Modeling of Translucency by Physical Measurement of Flat Surfaces

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Abstract
While transmittance is a physically measurable quantity, people perceive it as the translucency of object surfaces. However, transmittance does not always match translucency. We measured the physical properties of object surfaces, including physical transmittance, and analyzed the relationship between the physical properties and translucency. We prepared 107 samples of flat objects that primarily consisted of resin for the experiment. We visually evaluated the perpetual gloss using a magnitude estimation method. We conducted multiple measurements of physical properties such as transmittance, haze, distinctness of image, and gloss unit. Then we constructed a prediction model for evaluating the perceptual gloss using the abovementioned physical properties and translucency through multiple regression analysis. As a result, the prediction accuracy is found to be improved by combining various physical quantities with simple regression using transmittance.

Keywords
Material appearance, transmittance, translucency, appearance prediction

1. Introduction

Material appearance is significant in various fields. As technologies such as printing and computer graphics are used in diverse industries, research on material appearance is of great interest. Translucency is one of the subfields of material appearance. Translucency is an optical and perceptual phenomenon characterized by subsurface light transmittance through objects and materials. The research on translucency is practical and worthwhile as it has applicability in the fields related to food, art, and cultural heritage. However, the existing knowledge about the visual mechanisms of translucency perception is limited, and little is known about how the optical properties of a material are related to the perception evoked in humans [1].

In a previous study, we attempted to model the three perceptual qualities-gloss, transparency, and roughness-through visual evaluations and physical property analyses of 34 object materials of 10 types (stone, leather, cloth, paper, metal, resin, glass, rubber, wood, and ceramic) [2]. The study showed that the perceived "transparency" is highly correlated with the transmittance power. However, the translucency of the materials was not analyzed. Although the concepts of transparency and translucency are used interchangeably, it is generally known that transparent materials, unlike translucent ones, transmit light without diffusing it [3]. The samples in [2] were biased towards opaque materials and were insufficient to evaluate translucency. Translucency as an optical property of a material can be measured instrumentally [4]. However, no technique has been proposed yet for the instrumental measurement of perceptual translucency.

This study aimed to construct an improved prediction model for perceptual translucency by measuring physical properties-other than transmittance-and conducting experiments to evaluate perceptual translucency. Experimental samples with different transmittance levels were prepared to consider translucency and transmittance changes. For those samples, the physical properties and

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translucency data were analyzed through evaluation experiments, and an accurate prediction model was proposed to derive translucency from physical properties.

2. Experiments

A translucency evaluation was conducted using flat surfaces with different glosses. In the experiment, a target and reference sample were presented to the observers in succession to assess the translucency using the magnitude estimation (ME) method. In the ME method, observers rated the translucency for each target sample by comparing it with the reference samples.

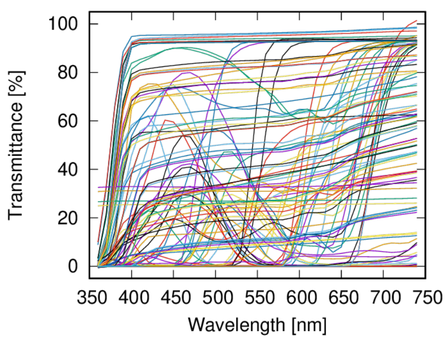
2.1. Stimuli

The four types of samples used in this study were JIDA standard samples by the Japan Industrial Design Association (hereafter referred to as JIDA), Kanase Lite by Kanase Inc., PARAGLAS by Kuraray Co., Ltd, and Hi-Plate Neo by Waazwiz Ltd (hereafter referred to as Hi-Plate). A total of 107 samples were used, including 42 JIDA samples, 32 Kanase Lite samples, 31 PARAGLAS samples, and 2 Hi-Plate samples. Every sample had a flat surface. In JIDA, one plate had two different textures; therefore, each texture was regarded as a different sample. The varying spectral transmittances of the samples are shown in Figure 1(a). A partial sample is shown in Figure 1(b).

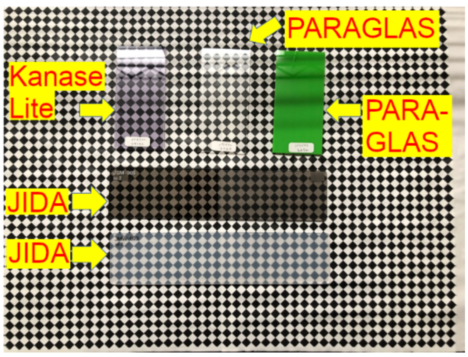
2.2. Physical measurements

Physical measurements were conducted to determine the physical properties of the experimental samples. Four types of physical properties representing the samples' surfaces were measured-spectral transmittance, gloss unit (GU), haze, and distinctness of image (DOI). The transmittances of the samples were measured using a spectrophotometer (CM-5, Konica Minolta, Inc.). In this study, "luminous transmittance" was measured as transmittance. A goniophotometer (Rhopoint IQ-S, Konica Minolta, Inc.) was used to measure the optical properties such as GU, haze, and DOI. For each surface of the experimental sample, each property was evaluated by measuring the parameters of same surface twice and averaging the measured values. The GUs were measured at three angles (20°, 60°, and 85°), defined as appropriate measurement angles [5]. The International Organization for Standardization (ISO) recommends a measurement angle corresponding to a sample as follows: 85° for low-gloss samples (0-10 GU), 60° for medium-gloss samples (10-70 GU), and 20° for high-gloss samples (70 GU and above).

Haze is the numerical value of the muddy highlights, which is higher for matte objects than glossy objects. DOI, another numerical value, indicates the clarity of the image reflected by the specular reflection from an object, and glossy objects have higher value of DOI than matte objects. The three optical properties-GU, haze, and DOI-were hypothesized to match multiple gloss types, which include specular gloss, sheen gloss, absence-of-bloom gloss, and distinctness-of-reflected-image gloss. The varying luminous transmittances of all measured samples are shown in Figure 2.



(a) Spectral transmittances



(b) Partial sample

Figure 1: Stimuli

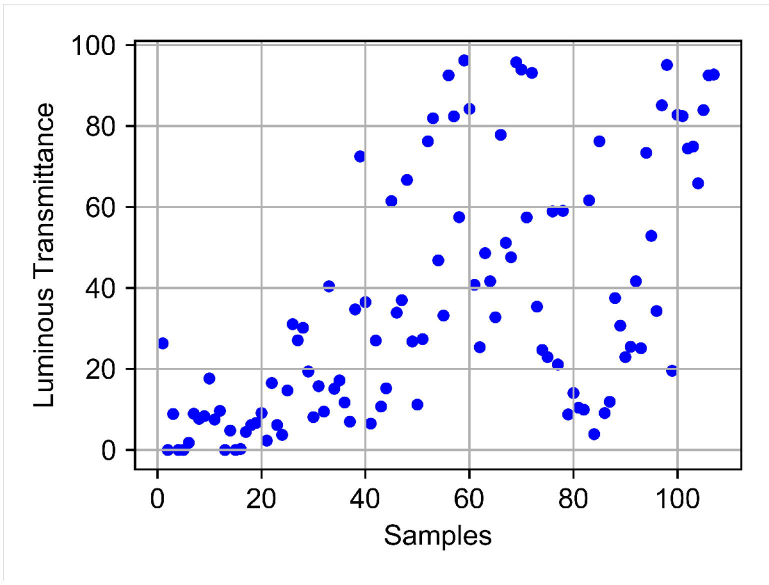
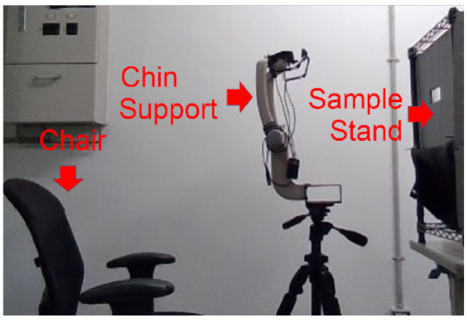


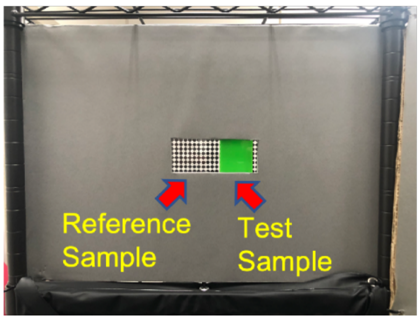
Figure 2: Luminous transmittances

2.3. Experimental condition

A subjective evaluation was conducted under fluorescent light (FLR40S N-EDL/M, Panasonic Corporation). The light is neutral white in color, with a high color rendering property and a color temperature of 5000 K. The perceptual translucency of the target sample's surface was evaluated using a chin support. The viewing distance was set to be 429 mm (with a viewing angle of approximately 5°20′). The samples were set on a sample stand. The experimental environment is shown in Figure 3(a). The view of the sample stand from the observer's position is shown in Figure 3(b). Two samples could be set on the sample stand. During the experiment, reference and test samples were set on the left and right sides of the sample stand, respectively. The reference sample was a sample used as a standard to evaluate the translucency of the samples, and the test sample was a sample whose translucency was evaluated during the experiment. The translucency of the test sample relative to the reference sample was evaluated by the observers. The background of the target sample was covered with an achromatic plaid pattern; the length of each side of the plaid was 5.5 mm.



(a) Side view of the experimental setup



(b) Front view of the sample stand

Figure 3: Experimental condition

2.4. Procedure

Ten observers with ages ranging from 20-29 participated in the experiment. Before the experiment, the observers watched the background behind the sample stand for 2 min sitting on the chair with their chins put on the chin stand. The samples were set on the sample stand such that the observers could not see the background. During the experiment, the observers evaluated the translucency of the test sample in comparison to the reference sample. The ME method was used for the evaluation. In the ME method, an observer assigns a score to the test sample in comparison to the reference sample, where the minimum score (usually 0) and the score of the reference sample (usually positive) are priory set. In this experiment, the reference sample had the highest value for transmittance. The minimum score was set as 0, and the score of the reference sample was set as 100. The observers assigned a score out of 100: when they felt that the test sample was twice as translucent as the reference sample, they assigned 0; when they felt that it was half as translucent, they assigned 50. The observers were asked to assign a score of 0 when they felt that the test sample was opaque. The observers could observe the samples for as long as they wished. The mean of within-observer standard deviations was 34.19 and the maximum of within-observer standard deviations was 40.54.

3. Modeling

To construct a perceptual translucency model, a linear regression analysis was conducted. The physical quantities of the samples were used as the independent variables of the model; the translucency scores attained from the psychophysical experiment were used as the dependent variables of the model. The outlier data of the subjective evaluations were removed using the Smirnoff-Grubbs test.

3.1. Verification of multicollinearity

The multicollinearity of the physical quantities was verified to construct a perceptual translucency model. Multicollinearity is a phenomenon in which the accuracy of a built model decreases when the independent variables of the model are highly correlated. The variance inflation factor (VIF) was used to evaluate the built model. The VIF is computed using Equation (1).

$$VIF = \frac{1}{1 - r^2}, \tag{1}$$

where r is the correlation between two independent variables. In this study, we computed the *VIF* of each variable pair and verified multicollinearity. In general, multicollinearity is verified if *VIF* is greater than 10.

The results of *VIF* computation are shown in Table 1, where *Gloss20*, *Gloss60*, and *Gloss85* are the GUs of the samples measured at 20◦ , 60◦ , and 85◦ , respectively. *Gloss* refers to the GU measured at the angle recommended by ISO, as described in Section 2.2. In Table 1, the *VIF* of the physical quantities related to GU tends to be greater than 10. In addition, the *VIF* between *DOI* and *Gloss85* is greater than 10. Therefore, in the modelling process, we used *haze*, *DOI*, and *gloss* in addition to *Transmittance*.

Table 1
Results of VIF computation

	Transmittance	*Gloss20*	*Gloss60*	*Gloss85*	*Haze*	*DOI*
Gloss20	1.01					
Gloss60	1.00	30.95				
Gloss85	1.04	11.83	15.65			
Haze	1.05	1.04	1.00	1.02		
DOI	1.06	8.50	9.95	138.86	1.02	
Gloss	1.00	228.99	27.22	10.05	1.04	7.30

3.2. Translucency and transmittance

First, a model using only transmittance was constructed to predict perceptual translucency. Simple regression analysis was conducted to construct a model with translucency as an objective variable and luminous transmittance as an independent variable. The result is shown in Equation (2), Table 2, and Figure 4. Table 2 shows the R-squared, P-value for F-test, and mean squared error (MSE). The MSE was computed using a cross-validation method called "leave one out". In this method, a prediction of translucency of each sample was made by constructing a model using the other samples. Further, MSE was computed by averaging the squared errors of all the samples. As shown in Table 2, the R-squared was 0.148, which meant that the model was not accurate. The P-value was found to be 4.18e-05, and the model was significant with a significance level of 5%. Figure 4 shows the predicted translucency score of the model, means of observed scores from the experiment, and standard deviations of the observed scores of each sample. The samples were sorted in ascending order with respect to the means of translucency scores. As shown in Figure 4, the translucency score began to rise sharply when it reached around 70, but the model did not adapt to the rise. The above results indicate that another physical quantity is required to explain translucency.

$$Translucency = 0.4308 \times Transmittance + 10.6911, \tag{2}$$

Table 2

Results of regression analysis

R-squared	P-value for F-test	MSE
0.148	4.18e-05	988.55

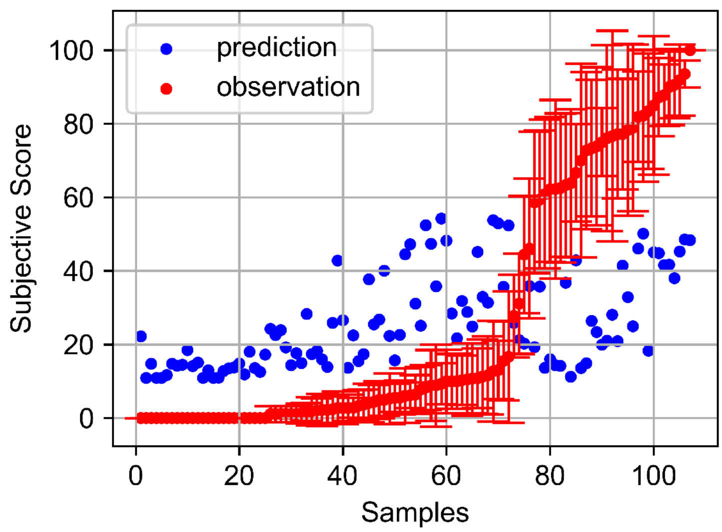


Figure 4: Prediction of translucency using transmittance

3.3. Translucency and multiple physical properties

People acquire and process complex scattering information of object surfaces; therefore, it is considered challenging to model translucency using only transmittance. We attempted to improve the modelling using more physical properties. We conducted a multiple regression analysis using haze, DOI, and GU acquired in the measurement as explanatory variables and translucency as the objective variable. The results of the analyses are shown in Equation (3), Table 3 and Figure 5. The R-squared was 0.623, adjusted R-squared was 0.608, and P-value was 8.46e-21. The significance level of the model was 5%. The MSE was 462.29. Compared with the model whose independent variable was only transmittance, the proposed model showed more accuracy. This shows that gloss, haze, and DOI have an impact on translucency, and only transmittance is not enough to explain translucency.

$$\begin{aligned} Translucency = {} & 0.2691 \times Transmittance + 0.3264 \times Haze - 0.6778 \times DOI \\ & - 1.2739 \times Gloss - 16.5037, \end{aligned} \tag{3}$$

Table 3
Results of regression analysis

R-squared	Adjusted R-squared	P-value for F-test	MSE
0.623	0.608	8.46e-21	462.29

Physical quantity	Luminous transmittance	*Haze*	*DOI*	*Gloss*
P-value	0.001	0.367	0.000	0.000
Significance	Yes	No	Yes	Yes

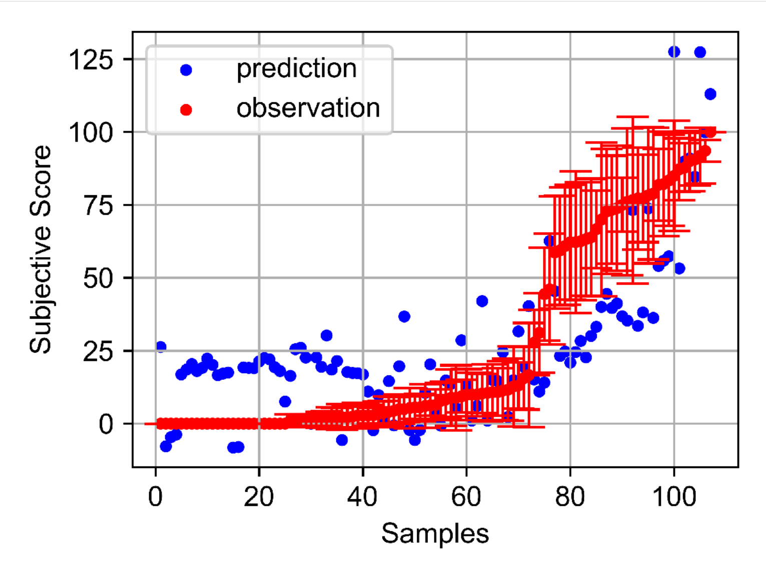


Figure 5: Prediction of translucency by the multiple physical properties

To evaluate the degree to which each independent variable has an impact on translucency, standardized regression coefficients were computed. The result is shown in Equation (4). The coefficients of the equation show that translucency is the most subjective variable compared to gloss, followed by DOI. It was found that transmittance was less impactful in this experiment.

$$\begin{aligned} Translucency = 0.2406 \times Transmittance + 0.0595 \times Haze - 0.9273 \times DOI \\ + 1.4884 \times Gloss - 1.388 \times 10^{-17}, \end{aligned} \tag{4}$$

4. Discussion

In this study, perceptual translucency models were constructed using various physical quantities as independent variables. As a result, it was found that not only luminous transmittance but also other physical quantities such as GU are required to examine the perceptual translucency of a material. Finally, from the results of the regression analysis, it was found that GU impacts translucency the most.

From the results in Figure 5, it can be observed that it is difficult to predict high- and low-translucent samples. Because high-translucent samples allow one to see through it and low-translucent samples do not, the evaluation of mid-translucent samples is expected to be difficult for the observers. Hence, when the translucency score increases steeply, it disturbs the modelling of perceptual translucency. Conducting an experiment such that evaluation of mid-translucent samples is easy or using another modelling method that can adapt to the sharp rise in translucency scores would be solutions to this concern. Use of non-linear regression might be a promising choice.

5. Conclusion

To construct the prediction model for perceptual translucency of flat-surfaced resin objects, we conducted a subjective evaluation of translucency and physical measurement of the object surface appearance. Through the physical measurements, transmittance, GU, haze, and DOI were obtained as physical properties. The ME method was used to evaluate the translucency. Using both perceptual and physical data, we constructed a prediction model with linear regression analysis, and the following two conclusions were made-the perceptual translucency model requires physical quantities such as GU, haze, and DOI other than transmittance for accuracy; GU is found to be the most impactful parameter on translucency among them.

The proposed model does not adequately estimate translucency in the high and low transmittance samples. Overcoming these limitations can be the subject of future research.

6. Acknowledgements

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7. References

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