that the appearance of the shading does not change based on the viewer's perspective or viewing angle, and therefore cannot accurately render materials like metal or plastic that rely on view-dependent highlights [1].

2.3 Ward's BRDF model

Ward's anisotropic distribution is a widely used reflectance model for generating specular reflections [13] (Fig. 1). BRDF (bidirectional reflectance distribution function) is a function that incorporates four angles (two reflective and two incident), as well as the polarization and wavelength of the incident radiation [14].

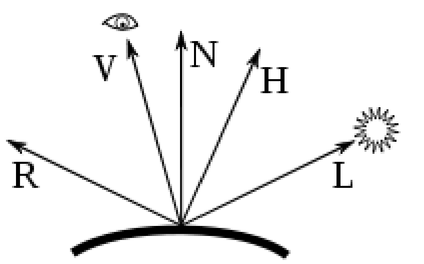

Figure 1: Ward's light reflection model, where L denotes the incident light vector, R the reflected light vector, V the vector to the viewer, N the surface normal, and H the halfway vector between the normal and L.

In Figure 2, the formula employed in the toon-shader for isotropic materials is depicted. This formula is also utilized in the base paper by Vangorp [12], where the parameters ρ_d represent the diffuse reflectance, ρ_s represent the specular reflectance, α denotes the isotropic surface roughness parameter, and θ_i, θ_o, and θ_h represent the elevation angles of the incident light direction ω_i, the outgoing light direction ω_o, and the halfway vector ω_h, respectively.

$$f(\theta_i, \theta_o) = \frac{\rho_d}{\pi} + \frac{\rho_s}{4\pi\alpha^2\sqrt{cos(\theta_i)cos(\theta_o)}} e^{-\frac{tan^2(\theta_h)}{\alpha^2}}$$

Figure 2: Ward's formula for isotropic materials.

2.4 Objective

The objective of this study is to examine and compare the visual perception of glossiness in toon-shaded objects that vary in shape and materials. A custom toon-shader was developed specifically for this research, utilizing Unity and drawing upon various tutorials and papers. The primary aim is to investigate how participants perceive and differentiate the glossiness of these objects.

To accomplish this, a perceptual study was conducted, involving participants who were tasked with selecting the object they deemed to be more glossy. For instance, pairs of spheres with different materials were presented to the participants, and they were required to choose one of the spheres based on their perception of glossiness. This study aims to shed light on whether the shape or material of an object has an impact on its perceived glossiness. Additionally, it explores whether certain shapes facilitate easier differentiation of glossiness.

The hypotheses for this study are as follows:

- Shape Perception: It is hypothesized that the shape of an object will influence the perception of glossiness. Objects with a less uniform shape, such as a triceratops, are expected to exhibit glossiness more prominently and be easier to perceive in comparison to objects with a more uniform shape, such as a sphere.

- Material Discrimination: The hypothesis posits that materials with a low perceptual distance will present a greater challenge in differentiating glossiness. In other words, when the perceptual differences between materials are minimal, participants may find it harder to distinguish variations in glossiness.

3 Related work

To date, there is a scarcity of perceptual studies specifically investigating the effects of a toon-shader. This can be attributed to the predominant preference within the rendering industry for achieving realistic effects and utilizing shaders that emulate real-world materials. Consequently, a significant body of research has been dedicated to exploring and refining realistic rendering techniques. As previously mentioned, Ward provides valuable insights into the importance of anisotropic reflection and offers practical methods for its accurate representation in virtual environments [14].

In their research conducted in 2001 using Ward's light reflection model, Pellacini et al. [2] demonstrated that, in general, lighter objects (high ρ_d) necessitate more significant alterations in material properties compared to darker objects (low ρ_d) in order to generate noticeable variations in gloss. This is due to the fact that, for a fixed ρ_s (specular reflectance), lighter objects exhibit lower contrast gloss than darker objects.

Moreover, they demonstrated that the space of gloss is composed of two dimensions: contrast and sharpness (Fig. 3), and defined an equation that computes the perceptual distance between two objects within the gloss space (Fig. 4).

$$c = \sqrt[3]{\rho_s + \frac{\rho_d}{2}} - \sqrt[3]{\frac{\rho_d}{2}}$$

$$d = 1 - \alpha$$

Figure 3: Definition of contrast (c) and sharpness (d) within the Ward's light reflection model.

$$D_{ij} = \sqrt[2]{[c_i - c_j]^2 + [1.78(d_i - d_j)]^2}$$

Figure 4: Perceptual distance equation of two objects within the gloss space.

Lastly, they introduced the concept of *iso-gloss contours*, which defines that objects with different sharpness and contrast values can be perceived as equally glossy. This emerges from the fact that gloss is a two-dimensional space, and therefore two objects can be equally distant from the origin (0,0) even if their coordinates are not the same.

Vangorp further expanded upon the research in this area [12] by conducting a perceptual study to delve into the perception of glossiness variations. The study revealed that using a sphere as the base model to visualize selected material parameters may not accurately represent the appearance of the chosen material on the target shape. It was discovered that spheres have relatively low discriminatory power in accurately judging materials, implying that alternative shapes, potentially tailored to the material class or resembling the target shape, could be more effective in material selection.

Building upon these insights, Vangorp conducted an additional perceptual study as a part of his research, with the goal of developing a novel concept termed *shape-dependent gloss correction* within material selection tools. This concept aims to ensure consistent perceptual gloss across different shapes, addressing a common challenge encountered by both novice and experienced artists. The integration of shape-dependent gloss correction into material selection processes enhances intuitive decision-making, streamlining the workflow for artists and designers.

The study employed image pair comparisons (Fig. 5), featuring objects with distinct or identical shapes and varying levels of glossiness. Leveraging the findings of Pellacini et al. [2], Vangorp utilized a single material with a constant ρ_d (diffuse reflectance) and manipulated the ρ_s (specular reflectance) and α parameters to control the contrast and sharpness of the objects. Participants were tasked with determining "Which object is more glossy?" based on their visual judgments.

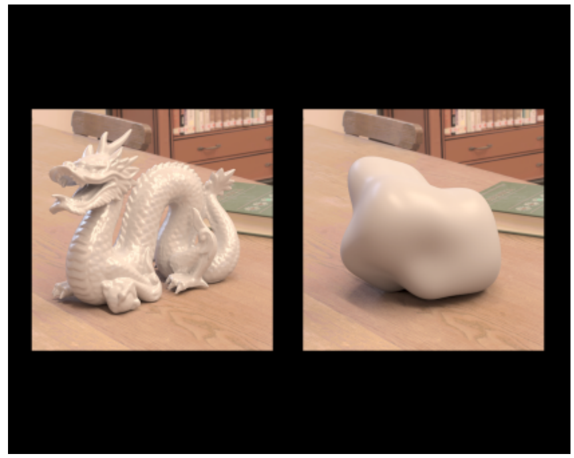

Figure 5: Example of image pair used in Vangorp's perceptual study [12].

4 Implementation

As a shader is part of the rendering process of a 3D scene, the project required a software tool capable of doing so while also allowing us to develop the shader algorithm and apply it during the rendering process.

A broad range of options are available on the market. The Unity engine was selected for this study as it could enrich the project by not only providing the necessary tools to build a shader but also by allowing users to make use of its multiple built-in functionalities and available assets.

Unity offers two different options when it comes to shader development:

- **Unity's ShaderLab**: Purely code-based development.
- **Shader Graph**: A GUI that allows developers to create their own shader without writing code.

The researchers decided to use **Unity's ShaderLab** since one of the goals of this project was precisely learning how to develop a shader in Unity. Moreover, ShaderLab also provides users with great adaptability and flexibility of shaders, which is vital to the development of the shader used in this evaluation as it is a combination of both a traditional toon-shader and the Ward model.

To begin the development of the shader, a toon-shader was developed with the help of a guideline provided by Erik Roystan [9]. This is a shader that's built on top of the Blinn-Phong model and applies some filters to the results in order to make it look cartoonish. The Blinn-Phong model is an efficient approximation of lightning that makes use of the same vectors as in the Ward light reflection model (fig. 1), however, their specular reflections are not as accurate as in the Ward model.

In order to recreate the study conducted by Vangorp et al. [12], our toon-shader needed to be based on Ward's light reflection model, not Blinn-Phong. Therefore, a Ward Model Shader was developed from scratch, which was able to depict realistic reflections and allowed the researchers to modify the surface roughness α, the specular reflection ρ_s and diffused reflection ρ_d of an object, enabling the team to create multiple materials with glossy properties.
This shader was then further enhanced by applying the same toon filters as in Erik Roystan's toon-shader [9], which resulted in a Ward model-based toon-shader.

Once the shader was complete, materials and 3D objects were obtained and selected. These were then implemented in a single Unity scene. Each material was then implemented with three different ρs values to create different levels of glossiness in the same material. These were then individually documented and included in the form used for the study.

4.1 Division of work

There was an equal division of labor in the project. The original toon-shader was implemented by Malin, the toon-shader with the ward model was implemented by Ferran. The objects used in the study were all assembled by Maria. She also made the blog page. The selection of materials was done together, and each person then applied the different steps to one of the materials. These were then put into a single scene and screen-shotted by Ferran. Malin and Maria then structured a set of questions and imported the images into a survey. The report has been written collaboratively.

4.2 3D objects

In this study, the 3D objects utilized were obtained from the website Free3D [3], which offers freely available assets suitable for conducting perceptual studies. Additionally, commonly used 3D objects such as a sphere, cylinder, and capsule, readily accessible within the Unity platform, were also used.

During the development phase of the study, the following items were initially considered for inclusion:

- knife [11]
- rabbit [6]
- teapot [4]
- triceratops [7]
- car [15]
- rock [8]
- dragon [10]

However, due to time constraints and considerations regarding participant workload, the final selection was limited to two shapes: the sphere and the triceratops. In order to have one uniform and nonuniform shape.

4.3 Materials rendered

In order to decide what materials to include in the study the researchers took inspiration from Vangorp's study: *Human Visual Perception of Materials in Realistic Computer Graphics* [12]. This study was at a much larger scale and investigated the glossiness perception for 10 materials rendered on 11 shapes in 2AFC (2-alternative forced choice). Below are the materials included in Vangorp's study.

```
Acrylic blue, aluminium, gold metal, copper,
metallic blue, metallic silver, nickel,
nylon, light red paint and pearl paint.
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The shapes included in that study are listed below.

```
A blob, buddha, bunny, car, cylinder,
dragon, rounded icosahedron, sphere, teapot,
tessellated sphere and a triceratops.
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A variety of materials were created for this study based on Vangorp's study, drawing inspiration from the popular video game *The Legend of Zelda: Breath of the Wild(2017)* [5]. The selected materials included are listed below.

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Glass, iron, gold metal, clay, metallic
blue, metallic silver, stone, leather, red
paint, and pearl opal.
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These materials were created based on reference images, ensuring visual accuracy and resemblance to the materials found in the game. Figure 6 displays an example of a material created and used on a sphere and a picture taken from the game, used for reference during the implementation process.

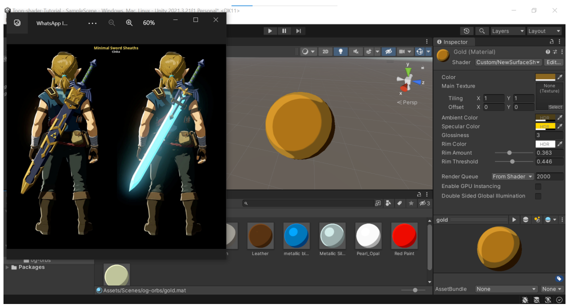

Figure 6: Example of how the gold material was created with a reference picture taken from the video game "The Legend of Zelda: Breath of the Wild" [5].

Upon conducting additional research, the researchers made the decision to adopt the specular gloss values proposed by Ward in his original study [14] to characterize the glossiness of different materials. These values are depicted in Figure 7. Additionally, to avoid participants identifying the materials based on their colors, a single color was chosen from the gold material depicted above. This approach ensures that the focus of the study remains on the perception of glossiness rather than the identification of specific materials.

Material	ρ_d	ρ_s	α_x	α_y
rolled brass	.10	.33	.050	.16
rolled aluminum	.1	.21	.04	.09
lightly brushed aluminum	.15	.19	.088	.13
varnished plywood	.33	.025	.04	.11
enamel finished metal	.25	.047	.080	.096
painted cardboard box	.19	.043	.076	.085
white ceramic tile	.70	.050	.071	.071
glossy grey paper	.29	.083	.082	.082
ivory computer plastic	.45	.043	.13	.13
plastic laminate	.67	.070	.092	.092

Figure 7: Ward's values for to generate the specular gloss associated with a number of materials [14].

The materials and objects chosen for this evaluation were extracted from this list, which initially included 10 materials and 10 objects. However, to focus the evaluation, only 2 objects and 3 materials were chosen. These were a sphere and a triceratops for the objects and a rolled brass, lightly brushed aluminium and painted cardboard box. The objects were chosen because they were the extremes on the scale of irregular and regularly shaped objects. While the materials were chosen both because versions of the materials appeared on both lists and also due to their variety in ρ_s value (Fig. 7).

Moreover, each material will have two variations (Tab. 1 and Tab. 2), as the study aims at finding insights into how the participants will perceive a change in glossiness within the same material properties. To do so, each material had a variation with less ρ_s and another with more ρ_s (the rest of the properties were fixed within each variation). Therefore, the study ended up including 9 material variations (3 cardboard, 3 aluminium, and 3 brass materials). Since the specular reflection (ρ_s) of the three original materials is approximately equally distant by 0.14, we designed that each variation would vary the ρ_s by 0.05 making each material, more or less, equally distant in the specular reflection space.

Material	α	ρ_s	ρ_d	c	d
Cardboard	0.085	0.00 0.043 0.093	0.19	0.00 0.043 0.081	0.92
Aluminium	0.13	0.14 0.19 0.24	0.15	0.12 0.15 0.18	0.87
Brass	0.16	0.28 0.33 0.38	0.10	0.22 0.24 0.26	0.84

Table 1: Material's values and their variations in ρ_s.

Material	ρ_s 1	ρ_s 2	D_{ij}	$\mu_{D_{ij}}$
Cardboard	0.00 0.00 0.043	0.043 0.093 0.093	0.043 0.081 0.038	0.054
Aluminium	0.14 0.14 0.19	0.19 0.24 0.24	0.027 0.05 0.023	0.034
Brass	0.28 0.28 0.33	0.33 0.38 0.38	0.019 0.037 0.017	0.025

Table 2: Perceptual Distance (D_{ij}) between all ρ_s variations within the same material, and their average distance within that material ($\mu_{D_{ij}}$).

5 Perceptual study

An empirical investigation was conducted involving 30 participants (between the ages of 21 and 50) to examine perceptual discrimination ability. The study employed the 2-alternative forced choice (2AFC) method, a psychophysical experimental technique utilized to measure individuals' ability to differentiate perceptual stimuli. This was done in accordance with Vargorp's study [12].

5.1 2-Alternative Forced Choice

In a 2AFC experiment, participants are presented with two options or stimuli and required to choose one based on specific criteria. The nature of the stimuli can vary depending on the experiment, encompassing images, sounds, or other sensory inputs. In this particular study, participants were given a survey consisting of 63 pairs of images. These images depicted either a sphere or a triceratops rendered with the toon-shader developed in this study. Participants were then prompted to answer the question, "Which object is more glossy?" (Fig. 8).

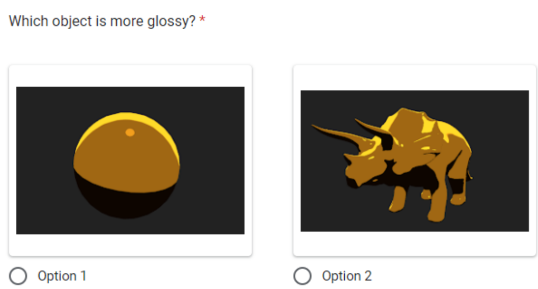

Figure 8: Example of image pair.

Among the image pairs, 9 pairs were identical in glossiness but differed in shape, while another 18 were identical in both shape and glossiness, despite the fact that both options are correct and incorrect answers to the presented question. The reason lies within Vargorp's study [12], where the same practice was performed. Since the objective was to replicate Vangorp's study as faithfully as possible, the researchers decided to include that step in their own study as well.

To provide participants with context, the study began with an explanation of glossiness and an illustrative example of image pairs.

5.2 Results

The study had a total of 30 participants who were able to accurately select the glossiness of the material 61% of the time. Many expressed that they thought the questions were very difficult.

The results show that there was a substantial difference between the different materials. particularly, painted cardboard was most accurately perceived with a percentage of 71%, whilst aluminium (62%) and rolled brass (67%) were both less accurately perceived and more similar to each other (Fig. 9).

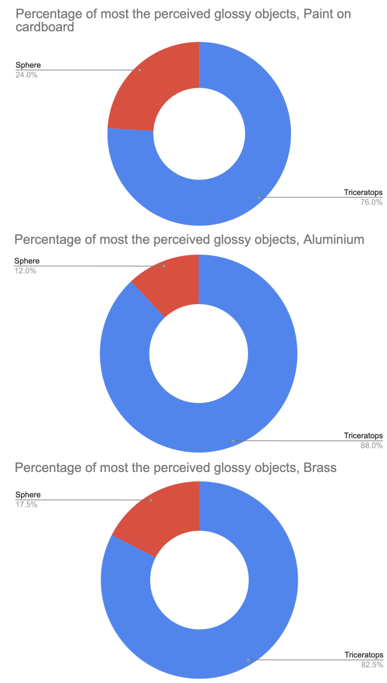

Figure 9: The percentage of triceratops answers vs the percentage of sphere answers in questions where both were compared.

However, when faced with the option between a triceratops and a sphere in 81% of the questions, the participants perceived the triceratops as more glossy than the sphere (chosen only 18% of the time), despite the fact that the correct answer was equally distributed between the sphere and triceratops. This bias was confirmed in questions with different objects but equal glossiness, where in 86% of the questions the triceratops was chosen (Fig. 10).

6 Conclusions

Our first hypothesis was found to be true: irregular objects are glossier (81%) compared to regular ones (18%). We conclude that the reflected surface is directly proportional to how glossy it is perceived. Such a reflected surface is dependent on the surface normal: the more perpendicular the surface normal is to the light vector (L), the shinier it will look. The triceratops presents a higher surface area whose normal is closer to being perpendicular to the L vector when compared to the sphere; therefore, the reflecting area

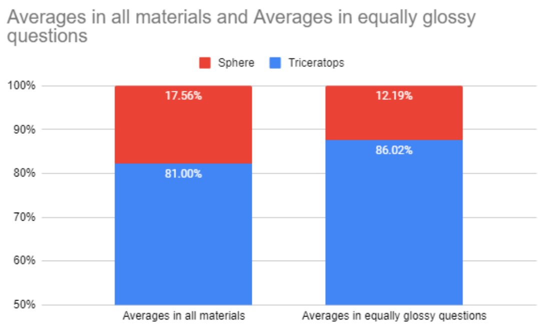

Figure 10: The distribution of answers depending for all questions with different objects rendered and for the questions with equal gloss displayed with different objects rendered.

is greater and the object is perceived as glossier. This fact has also been pointed out by one of our participants. We believe that, in general, irregular objects can be glossier than regular objects, but that doesn't depend on their shape but on the reflecting surface area at a given time.

Regarding our second hypothesis, we conclude that the perceptual distance (Fig. 4) is directly proportional to the difficulty experienced by our participants when guessing which material was glossier. Therefore, we validate the conclusions found by Pellacini et al. [2].

However, participants seemed to find it easier to spot a difference in glossiness within brass materials than in aluminium materials, despite the fact that aluminium had a higher average perceptual distance ($\mu_{D_{ij}} = 0.034$) than brass ($\mu_{D_{ij}} = 0.025$) (Fig. 11 and Tab. 2).

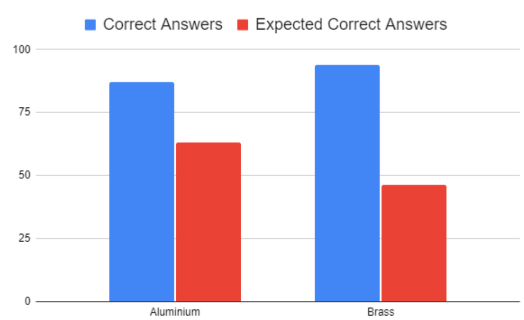

Figure 11: Percentage of correct responses compared to the percentage of expected correct responses following the average perceptual distance within Brass and Aluminium. The cardboard correct responses have been taken as ground truth.

We relate this finding to our study structure, as we believe that *2AFC* imposed our participants to guess between both options whenever they had doubts, which led to such differences. We conclude that another study approach could have solved this issue by, for example, adding the option: *"They are both equally glossy"* to our questions.

7 Future work

The current study provides a foundation for potential extensions and further investigations. Several possibilities for future research include:

- Parameter adjustments: Expanding the study by allowing users to customize and adjust specific parameters within the toon-shader. This would enable participants to explore the impact of various shader settings on their perception of glossiness.

- Diverse 3D objects: Applying the developed toon-shader to a wider range of 3D objects, including those that were not utilized in the present study. This would provide a broader understanding of how different shapes and materials interact with the toon-shader and influence the perception of glossiness.

- Expanded material variation: Increasing the range of materials used in the study to explore how different material properties impact the perception of glossiness in toon-shaded objects. By incorporating a wider selection of materials, researchers can gain insights into the specific characteristics that influence gloss perception within the context of toon-shading.

- Database development: Exploring the development of a comprehensive database for toon-shading materials by defining the different parameters. This database could serve as a valuable resource for the research community, providing a collection of pre-defined toon-shader settings and corresponding materials. Such a database could facilitate consistent and standardized experiments, as well as encourage further exploration and advancements in the field of toon-shading research.

- Enhanced perceptual study: Conducting a more comprehensive and detailed perceptual study. This could involve a larger participant sample, additional experimental conditions, and more refined methodologies to gather data. Such an approach would offer a deeper understanding of the factors affecting glossiness perception in the context of toon-shaded objects.

These proposed extensions could contribute to a more comprehensive understanding of the perceptual aspects of toon-shading and further enhance our knowledge in this area.

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