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The Importance of Object-to-Background Distance when Evaluating Perceived Transmittance

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Abstract

Transparent and translucent objects transmit part of the incident radiant flux permitting a viewer to see the background through them. Perceived transmittance and how the human visual system assigns transmittance to flat filters has been a topic of scholarly interest. However, these works have usually been limited to the role of filter's optical properties. Readers may have noticed in their daily lives that objects close behind a frosted glass are discernible, but other objects even slightly further behind are virtually invisible. The reason for this lies in geometrical optics and has been mostly overlooked or taken for granted from the perceptual perspective. In this work, we investigated whether the distance between a translucent filter and a background affects perceived transmittance of the filter, or whether observers account for this distance and assign transmittance to the filters in a consistent manner. Furthermore, we explored whether the trend holds for broad range of materials. For this purpose, we created an image dataset where a broad range of real physical flat filters were photographed at different distances from the background. Afterward, we conducted a psychophysical experiment to explore the link between the object-to-background distance and perceived transmittance. We found that the results vary and depend on filter's optical properties. While transmittance was judged consistently for some filters, for others it was highly underestimated when the background moved further away.

Introduction

We can easily see through a transparent window. This becomes increasingly difficult if the window is tinted or frosted, since the background appears dimmer or blurrier, respectively. Different materials permit different amount of transmittance, i.e. *"the ratio of transmitted flux to incident flux"* [1]. Transmission can be with or without diffusion, i.e. *"change of the angular distribution of a beam of radiant flux"*. Transmission that involves no diffusion is called regular transmission. Total transmittance refers to the ratio of all transmitted flux at all forward angles (both regular and diffuse) with respected to incident flux [1].

How visual system separates background from the filter as different spatial layers and how it perceives filters to have a certain degree of transmittance has long been a topic of scholarly interest [2]. Certain geometric and colorimetric regularities have been shown to be used as cues to assess layer's transmittance [3, 4]. For instance, Singh and Anderson demonstrated that perceived transmittance depends on Michelson Contrast [5] and is also affected by background blur even if Michelson Contrast is fixed [6]. Mivehforoushi *et al.* [7] also demonstrated that contrast and blur affect perceived translucency, while they made a distinction between the cases where contrast variation results from additive (scattering) or subtractive (absorption) processes.

The majority of the previous works have focused on how filter's optical properties and resulting image statistics affect perceived transmittance. However, the image statistics that are pro-

Figure 1: The hand quickly disappears behind a frosted glass when moved further behind.

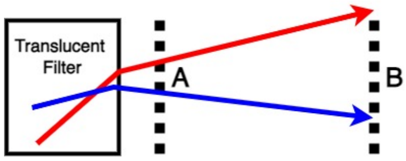

Figure 2: When the distance from a filter to a background increases (from point A to point B), the rays exiting a filter at different angles diverge more and hit the background further away from one another.

posedly used by the human visual system to assign transmittance to filters also can be impacted by the distance between the filter and the background. This phenomenon is commonly observed in daily life, where objects closer behind a frosted glass window appear sharper than those that are further behind (Fig. 1). The reason lies in geometrical optics and was well summarized by Fleming *et al.* [8]:*"when the back plane is moved farther from the object, rays that diverge as they exit the transparent object strike the back plane at a greater distance from one another, and this leads to a greater degree of compression."* (Fig. 2) The need for a distance to yield blurry appearance is even reflected in the technical definition of translucency, which defines the term as *"the property of a specimen by which it transmits light diffusely without permitting a clear view of objects* ***beyond the specimen and not in contact with it"*** [1]. However, it is not clear whether humans can account for these differences in distance to the background and assign consistent transmittance to the filter despite higher blur, and whether this equally applies to a broad range of materials. Fleming *et al.* [8] used a 3D blob with no subsurface scattering and studied how accurate humans are in estimating refractive indices of materials. They found that background distance has a substantial impact on this estimation. The further away the background from the 3D object was, the higher was the estimated refractive index, which they explained by the magnitude of the distortion field – the further the background, the stronger the distortions.

The contribution of this work is as follows: we created a dataset of translucent filters with different properties photographed at 7 different distances from the background; we conducted psychophysical experiments to identify how the distance to the background affects the estimated transmittance of the filters; we analyzed how the dependence on the background distance varies among materials; and finally, we explored whether the results could be explained by the luminance contrast metrics.

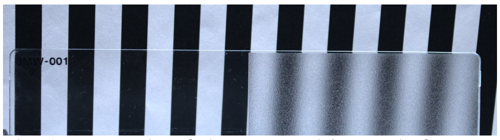

Figure 3: An example of the captured image before cropping. Both the sample tag number as well as two different halves are visible.

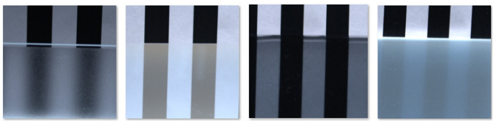

Figure 4: The examples of frosted glass, milky white, clear black, and pearl molding filters, from left to right, respectively.

Methodology

The primary objective of this work was to answer two research questions: whether perceived transmittance of a flat translucent filter is constant regardless of the distance from the filter to the background, and whether this depends on the optical properties of the filter. This section describes the research methodology used to shed more light on these questions.

Stimuli generation

We decided to photograph actual physical filters at different distances to the background and conduct phsychophysical experiments to explore how perceived transmittance of a given filter varies at different distances to the background. We did not use synthetic images generated with computer graphics [8] or other image processing manipulations [7] to ensure that the filters in question are physically plausible and actually exist. The difficulty to conceal background movement from the observers made us use photographs instead of showing actual physical filters to the observers.

We used the Standard Samples from the Japanese Industrial Design Association (JIDA) [9], which includes flat plastic and metallic patches with varying properties. The metallic ones and those with high opacity were intentionally excluded. Finally, the following JIDA filters were selected: Floasted glass (JTX series) – with varying degree of surface roughness; Milky white (JMW series) – with varying degree of white diffusing tinting; Clear black (JSM series) – with varying degree of black tinting without scattering behavior; Pearl molding (JPE series) – with a varying size of pearl pigments. When filters had two halves with different surface roughness, both halves were considered as separate filters (see Fig. 3 and 4). A striped background, similar to the one in [6] was used, with black and white strips of 1 cm in width.

The filters and the background pattern were placed in a viewing booth under D65 lighting, and the images were acquired using Nikon D610 DSLR camera. The camera-to-filter distance for all captures remains constant at 35 cm, but the filter-to-background distance varies from 0 to 12 cm with an increment of 2 cm for each capture (7 images per filter; Fig. 5). In total, the experiment included 176 images. The raw images were gamma corrected (gamma=2.2) and finally, sRGB images in PNG format were used for the actual experiments. The images were cropped to remove the tag numbers that are written on the filters and to show both the filter and unoccluded part of the background.

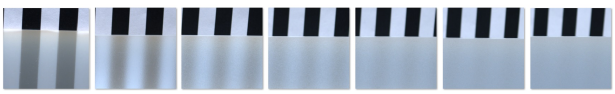

Figure 5: The impact of background distance illustrated on the example of JMW003 filter. The distance to the background is 0, 2, 4, 6, 8, 10, and 12 cm, from left to right, respectively.

Experimental procedure

22 observers participated in the study with normal or corrected-to-normal visual acuity (checked with a visual acuity test). Before experiment, each observer went through a training process to see the illustrations and familiarize with the concepts of transparency and opacity. QuickEval tool was used for the experiment [10]. The task in the experiment was to rate the transmittance of the filter in each image using a scale slider ranging from 1 to 100, from fully transparent to fully opaque, respectively. The images were shown in a random order.

The experiment was conducted in a dark room where the display was the only source of light. The distance between the observer and the display was fixed to 65 cm. The BenQ flagship monitor was calibrated following the suggested configurations for sRGB space, as specified in [11]: maximum luminance of 80 cd/m^2, gamma=2.2, and D65 white point.

Luminance mapping

To explain the results of the experiment with image statistics, contrast metrics such as contrast ratio (CR), luminance range (LR), Michelson contrast (MC), and Weber contrast (WC) have been calculated. These metrics have been calculated based on the luminance. Since the images do not contain chromatic content, the luminance differences between RGB and grayscale versions of the images were negligible. To map pixel RGB values to actual luminance, they were first converted to grayscale. For each grayscale value ranging from 0 to 255 luminance was measured on a homogeneous patch with CS-2000 spectroradiometer.

Results

This section summarizes the results of the psychophysical experiment and subsequent analysis.

Obtaining single value for each stimulus

Mean opinion score (MOS) has been computed to get a single value for each image from the corresponding estimated magnitudes by observers. The MOS calculation can be performed using either arithmetic or geometric means. The sensitivity of the arithmetic mean to outlier values can bias the result [12]. Therefore, the geometric mean was used to obtain the MOS (starting the scale from 1 instead of 0 was intentional, since a geometric mean is not applicable when the magnitudes are 0). The geometric mean-based MOS has been calculated using the recommended methodology proposed in [13, 14]. Firstly, on the entire dataset from the subjective study, a logarithmic transformation has been applied. From this log-transformed data, the arithmetic mean has been computed. The geometric mean is obtained by taking the anti-log of the log-transformed arithmetic mean.

Inter-rater agreement

Inter-rater agreement is a quantitative assessment of consistency among observers. The average standard deviation for each side of each filter series, along with the maximum and minimum standard deviation values is presented in Table 1. The JPE series generally exhibits lower standard deviation, which can be explained with the fact that it quickly becomes opaque as the filter-to-background distance increases. For JMW and JSM, the smooth side is assessed more consistently than the rough side.

Table 1: Standard deviation for each filter series

Filter series	Filter side	Avg	Max	Min
JTX	Smooth	12.27	20.45	2.15
	Rough	13.18	20.48	5.21
JMW	Smooth	10.48	19.57	1.34
	Rough	13.68	21.89	3.44
JSM	Smooth	10.91	20.03	2.62
	Rough	12.55	23.19	1.53
JPE	Smooth	7.76	21.04	1.91
	Rough	7.50	17.35	3.55

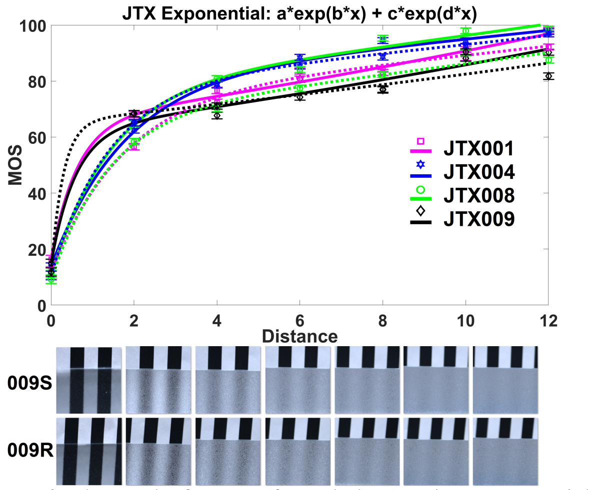

Figure 6: The results for JTX (frosted glass) series. Exponential curve is fit between background distance and MOS. Error bars show the 95% confidence intervals. Solid lines correspond to smooth filters, while dotted lines of the same color correspond to the rough version of the same filter. The images below the plot illustrate the examples of JTX009 at increasing distances from left to right. "S" and "R" stand for "smooth" and "rough".

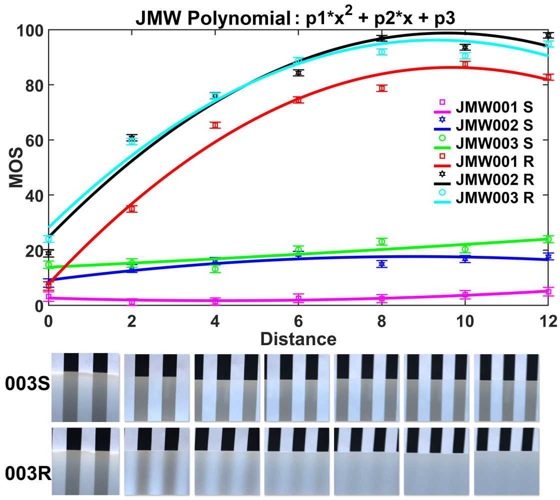

Figure 7: The results for JMW (milky white) filters. "S" and "R" in the labels stand for "smooth" and "rough", respectively.

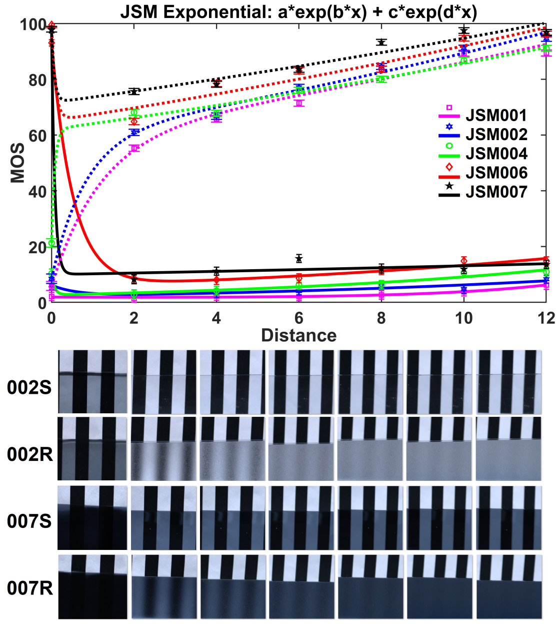

Figure 8: The results for JSM filters. Dotted lines correspond to the rough versions. All other labeling is the same as in Fig. 6.

Experimental Results

Mean Opinion Score (MOS) as a function of distance between the filter and the background is shown in Figures 6-9. We fit different models to the data. Second order polynomial provided best results for JMW series filters, while exponential shown below turned out most accurate for others:

$$MOS = a.e^{(bx)} + c.e^{(dx)} \tag{1}$$

where a, b, c, and d are coefficients and x denotes the distance.

The JTX series frosted glass filters were considered mostly transparent when the distance was 0, and then they became gradually opaque as the distance increased (Fig. 6). The plot as well as the illustrations in the figure show that there was no fundamental difference between the smooth and rough sides.

The trend was different for JMW series milky white filters (Fig. 7). For the smooth side that only slightly blurs the image, the distance had no statistically significant impact. On the contrary, for the rough version of the filters, the opacity increased as the distance increased, similarly to the frosted glass filters.

Interesting results were observed for JSM series filters that have increasing degree of absorption but no subsurface scattering. The results differ substantially between smooth and rough sides, as well as among those with different amounts of absorption (Fig. 8). From a distance of 2cm and larger, the observation is similar to that of JMW filters: smooth side remains consistently transparent, while rough side appears more and more opaque as the distance increases. This is true regardless the absorption coefficient. Fundamental differences are exhibited at the distance of 0 centimeters. Filters with low absorption appear transparent at 0 cm and increase in opacity gradually, similarly to JMW. However, when absorption is large (JSM006 and JSM007), both smooth and rough ones appear fully opaque and increasing the distance actually makes them more transparent. Most of the JPE filters immediately turned opaque even at the slightest increase in the distance. JPE003 didn't exhibit visual differences after 6 centimeters. Therefore, we included those with only 0, 2, 4, and 6 cm distance to the background. Subtle difference is visible at 0 cm distance between the smooth and rough sides. However, this highly scattering filter quickly becomes fully opaque in both cases (Fig. 9). Since there is no change in MOS between 2 and 6 cm and no other data points between 0 and 2 cm, it is not obvious, whether the exponential model is the best. Future work should increase the distance with smaller steps to study appearance change between 0 and 2 cm.

Image Statistics

The contrast metrics for each filter series, both smooth and rough, have been calculated with the mapped luminance values obtained from patches. This calculation involves determining the

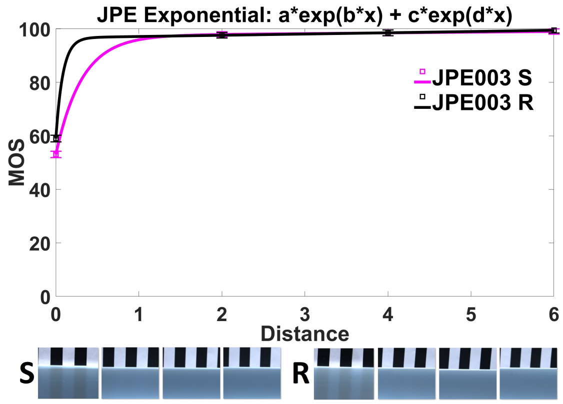

Figure 9: The results for JPE (pearl pigment) filters. Except for the case when the background touches the filter (0 cm), the filter appears fully opaque (MOS approaching 100).

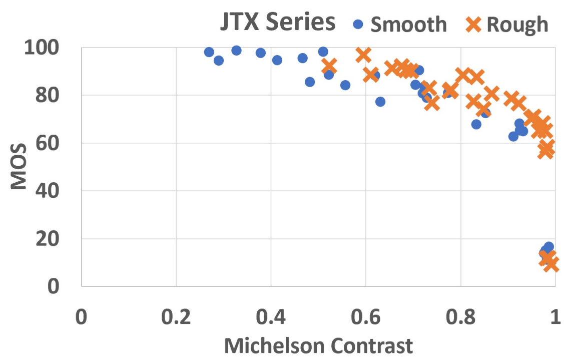

Figure 10: MOS as a function of MC. JTX series. Filters with low MC are usually considered opaque.

maximum and minimum luminance values. The metrics consist of the luminance range (LR) L_{max} - L_{min}, the contrast ratio (CR) $\frac{L_{\max}}{L_{\min}}$, the Michelson contrast (MC) $\frac{L_{\max}-L_{\min}}{L_{\min}+L_{\min}}$, and the Weber contrast (WC) $\frac{L_{\max}-L_{\min}}{L_{\min}}$. To assess the relationship between MOS and contrast metrics, Pearson's and Spearman's correlation coefficients have been calculated (Table 2), which shows that MOS is negatively correlated with contrast, being consistent with [5, 7]. As their luminance contrast decreases, the filters appear more opaque, especially for the JTX and JMW series (see Fig. 10-11).

Table 2: The correlation between contrast metrics and MOS is usually negative – the lower the contrast, the higher the opacity.

Filter	Side	CC	LR	CR	MC	WC
JTX	Smooth	Pearson's	-0.45	-0.94	-0.80	-0.94
		Spearman's	-0.64	-0.94	-0.94	-0.94
	Rough	Pearson's	0.46	-0.90	-0.71	-0.91
		Spearman's	-0.63	-0.95	-0.95	-0.95
JMW	Smooth	Pearson's	-0.46	-0.89	-0.90	-0.89
		Spearman's	0.60	-0.63	-0.52	-0.82
	Rough	Pearson's	-0.49	-0.57	-0.79	-0.57
		Spearman's	-0.76	-0.88	-0.88	-0.88
JSM	Smooth	Pearson's	-0.43	-0.44	-0.71	-0.44
		Spearman's	-0.83	-0.82	-0.81	-0.81
	Rough	Pearson's	-0.34	-0.73	-0.69	-0.74
		Spearman's	0.64	-0.86	-0.85	-0.85
JPE	Smooth	Pearson's	0.84	-0.42	-0.45	-0.44
		Spearman's	0.2	-0.80	-0.80	-0.80
	Rough	Pearson's	-1.00	-1.00	-1.00	-1.00
		Spearman's	-1.00	-0.20	-0.20	-0.20

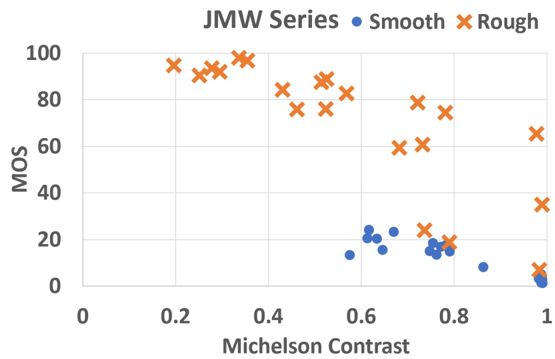

Figure 11: MOS as a function of MC. JMW series. Rough filters usually appear more opaque and exhibit lower MC.

Discussion

The results show that when filters have smooth surface and low subsurface scattering and absorption, their transmittance is judged consistently regardless the distance to the background (e.g. the smooth side of JMW series). However, when the filter blurs the background due to scattering, the larger the distance to the background, the more opaque the filter appears, similarly to [8]. This relationship was best fit with exponential functions. In our case, we observed that when the scattering primarily happens on the surface due to roughness (JTX series, rough JMW series), the decrease in perceived transmittance is more gradual, while when the subsurface scattering is high (JPE series), the decrease is more abrupt and the filter quickly looks fully opaque. Interestingly, when the filter absorbs large amounts of light (JSM006-007), it may appear more opaque when it touches the background. We also observed that perceptual scores co-vary with the luminance contrast. This does not necessarily imply that these metrics are used by the HVS, but they may play an important role in computer vision applications to estimate object's properties when the background distance is known, or to estimate the background distance from known filter's appearance.

This work has several limitations. A variation in distance leads to a change in the size of the grating, which gives an observer additional cues regarding the filter-to-background distance. Despite this cue, in many cases, the observers did not attempt to account for the distance and did not judge the transmittance of a given filter consistently at different distances. Future work can adjust strip width accordingly to make it look equally wide at different distances; this way the impact of the distance can be isolated. Besides, future work should develop an optical model that predicts the amount of radiance reaching the observer and explain the results from the optical perspective. A quantitative model can be developed, which will predict perceived transmittance as a function of filter's optical properties and background distance. The optical properties were not included in the unified model in this work, since manufacturer's data explicitly specified and varied different properties for different filter series, while other properties remained unclear.

Conclusion

We conducted psychophysical experiments to investigate whether human observers judge transmittance of see-through filters consistently despite the distance to the background. The results have shown that for filters that scatter light, the distance to the background has a significant impact on their perceived transmittance, which implies that background distance is a significant factor that should be considered when studying transmittance of flat see-through filters both in human and computer vision.

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