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Transparency and Translucency in Visual Appearance of Light-Permeable Materials

Davit Gigilashvili[1,▲] and Tawsin Uddin Ahmed[1,▲]

[1] *Department of Computer Science, Norwegian University of Science and Technology; Gjøvik, Norway*
E-mail: davit.gigilashvili@ntnu.no

Abstract. *Light-permeable materials are usually characterized by perceptual attributes of transparency, translucency, and opacity. Technical definitions and standards leave room for subjective interpretation on how these different perceptual attributes relate to optical properties and one another, which causes miscommunication in industry and academia alike. A recent work hypothesized that a Gaussian function or a similar bell-shaped curve describes the relationship between translucency on the one hand, and transparency and opacity, on the other hand. Another work proposed a translucency classification system for computer graphics, where transparency, translucency and opacity are modulated by three optical properties: subsurface scattering, subsurface absorption, and surface roughness. In this work, we conducted two psychophysical experiments to scale the magnitude of transparency and translucency of different light-permeable materials to test the hypothesis that a Gaussian function can model the relationship between transparency and translucency, and to assess how well the aforementioned classification system describes the relationship between optical and perceptual properties. We found that the results vary significantly between the shapes. While bell-shaped relationship between transparency and translucency has been observed for spherical objects, this was not generalized to a more complex shape. Furthermore, how optical properties modulate transparency and translucency is also dependent on the object shape. We conclude that these cross-shape differences are rooted in different image cues generated by different object scales and surface geometry.* © *2022 Society for Imaging Science and Technology.*
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1. INTRODUCTION

The appearance of light-permeable materials is usually characterized with adjectives *transparent* and *translucent*. The concepts of transparency and translucency are oftentimes used interchangeably in everyday life [22]. However, conceptually they are understood to be different, even by the speakers of those languages, e.g. Japanese, that offer no clear lexical distinction between the two [15, 24].

Optically, propagation of light in the material volume is characterized with the *radiative transfer equation (RTE)*—in particular, wavelength-dependent coefficients of absorption (σ_a) and scattering (σ_s), as well as scattering phase function. σ_a and σ_s are usually specified in inverse scene units and indicate the distance a photon travels on average in a straight line within the material before it gets absorbed or scattered, respectively [17]. The lower absorption and scattering are, the easier it is to see-through the material. Conversely, higher absorption coefficient means that less photons manage to go through the material, making the see-through image appear darker and decreased in contrast; and higher scattering coefficient means that more photons get redirected to different paths, less structure is preserved, and the see-through image appears more blurry. The scattering phase function characterizes distribution of directionalities after a scattering event. If absorption and scattering are large enough, or the object is thick enough (i.e. the distance a photon needs to travel is large and a likelihood of a scattering or absorption event is respectively larger), the background image can become indiscernible, but some degree of subsurface light transport might be still detectable (e.g. in materials such as wax, marble, or milk) [17]. If no subsurface light transport is detectable, the material is said to be *opaque* [1].

The ASTM Standard Terminology of Appearance [1] defines *transparency* as *"the degree of regular transmission, thus the property of a material by which objects may be seen clearly through a sheet of it"*, and *transparent* as *"transmitting radiant energy without diffusion"*. According to the same dictionary, *translucency* is *"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"*. According to Gerbino [8], *"transparent substances, unlike translucent ones, transmit light without diffusing it"*. In other words, the central distinction between transparency and translucency from the optical point of view is the magnitude of subsurface scattering (or the lack thereof). The CIE (International Commission on Illumination) emphasizes the perceptual aspect of it: *"if it is possible to see an object through a material, then that material is said to be transparent. If it is possible to see only a "blurred" image through the material (due to some diffusion effect), then it has a certain degree of transparency and we can speak about translucency"* [3, 4].

The primary distinction marked between transparent and translucent materials is the presence or absence of scattering, and the distinctness of the image seen through the material. Neither dictionary definitions, nor the state-of-the-art research in material appearance, provide more specific distinction, or objectively measurable boundary

▲ IS&T Members.

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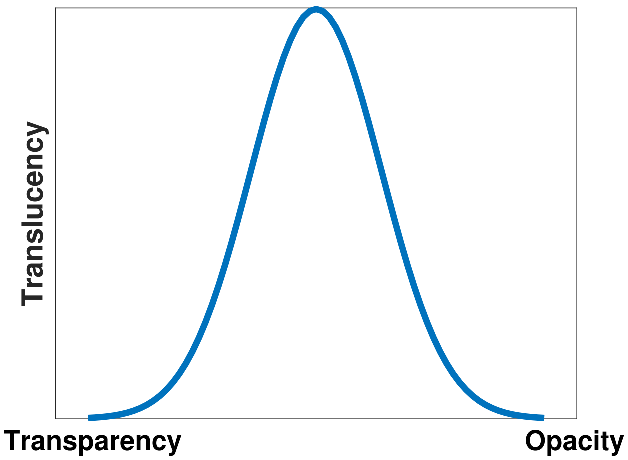


Figure 1. According to the *bell-shaped curve hypothesis* [13], translucency is not mutually exclusive with transparency and opacity, and as we move across the transparency-opacity spectrum from complete transparency, translucency gradually increases, reaches an yet undetermined peak, and then decreases reaching the complete opacity. The figure is reproduced from [13].

between the concepts of *transparency* and *translucency*. According to the CIE, *"translucency is a subjective term that relates to a scale of values going from total opacity to total transparency"* [3], also highlighting the lack of universal definition of *translucency*. More standardized and objectively quantified concepts are *haze* – resulting from wide angle (>2.5°) scattering and *"defined as a property of the material whereby objects viewed through it appear to be reduced in contrast"*, and *clarity* – associated with narrow angle (<2.5°) scattering, and *"defined in terms of the ability to perceive the fine detail of images through the material"* [26, 30]. While the contrast and blur differences between the images of the scene observed through a material and in a plain view can help us measure haze and clarity, also providing visual cues to transparency and translucency of see-through materials [15, 29], not all translucent materials permit to see-through (e.g., above-mentioned wax and milk), and broad range of other cues, such as luminance contrast between specular and non-specular areas [5, 24], and co-variation of 3D shape and shading [20, 21] are used by the Human Visual System (HVS) for translucency perception (see [15] for a comprehensive review).

Translucency is commonly considered to be a phenomenon *"between the extremes of complete transparency and complete opacity"* [4]. However, from optical and perceptual perspectives, it remains largely ambiguous how *transparency* and *translucency*, as well as *translucency* and *opacity* relate to each other, the boundaries between them, and whether transparency-translucency-opacity is a single continuum. The position paper by Gigilashvili et al. [13] has been the first one to discuss this problem thoroughly: *"Can a material possess some degree of transparency and translucency, or some degree of translucency and opacity at the same time? When do transparent materials begin to be considered translucent, or when do translucent ones become opaque?"*—they ask. Referring to previous works [11, 12, 14],

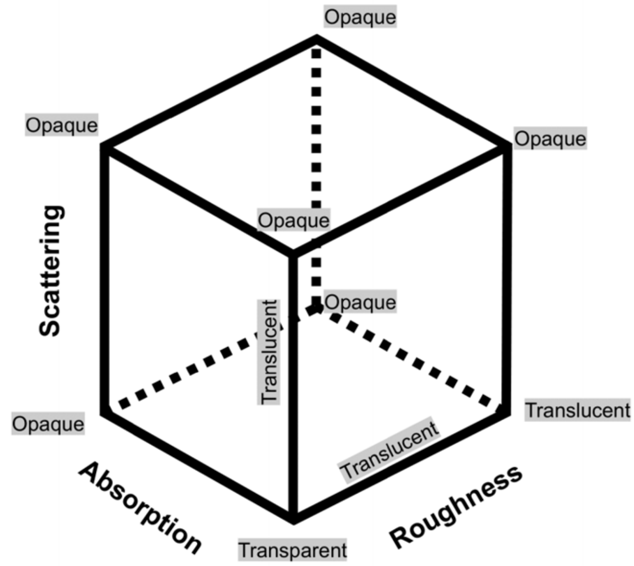


Figure 2. According to the classification system for computer graphics proposed by Gerardin et al. [7], increase in subsurface absorption gradually makes transparent materials opaque, but not translucent; increase in subsurface scattering makes materials translucent and eventually fully opaque; and increase in surface roughness makes transparent materials appear translucent, but not fully opaque.

they conclude that perceptually, transparency and opacity are ranges of a spectrum, rather than extreme discrete points, and translucency can co-exist with them in the same stimulus. They argue that the conceptual boundary between transparency and translucency, as well as between translucency and opacity, is fuzzy rather than discrete, and hypothesize that the magnitudes of translucency and transparency-opacity are correlated with a bell-shaped curve (Figure 1), where translucency *"gradually increases, reaching a peak and then decreasing again while moving from transparency to opacity"* [13].

The boundary is fuzzy from optical perspective as well. The state-of-the-art research confirms that translucency is impacted by σ_a, σ_s, and roughness, but the exact nature of this impact remains to be investigated [15]. For instance, what is the magnitude of subsurface scattering for the material to appear and to be considered translucent? Gerardin et al. [7] proposed a cuboid classification system (Figure 2) for computer graphics applications, where subsurface absorption, subsurface scattering, and surface roughness – i.e. surface scattering are considered three axes. On the absorption axis, the materials range from transparent that become gradually opaque, but never translucent; on the subsurface scattering axis, transparent materials become gradually translucent as the scattering increases, and eventually opaque, if scattering is too high; and finally, on the roughness axis, transparent materials become gradually translucent, but they never reach full opacity, as *"there is always some light transmitted by the object"* [7].

Measurement, modeling, and reproduction of appearance of light permeable materials are important issues both in academia and industry alike (for instance, in 3D printing applications) [15, 34]. The question whether different appearance attributes, such as, transparency, translucency, and opacity, are orthogonal, or whether they co-vary is important for material design applications [13, 15]. Furthermore, disambiguation of the conceptual boundaries is essential to visual appearance research, as conceptual misinterpretations of translucency and transparency in psychophysical experiments has been reported [13, 15], which can bias the experimental results as well as the scientific communication. For this purpose, we conducted two psychophysical experiments to quantify the magnitude of perceived transparency and perceived translucency of the stimuli and subsequently, to test Gaussian-like bell-shaped curve hypothesis by Gigilashvili et al. [13]. Furthermore, the stimuli of varying σ_a, σ_s, and roughness was used in the experiments to evaluate how well Gerardin's [7] classification system of optical properties relates to perceptual attributes.

However, we hypothesize that the correlation between transparency and translucency, and the role of optical properties in that correlation, vary among shapes. This hypothesis is rooted in three observations made in the state-of-the-art works: first the amount of light that emerges from an object after subsurface light transport depends not only on σ_a and σ_s, but also on the thickness of the object—thin objects appearing more transmissive than thick objects made of the same material [5, 15]; second, visibility of the transmission image, i.e. the magnitude of transparency and translucency depends not only on a micro-scale surface roughness, but on a macro-scale surface geometry as well—even if no subsurface scattering and absorption happen, and the surface is perfectly smooth on a microscopic level, background might not be still visible, if the shape of the object is complex (compare ability to see through between a flat window glass and a complex-shaped crystal vase) [15]; third, the HVS has a poor ability to assess and invert optical processes in the scene, and rather relies on luminance distribution and other statistical regularities in the image, dubbed *image cues* that are modulated by above-mentioned scale and geometry. For this reason, objects made of the identical material can considerably differ in appearance if they differ in size and shape—making Gigilashvili [9] propose to refer to the visual appearance as an *object appearance* problem rather than *material appearance*. For this reason, we conducted the study on two different shapes—a simple and compact spherical object, and a complex Stanford Lucy [32] object with a broad range of thickness distribution.

The contribution of this work is three-fold:

- We study the correlation between the magnitudes of translucency and transparency-opacity, and test the bell-shaped curve hypothesis proposed in previous works [13, 15].
- We study how the magnitudes of perceived translucency and transparency are modulated by subsurface absorption and scattering, as well as surface roughness.
- We test the hypothesis that the correlations mentioned in the two previous points differ between the shapes.

Figure 3. Bernhard Vogl's museum environment map (also known as At the Window (Wells, UK)) [2, 19] was used for rendering the visual stimuli, which was rotated with 180° to put the objects under side-lit illumination condition (refer to Supplementary Material 3 for exact transformations).

The manuscript is organized as follows: in the next section, we present the research methodology. In the following section, we present the results, which is followed by discussion. Finally, we conclude and outline directions for future work.

2. METHODOLOGY

In this section, we first explain the process of the visual stimuli generation. We, then describe the experimental setup, and finally provide information about observers.

2.1 *Stimuli*

2.1.1 *Scene Composition*

We used Bernhard Vogl's museum environment map [2, 19] illustrated in Figure 3. The caustics, which are projected by a light-permeable object onto a surface this object is placed on, contain important translucency cues [10]. Besides, we usually interact with transparent and translucent objects that are placed on a surface. Therefore, we decided to place objects on a checkerboard textured surfaces, rather than having them floating in the air, as in [7]. Additionally, a heterogeneous checkerboard texture makes it easier for the observers to judge the visibility of the background. Illumination direction has a significant impact on translucency appearance [15, 38] – back-lit objects usually appearing more translucent and less opaque than front-lit ones. We rotated the environment map to evaluate multiple illumination directions and finally opted for side-lit condition (illuminated from the left; 180° rotation) that helps us avoid saturation after tone-mapping to low dynamic range, and ensures that broad range of translucency and transparency cues are present in the stimulus.

2.1.2 *Rendering*

We used a volumetric path tracer of Mitsuba Physically-based Renderer [19] to generate synthetic images of light-permeable materials. To model scattering at the boundary of the object and the outer medium, Mitsuba's *roughdielectric* plugin was used, which is an implementation of a microfacet-based model proposed by Walter et al. [19, 37]. In microfacet theory the surface is represented as a composition

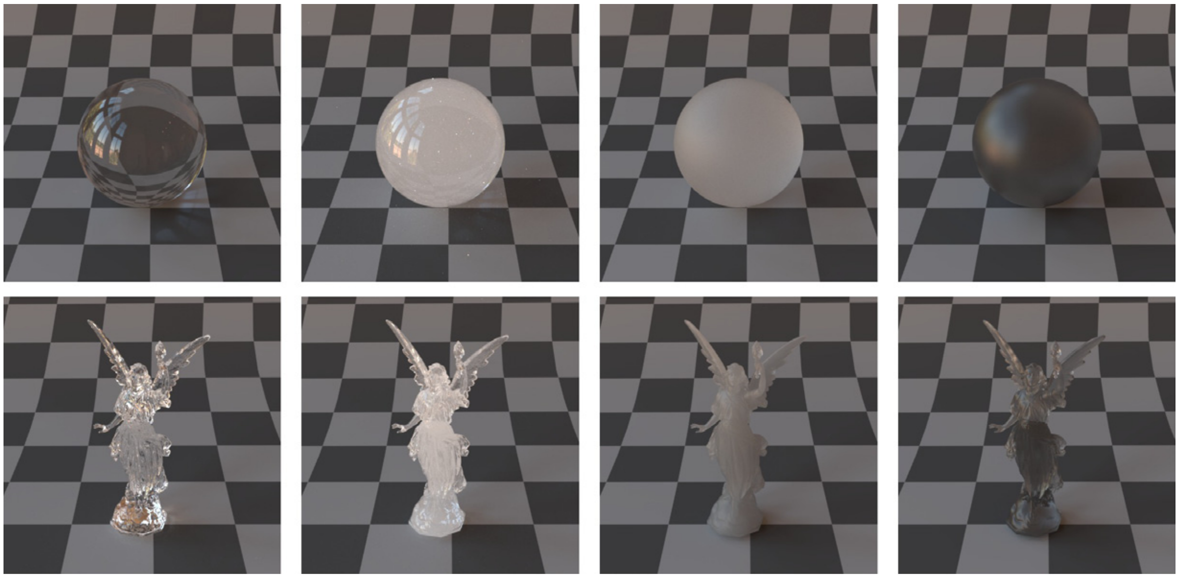


Figure 4. Examples of the images used in the experiment. [σ_T-Albedo-Alpha] are as follows: [0.5-0.2-0], [1-1-0], [0.5-1-0.3], [1-0.2-0.15] for sphere, from left to right, respectively; and [0-0-0], [4-1-0], [8-0.8-0.3], [4-0.2-0.15] for Lucy. To see all other images and a detailed illustration of how each of the rendering parameters affects appearance, refer to Supplementary Material 1.

of small perfectly specular facets, which vary in orientation. The distribution of surface normal directions of these facets, i.e. surface roughness is specified by microfacet normal distribution. In this case, we used a Beckmann distribution, which is a default setting in Mitsuba. To simulate radiative transport for describing light propagation inside the object's volume Mitsuba's *homogeneous participating medium* plugin was used, assuming that the object is made of a homogeneous material. For reproducibility of the rendering process, Mitsuba rendering files are attached in Supplementary Material 3.

These images were rendered in 512 × 512 pixel resolution, with 16384 samples per pixel. We used two shapes: a perfect sphere with homogeneous thickness and simple surface geometry, and Stanford Lucy [32] with a distribution of thick and thin parts, and complex surface geometry (the dimensions of the objects are summarized in Table I). The index of refraction was fixed in all stimuli to 1 for the outer medium (assuming the objects were placed in the vacuum) and to 1.5 for the objects, which is typical for transparent and translucent materials, such as glass, wax, and a broad range of polymeric materials [23, 28]. Extinction coefficient (σ_T) and albedo have been used to specify subsurface scattering properties. σ_T is the sum of σ_a and σ_s (All values are in cm^{-1} units.), while albedo is a unit-less parameter specifying the portion of σ_s in σ_T. Thus, $\sigma_s = \sigma_T \times albedo$, and $\sigma_a = \sigma_T \times (1 - albedo)$. Surface roughness was varied using *Alpha* parameter in Mitsuba, which is equivalent to the Root Mean Square slope of microfacets—the larger the Alpha, the rougher the surface. For each shape, five different extinction coefficients, six different albedos, and three different *Alphas* have been studied. We have 5 σ_T, 6 albedo, and 3 Alpha values. However, for $\sigma_T = 0$ (i.e., $\sigma_a = 0$ and $\sigma_s = 0$), changing albedo does not make a difference. Thus, we have $(5 - 1) \times 6 \times 3 + 1 \times 3 = 75$ stimuli per shape, and 150 in total. The optical properties used for sphere and Lucy are summarized in Tables II and III, respectively. The example images are shown in Figure 4 (all images used in the experiment can be found in Supplementary Material 1). It is worth noting that a sphere and Lucy differ greatly in thickness and scale (Table I). Hence, no single set of optical parameters was able to produce equivalently broad range of transparent, translucent, and opaque appearances for both shapes. Therefore, after thorough trial-and-error, we decided to use different extinction coefficients for sphere and Lucy. As Lucy is smaller in scale, larger extinction coefficients were used to produce comparable appearance. All parameters for both shapes have been equidistantly sampled.

Table I. The maximum span of the objects relative to a radius of a sphere (sphere radius = 1) in X, Y, and Z dimensions, where Z corresponds to the vertical dimension. If the span of the wings is considered, the difference in thickness between the objects does not seem to be large. However, if only the torso of the Lucy is considered (the values given in the parentheses), Lucy is approximately four times thinner than a sphere. The table is reproduced from [16].

	X	Y	Z
Sphere	2	2	2
Lucy	0.94 (0.45)	1.48 (0.45)	2.73

2.2 *Experimental Setup*

In order to detect potential flaws in the experimental setup, we conducted a pilot experiment with 3 observers and 72 images, each rendered with 4096 samples per pixel. As we confirmed that the setup worked properly, we conducted the final experiment.

Table II. Rendering parameters (Sphere).

Name of the Parameters	Parameter Values
σ_T (sub-surface scattering + absorption coeff.)	0, 0.5, 1, 1.5, 2
Albedo (% of sub-surface scattering)	0, 0.2, 0.4, 0.6, 0.8, 1
Alpha (roughness parameter)	0, 0.15, 0.3

Table III. Rendering parameters (Lucy).

Name of the Parameters	Parameter Values
σ_T (sub-surface scattering + absorption coeff.)	0, 1, 4, 8, 12
Albedo (% of sub-surface scattering)	0, 0.2, 0.4, 0.6, 0.8, 1
Alpha (roughness parameter)	0, 0.15, 0.3

Figure 5. An example screenshot from the experiment.

All experiments were conducted under controlled laboratory conditions on a color-calibrated EIZO CG246 display, with the luminance of 80 cd/m^2 and D65 white point. We used QuickEval (www.quickeval.no) [36] web-based platform to conduct two magnitude estimation experiments [33]. Magnitude estimation is a direct scaling method that has been previously shown to be effective for other appearance attributes, such as gloss [27]. The example screenshot from the experiment in shown in Figure 5. In this format, a single random image from the dataset is shown to observers with a scale slider (0–100 scale, similarly to [27]) below it. For the transparency experiment, observers had to rate the image based on its level of transparency-opacity, where 0 corresponds to maximum transparency and 100 corresponds to maximum opacity. Similarly, in translucency experiment, observers were instructed to rate an object image on a scale of 0–100 based on its level of translucency, where 100 corresponds to the highest level of translucency and 0 corresponds to the lowest level of translucency. In order to counterbalance the order effect, the images were shown in a random order for each shape. It took around 45 minutes per observer to complete both experiments. To avoid fatigue and exhaustion, each observer assessed each image once. And to avoid subjective misinterpretation of the terms, before each experiment, the following definitions of transparency, translucency and opacity were given from the ASTM Standard Terminology of Appearance [1]:

- *transparency—the degree of regular transmission, thus the property of a material by which objects may be seen clearly through a sheet of it.*
- *translucency—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.*
- *opacity—the ability of a specimen to prevent the transmission of light; transmitting no optical radiation.*

2.3 *Observers*

12 observers with normal or corrected-to-normal vision, including one co-author of this paper, volunteered to participate in the experiment, out of which 9 were male and 3 were female. The median age was 25, ranging from 22 to 42. The observers consented to voluntary uncompensated participation in the study. Information pertaining to name, age, and gender was collected. They were informed that the personal data was collected for research purposes only, which will be reported only as an aggregated data in the publication without personally identifiable information, and which will be anonymized after the study is complete. The standard deviation among the scores given by the 12 observers for each individual image was on average 20 for translucency assessment and 14 for transparency-opacity assessment, which reflects the subjectivity of the magnitude estimation experiments. However, no specific group of observers were identified that were more or less consistent than the others. Half of the participants were naïve and had little to no knowledge on transparency and translucency perception, while another half had had a lecture on the topic that mentioned both the cuboid representation by Gerardin et al. [7], as well as the hypothesis on a Gaussian relationship [13]. We analyzed the two groups separately and conducted two-sample t-test on their responses, as well as visual inspection of the plots of mean translucency score as a function of mean transparency-opacity score. We anticipated that it would be less likely to observe a bell-shaped curve in a naïve group. However, the difference between the two groups did not turn out to be statistically significant (at 95% significance level). Visual inspection of the plots did not reveal any considerable differences either. Therefore, only the aggregated results are reported.

3. RESULTS

3.1 *Summary Statistics*

The average transparency-opacity and translucency scores among the 12 observers was found for each stimuli. All values reported for each stimulus in the subsequent analyses is an average of 12 observers' scores. For both shapes, there is no significant correlation between transparency-opacity and translucency scores (both in terms Pearson's linear as well as Spearman's rank order correlation), which was

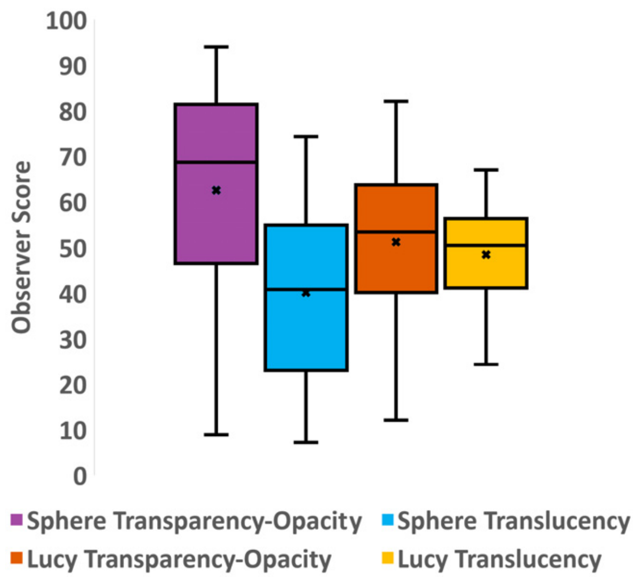


Figure 6. A box plot summarizing statistics of transparency and translucency scores. The bottom and top edges of the box correspond to the first and third quartiles, respectively. The horizontal line inside the box is median, while × sign shows mean value. The top and bottom whiskers extend to the maximum and minimum values, respectively.

expected, because of highly non-monotonous nature of translucency and non-linear relationship with transparency as hypothesized. The statistics of the scores for each shape and experiment are summarized in Figure 6. While the scores on transparency-opacity axis ranged from 8 to 94 for a sphere, and 12–82 for Lucy, the range of translucency scores was narrower as the maximum translucency score was 74 and 66 for sphere and Lucy, respectively. The hypothetical peak was never reached within this set of stimuli. As the materials differ, the results for sphere and Lucy shapes are not comparable directly. However, it is still worth mentioning that on average, spheres were considered more opaque and less translucent even though extinction coefficients for spheres were lower than those of Lucy shapes, once again demonstrating that scale and thickness of an object affects both translucency as well as transparency of the objects and materials.

3.2 *Curve Fitting: Correlation between Transparency-Opacity and Translucency Values*

One of the primary objectives of this work is identifying how translucency relates to transparency and opacity, and whether the bell-shaped curve hypothesized by Gigilashvili et al. [13] actually describes the relationship between them. Translucency scores as a function of transparency-opacity score are shown in Figures 7 and 8. It is worth mentioning that although the difference between the two shapes is apparent from the plots, we attempted to fit the curve for the aggregated data (including both sphere and Lucy results), and we have not been able to find a model that could describe the functional relationship for both shapes as precisely as when it was done for each shape separately.

Table IV. Polynomial curves and their R^2.

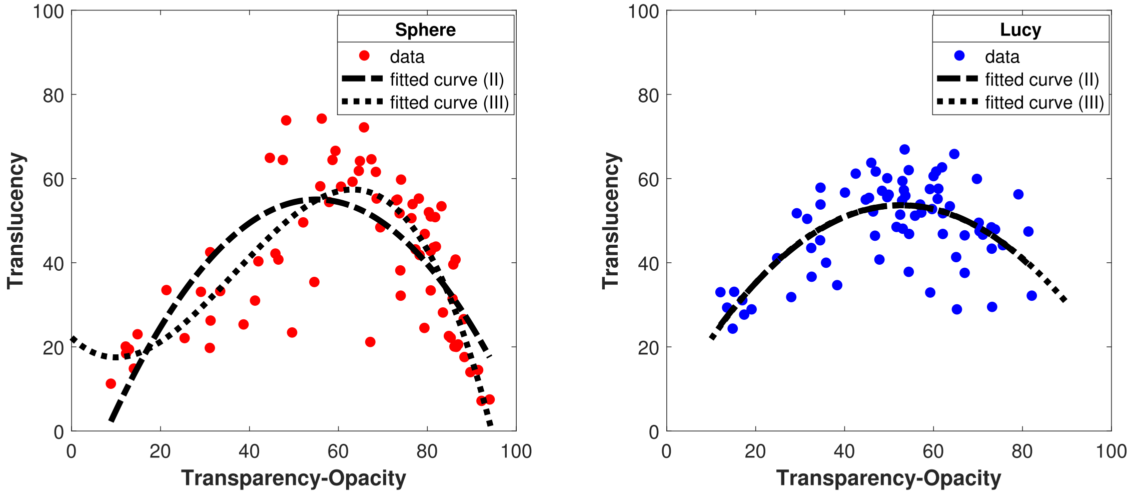
	Equation	R^2
Sphere Second Degree	$y = -0.0247x^2 + 2.7196x - 19.839$	0.54
Lucy Second Degree	$y = -0.0172x^2 + 1.8169x + 5.7501$	0.44
Sphere Third Degree	$y = -0.0005x^3 + 0.058x^2 - 0.998x + 22.217$	0.65
Lucy Third Degree	$y = 1E - 05x^3 - 0.0192x^2 + 1.8982x + 4.8131$	0.44

3.2.1 *Polynomial*

At first glance, the relationship resembles a bell-shaped curve, more for spherical object than it is the case for Lucy. To characterize and model the potential relationship more thoroughly, we decided to fit the curve. Although not explicitly hypothesized in previous works, before testing a Gaussian function, we found it interesting to investigate how well the functional relationship could be described by polynomials of different degrees. Initially, we started with second and third degree polynomial models. The fitted curves are shown in Fig. 7. The models and R^2 are shown in Table IV. While the third degree polynomial provides a slight improvement in R^2 for a spherical object (from 0.54 to 0.65), it did not provide any improvement for a Lucy shape (0.44). In case of the third degree polynomial for a spherical object, the independent variable, i.e. transparency-opacity explains 65% of the variation in the dependent variable—i.e. translucency.

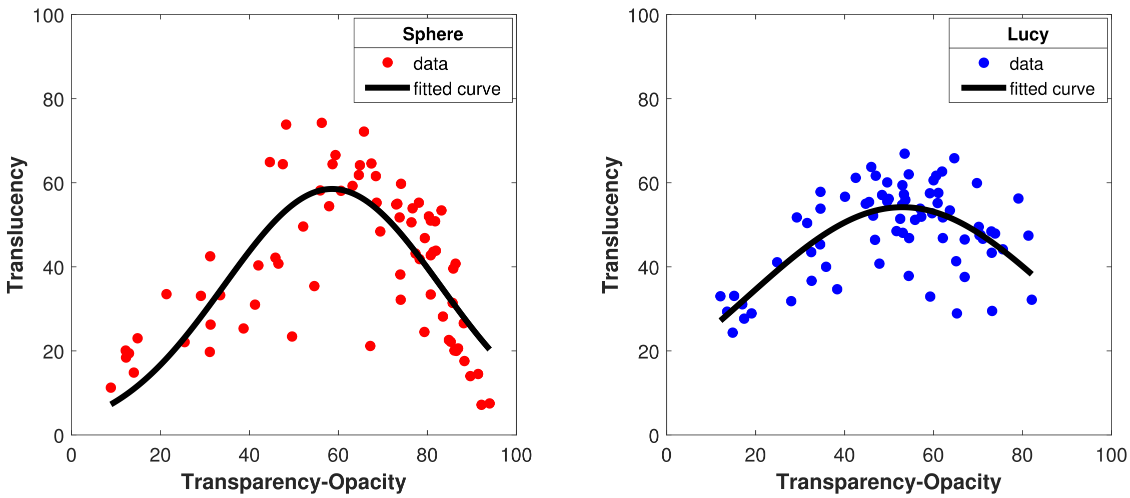
3.2.2 *Gaussian*

As the hypothesis by Gigilashvili et al. [13] referred to a Gaussian bell-shaped curve, we decided to fit the Gaussian curve. A general Gaussian function is as follows: $y = a\exp(-\frac{(x-b)^2}{c^2})$, where a is the height of the peak of the curve, b is the center of the peak, c is a standard deviation, x is an independent variable—in our case, transparency-opacity, and y is a dependent variable—in our case, translucency. The starting point for the fitting was $a = 100$, $b = 50$, and $c = 10$. The results are shown in Fig. 8. The curve equations and the goodness-of-fit are summarized in Table V. The R^2 is comparable to that of polynomial. The Root Mean Square Error (RMSE) is 11.55 for sphere and 7.98 for Lucy, as the dispersion of the Lucy values is smaller. However, the curve explains the overall variation better for a spherical object. While the stimuli with medium transparency-opacity usually have a higher translucency score, we noticed that for a spherical object, there are outliers with medium transparency and low translucency. We removed these three outliers and fitted the curve again that increased R^2 to 0.71 and decreased RMSE to 9.84. These outliers are discussed in the subsequent section.



(a) (b)

Figure 7. The second and third degree polynomial fitting for Sphere (a) and Lucy (b) shapes. Red and blue dots represent average scores for each of the 75 sphere and Lucy stimuli, respectively. The fitted curves are shown in black dashed and dotted lines, for second and third degree polynomials (marked with Roman numerals in the legend), respectively. For Lucy, the two are nearly identical.



(a) (b)

Figure 8. Gaussian bell-shaped curve fitting for Sphere (a) and Lucy (b) shapes. The data of the spherical object resembles more to and is better described by a hypothesized bell-shaped curve, while the curve is less apparent for Lucy. Red and blue dots represent average scores for each of the 75 stimuli for sphere and Lucy, respectively. The fitted curve is shown in black.

One of the assumptions is that the error, our model does not account for is randomly distributed. To check this assumption, we plot the residuals against an independent variable in Figure 9. While in most cases the residuals are equally dispersed in both sides of the zero line, for spherical objects with high transparency (i.e. low opacity) the residuals are only positive. This means that for this type of materials, the model does not account for an important factor and underestimates perceptual translucency scores. This can be explained with the recent finding that the HVS is more sensitive to translucency differences when the background is visible through a translucent material [17]. Thus, a change in transparency-opacity might have larger effect on translucency in highly transparent part of the spectrum.

Table V. Gaussian curves and their goodness-of-fit.

	Equation	SSE	R^2	RMSE
Sphere	$y = 58.52\exp(-\frac{(x-58.58)^2}{34.45^2})$	9619	0.58	11.55
Sphere w/o Outliers	$y = 62.63\exp(-\frac{(x-58.3)^2}{32.68^2})$	6688	0.71	9.84
Lucy	$y = 54.18\exp(-\frac{(x-52.99)^2}{49.27^2})$	4598	0.45	7.98

3.3 *Impact of the Optical Properties*

Although the definitions given to the observers refer to transmission of optical radiation, they do not establish explicit links between magnitudes of perceptual attributes and specific optical properties, neither specify their bound-

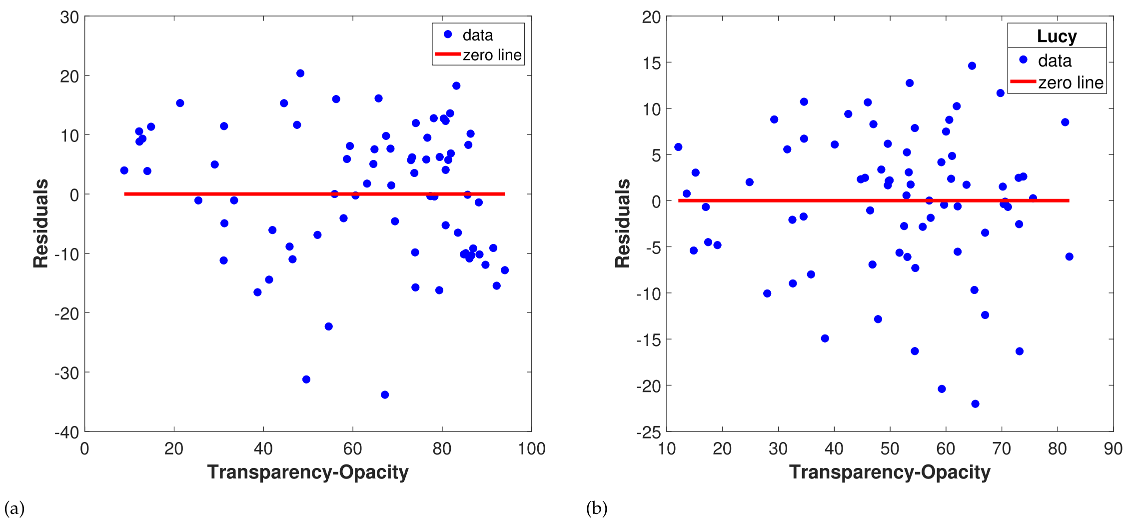


Figure 9. Residuals as a function of Transparency-Opacity score for Sphere (a) and Lucy (b). While the error looks mostly randomly distributed, it tends to be positive for highly transparent spheres.

aries nor extremes. For instance, although the definition of translucency refers to transmitting light diffusely, it does not specify whether scattering happens on the surface, inside the volume, or both, and whether absorption also plays any role in this process. Therefore, we decided to investigate whether our results are consistent with the relationship between optical and perceptual properties proposed by Gerardin et al. [7]. The results for sphere and Lucy is summarized in Figure 10. The figure presents a cuboid representation of optical properties, similar to the one proposed by [7], where axes correspond to absorption, subsurface scattering, and roughness, while the translucency score is color-coded. 2D plots of each of the three planes can be found in Supplementary Material 2.

For spherical objects, we observe that translucency score remains low across the absorption axis when scattering is zero and surface is smooth, which supports the notion by [7] that absorption alone increases opacity but does not affect apparent translucency. Furthermore, when absorption and scattering are low, roughness alone is capable of producing translucent appearance—never becoming opaque. However, with high absorption, rough objects appear opaque and minimally translucent. The materials in the center of the cube and the rough objects with low absorption and scattering were reported to be the most translucent.

There are similarities as well as differences for Lucy. Similar to sphere, absorption alone does not produce apparent translucency. The most translucent parts are found in the area where absorption is low and scattering and roughness range from moderate to high. However, absorption still affects the magnitude of translucency—increase in absorption decreases translucency and increases opacity when roughness and subsurface scattering coefficients are high. However, due to the presence of thin parts on Lucy, even for the most opaque objects, translucency scores are not as low as for spherical ones. The key difference with the sphere is the fact that highly scattering spheres start to decrease in translucency, while translucency scores remain high even for the most highly scattering Lucy shapes that might be attributed to thin parts present in the wings of Lucy.

4. DISCUSSION

The plots in Figs. 7–8 show that the relation between transparency-opacity and translucency follows the hypothesized bell-shaped curve for a spherical object. With the Gaussian function, transparency score explains 71% of the variance in translucency evaluations. As hypothesized by Gigilashvili et al. [13], translucency is not mutually exclusive with transparency and opacity, and the boundary between them is fuzzy rather than a discrete point. Perceived translucency peaks with medium transparency-opacity and is low for highly transparent and highly opaque objects. Interestingly, this hypothesis does not hold for Lucy shape. The variance in translucency scores is smaller for Lucy, and the tails of the curve are less visible. However, it is also worth mentioning that the range of transparency-opacity is also narrower for Lucy objects. In other words, while we can find spherical objects in our dataset that have been considered very transparent or very opaque, Lucy objects are usually considered neither very transparent nor very opaque, and even the ones nearer to the extremes of transparency-opacity axis have moderate translucency values. This can be attributed to shape and scale differences between sphere and Lucy. Sphere is a compact object with simple surface geometry that if scattering, absorption and roughness are low, permits to see through the scene behind it, while the Lucy made of the same transmissive smooth material does not permit seeing the background through as its complex surface geometry blurs, distorts and occludes background image (see marked red in Figure 11). On the other hand, if a sphere is highly absorbing and/or scattering, it occludes background completely, while similarly absorbing and scattering Lucy would block passage of light in its torso,

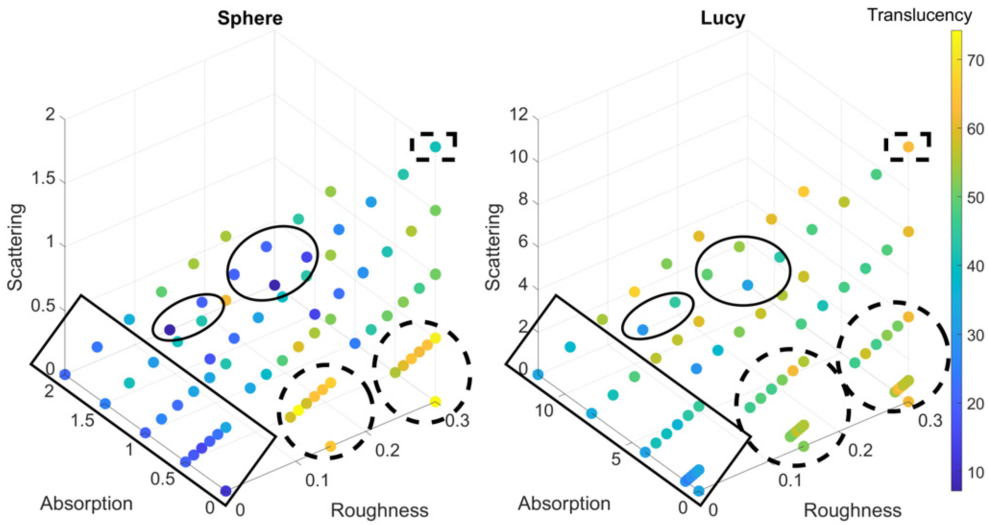


Figure 10. 3D scatter plot of perceived translucency scores given by the observers on the scattering-absorption-roughness plane. Also see all 2D planes in Supplementary Material 2. For both shapes, absorption alone does not increase perceived translucency, when scattering and roughness are low (marked with a rectangle). However, the scores are usually higher for a Lucy shape, which could be explained by the fact that, unlike a sphere, Lucy's complex shape does not permit to see through the background (compare the color of the markers inside the two rectangles). As expected, increase in absorption has a negative effect on translucency score for both shapes. Spheres with high absorption, scattering and roughness are considered opaque and minimally translucent, while scores for Lucy are relatively higher, which could be attributed to its thin parts that do not look completely opaque (compare the parts marked with a circle). The highest translucency is reported for objects with relatively low absorption and high roughness (marked with a dashed circle). However, high scattering coefficient usually produces higher translucency scores for Lucy, while spheres with high scattering coefficient are considered less translucent and more opaque due to its thickness (compare materials marked with a dashed rectangle).

but its thin parts, such as wings and hands (see marked yellow in Fig. 11), would still permit observing part of the background—thus, can be considered opaque and somewhat translucent at the same time. Furthermore, although the impact of optical properties on perceptual attributes of transparency, translucency, and opacity largely follow the cuboid representation proposed by Gerardin et al. [7], the way optical properties affect perception differs between the shapes.

Even though the small number of shapes and materials do not permit us to generalize our findings, observed differences between a simple sphere and complex Lucy indicate that no universal model may exist in practice capable of characterizing transparency and translucency perception, as well as correlation among them solely based on optical properties. Observed differences between spherical and Lucy shapes have a practical relevance in material design, modeling, and cross-shape appearance reproduction. Even if we understand how manipulation of one perceptual attribute affects the other for a given object, it might not generalize to other shapes, and manipulation of transparency might have unintended effects on object's translucency appearance, or the other way round. For instance, Lucy made of a highly transparent material can look more translucent than a spherical object either made of the same material or having the same apparent transparency. The state-of-the-art studies on translucency perception propose that the HVS relies on images cues [5, 15, 38] that in addition to optical properties, are also modulated by illumination, scale, shape, and surface geometry of an object. The *bell-shaped curve hypothesis* holds for objects with simple surface geometry that permit to see through if sufficiently smooth and transmissive, while a Gaussian function describes less of the variation in the data when an object with complex surface geometry and varying thickness is examined. Low number of samples did not permit us to model the correlation between optical and perceptual properties, but we demonstrated that even if this kind of model exists, it would not generalize to all objects, and should be tailored to each object's shape, scale, and surface geometry (compare marked regions between the two plots in Fig. 10). For above-mentioned reasons, we believe that the relationship between transparency and translucency is more likely to be explained better from the perspective of image cues.

For spherical objects, we noticed three outliers with moderate transparency and very low translucency. All three objects turned out to have smooth surface, high extinction coefficient and low albedo. One of them is illustrated in Figure 12. As absorption process is dominant and there is little scattering, object looks dark and mostly opaque that does not include any cues to scattering and translucency. However, some photons manage to go through and focus on the right side of the sphere, forming a small caustic pattern (marked red in Fig. 12) that, if inspected carefully, might indicate to the presence of transmission that apparently made observers assess it as not highly opaque. This once again illustrates that perceptual considerations are rooted in image cues that are extremely challenging to be predicted and envisioned by knowledge of optical properties alone.

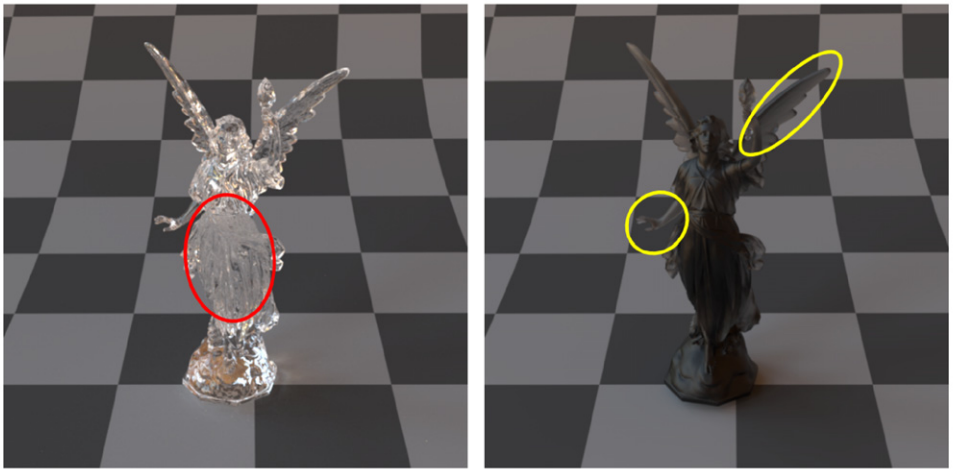


Figure 11. Difference in image cues explain the cross-shape differences in the results. It is possible to see the background through a smooth sphere made of a material with low extinction coefficient (see Fig. 4). However, the same does not apply to Lucy. Its complex surface geometry distorts (marked with a red circle) or completely occludes (see the upper part of the torso in the left image) the background even if its micro-level roughness and extinction coefficients are low. On the other hand, complex shape provides broad range of cues. In the right image, the torso looks opaque while wings and hand appear translucent (marked with an yellow circle).

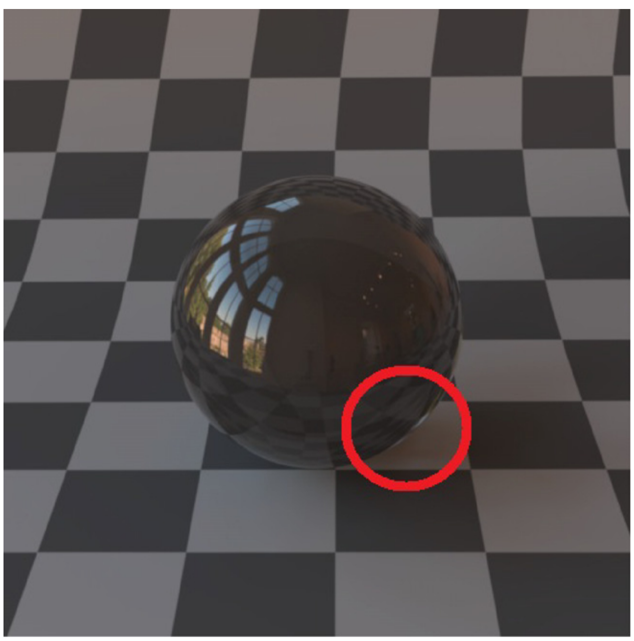


Figure 12. A material with high extinction coefficient and low albedo turned out an outlier. Its translucency is considered low due to lack of scattering, but it is not considered fully opaque due the the caustic pattern observed on the right side (marked with a red circle).

We made one interesting observation that the highest translucency scores given by the observers is significantly lower than the maximum permitted by the scale (100). While we have stimuli considered very transparent or very opaque, no stimuli was considered very translucent. There can be two explanations for this. First, the limited range of the stimuli used in this experiment might not contain sufficiently translucent materials. However, we believe this could be attributed to the conceptual ambiguity of translucency. While the understanding of what are the extremes of opacity and transparency is more universal, the observers do not know what is the extreme or the peak of translucency, and the lack of this clear reference forces them take translucency assessment with care and leave the possibility that more translucent materials might exist on the scale.

Finally, the work comes with limitations that need to be considered: first, all findings reported above are limited to the small range of materials and shapes studied in this work. For instance, while we use isotropic phase function for all stimuli, the phase function alone [18] can have a considerable impact on appearance, and broad range of materials need to be studied in the future. Second, even though we provided technical definitions of the concepts, these definitions still leave the room for subjective interpretation in terms of perception. For instance, similar to the reports in previous studies [13, 14], the observers mentioned in post-experiment interviews that assessment of transparency, translucency and opacity is a challenging task when the object has varying thickness and the appearance differs strikingly between different parts of the same object (e.g. refer to Fig. 11). Besides, in this work, we assume that transparency and opacity are two mutually exclusive ends of the same continuum and increase in opacity automatically means decrease in transparency. In this regard, we rely on the technical definition [1], which defines that opacity is *"the reciprocal of the transmittance factor"*. However, the actual perceptual correlation between transparency and opacity can potentially be more complex than that.

Future work should address other important questions:

- If identical rendering parameters are used for different shapes, we could assess how consistent observer responses are across different shapes for a given material, which helps us understand the limits of appearance constancy and specifically, translucency constancy. For instance, it has been demonstrated previously that gloss constancy is limited, and identical material presented in different shapes does not look equally reflective [25, 35]. This could eventually reveal whether observers assess appearance of a material, or that of a specific object (see *Section 4.2.6* in Ref. [9] for a broader discussion on this topic).

- While this work is limited to still images, future work should consider using dynamic visual stimuli. Translucency, as a second-order visual attribute, which involves a complex analysis of interactions among object, scene, and illumination [15], can be impacted by motion. Previous works have demonstrated that motion affects perception of color transparency [6], it facilitates distinction between transparent and opaque materials [31], and human observers oftentimes rely on motion in translucency assessment process when they are permitted to do so [14].
- The question regarding the hypothetical maximum of translucency remains open. Future work should disambiguate this issue. One potential way of achieving this goal is by fixing the opposite extreme with a perfectly opaque material and increasing translucency gradually with small steps to investigate how perceptual distances from the opaque extremum and respective image cues change.

5. CONCLUSION

We conducted two psychophysical experiments to scale perceived transparency and translucency of light permeable materials. We tested the hypothesis from the literature that the magnitudes, translucency and transparency are related with a bell-shaped curve, similar to a Gaussian function. We demonstrated that for spherical objects Gaussian function characterizes the relationship of translucency with transparency-opacity sufficiently well. However, this does not generalize to complex shapes with complex surface geometry that distorts the background image observed through the object. We also demonstrated how optical properties correlate with perceptual transparency, translucency and opacity also differs between the shapes. We confirmed previous proposals in the literature that both subsurface as well as surface scattering are contributing to perceived translucency, while absorption makes translucent materials opaque but does not alone produce translucent appearance when surface and subsurface scattering is low.

This work is a step toward disambiguation of how perceptual attributes relate with each other, and whether they are orthogonal. This is essential for proper design and communication of appearance both in industrial applications as well as within the scientific community. However, rigorous future work is yet to be done to properly model these relationships, which we believe can be achieved by identification of image cues used by our visual system and modeling their relationship with the optical and geometric properties of the scene.

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