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Can we grasp the color of translucent objects?

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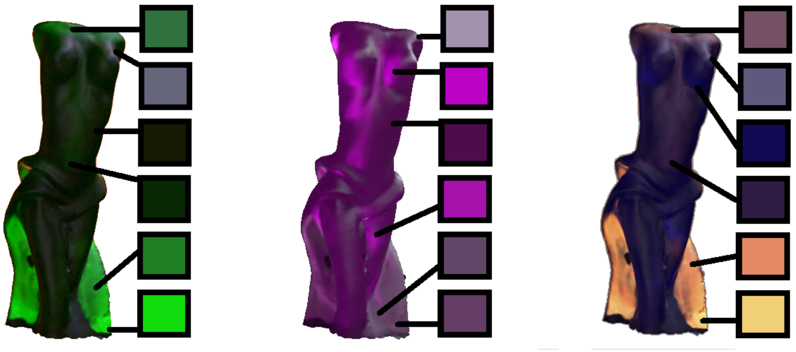

Figure 1: *Translucent objects exhibit high degree of color variation, which complicates measurement and description of their colors. In your opinion, which of these uniform patches are best to represent the color of these objects?*

Abstract

While colorimetry is traditionally measuring point colors, there is an increasing need to quantify colors of 3D objects in real-world scenes. 3D objects, especially translucent ones, exhibit high spatio-temporal variation in color. This raises multiple questions on how to measure color of 3D translucent objects, how to describe their color appearance, and how to quantify color differences among them. Or are these ill-posed problems in the first place? We discuss the first steps on this topic and suggest the future directions for color and appearance research.

Categories and Subject Descriptors (according to ACM CCS): I.3.6 [**Computer Graphics**]: Methodology and Techniques—
—Standards J.4 [**Social and Behavioral Sciences**]: Psychology—

1. Introduction

Color vision plays an immense role in many daily tasks that humans perform. Color is important for identifying different objects and materials, and communicating their appearance [WG18]. The light spectrum incident onto the human retina from the object is not necessarily the result of reflection from object's surface, but it can also be the light transmitted through the object. Light penetrates the subsurface of translucent materials, propagates through them, and re-emerges from a different point. Translucency has a significant impact on how objects and materials look, and visual perception of translucency is a topic of active research (see [GTHP21] for a review). There is little knowledge on how translucency affects color. It affects color preferences proposedly stemming from evolutionary aesthetics, being usually associated with ripe fruit and sugar [HC22].

Despite significant advancements throughout the past century, colorimetry mostly deals with measuring isolated spot colors and uniform flat patches. However, in real life, the objects are hardly ever uniform, and they usually exhibit large spatio-temporal variation in color, as shown in Figs. 1-2. How point measurements of uniform patches relate to actual color perception of 3D objects remains largely unexplored. Multiple authors highlight the importance of studying color as a property of 3D objects and materials in the real-world [WG18, XB08]. Translucent objects are prone to color variations (Fig. 2), especially across different illumination conditions, as demonstrated in [GTHP21].

Color alone is not enough to fully convey how objects and ma-

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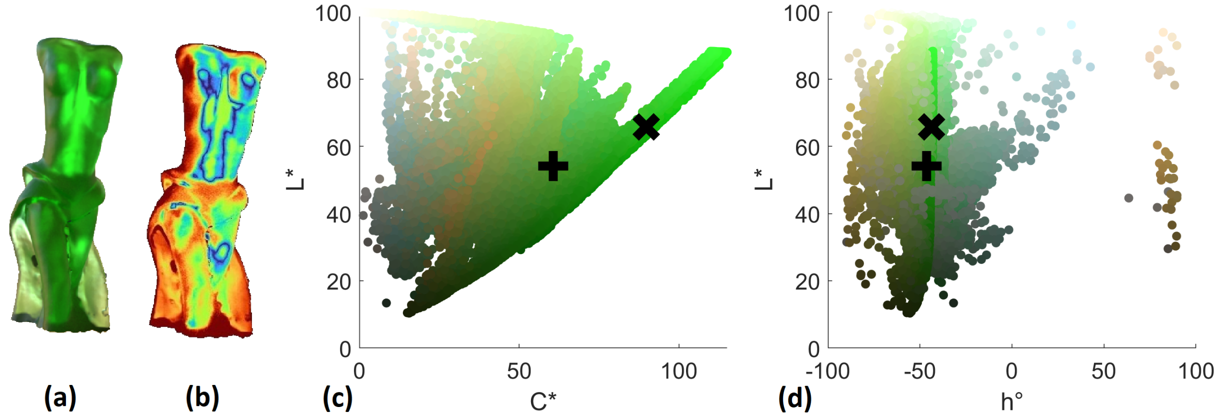

Figure 2: *Images of translucent objects (a) contain pixels with highly diverse colors. Each point in the Lightness-Chroma (c) and Lightness-Hue angle (d) plots (CIE L*C*h) correspond to individual pixels in (a). The black + in each plot marks the location of the average color, while the black × marks the most representative color matched by observers in [GA23]. (b) shows the color difference heatmap between individual pixels and picked color, with lower differences showed in blue, higher in red.*

terials look, and other appearance attributes, such as gloss, translucency, texture, and their interactions with color should be also considered [Int06]. This is also acknowledged by introduction of a novel chapter on gloss and translucency [GT23] in the latest edition of the Colour Engineering handbook, which offers an interesting perspective on translucency's impact on future color technologies. The authors demonstrate how large the color variation among different local spatial regions of translucent objects is, shown in Fig. 1. They raise a question on how colors of such objects can be measured and communicated. These questions are not only academically relevant for future color research but also have significant implications for existing industrial problems. The rapid development of multi-material 3D printing made it possible to produce spatially-varying color and translucency [BAU15]. While translucency management is an open problem [UTB*19], it also complicates the reproduction of color. Spot color measurements on flat 3D printed samples with a given thickness can be poor predictors of color appearance of a 3D printed translucent object, whose translucency affects color due to variations in thickness, surface, and illumination [UTB*19, GTHP21]. Another example where translucency may complicate color measurement procedures is wine industry [Fai18]. In this position paper, we briefly introduce the recent efforts for answering the questions on color naming, color matching, and color difference for 3D translucent objects, followed by discussion and suggestions for color and material appearance research.

2. Color naming for translucent objects

To make cross-human communication of colors practical, we assign certain names to certain ranges of colors. Color naming varies across languages and cultures and is an active topic of research [GA23]. However, most works are limited to naming uniform color patches, and few works addressed color naming for 3D opaque objects [THT15]. Gigilashvili *et al.* [GA23] were the first ones to explore how colors of translucent 3D objects are communicated. They noticed that the results are strongly dependent on the illumination conditions. Due to shine-through cues, the objects on a strong backlight were usually described lighter, brighter or more vivid, than the identical objects under different illumination; e.g., all objects in the first row of Fig. 3 were described as red, but those in the middle columns were described as "light/bright red". In specific cases, if the lighting or the background were highly chromatic, the basic color term changed completely: purple object in the second row became red (second column), and a blue object shown in the third row was described as black or dark gray when shown on the red background, since mostly longer wavelengths are incident from the background that are completely absorbed by the object. This indicates that color of a translucent object can be strongly impacted by illumination direction, spectral power distribution, and color composition in the scene.

3. Color matching – the most representative color

As Figs. 1 and 2 illustrate, real 3D objects have large spatial variation in color. Sometimes dominant color palettes need to be extracted from complex images for retrieval, fashion, aesthetics, and color harmony applications [TMHG13, YWF*19] – often achieved by K-means clustering [CM22]. Humans easily assign single color name to the objects. However, Xiao *et al.* [XB08] argue that there is no evidence that the HVS extracts single well-defined color for the object. Even though observers do not usually point out that this is an ill-posed task, when such task is given, the cross-observer variation is usually large [XB08, GA23]. Xiao *et al.* [XB08] demonstrated that human observers do not simply spatially average the color. Kuriki [Kur04] also found that the match deviates from average color, and the element with the highest saturation largely impacts observers' choices. While Kuriki used mosaic of uniform patches, Gigilashvili *et al.* [GA23] conducted similar color matching experiments for 3D translucent objects, where observers were asked to pick a single uniform color that best represented the translucent object. Fig. 2 shows that the hue angle between the aver-

Figure 3: *Translucent objects and their uniform colors matched by observers. Each row illustrates the identical object under four conditions. Reproduced from [GA23].*

age and matched colors does not differ much (d), but similarly to [Kur04], observers picked more chromatic, lighter colors (c) that were mostly present in flat areas with strong shine-through highlights (a-b). Fig. 3 shows the matched color next to each image, which varies substantially across different conditions. Gigilashvili *et al.* [GA23] showed that the most salient areas that are closest to the matched color, change across the scenes.

4. Color differences

Measuring color differences play a pivotal role in evaluation of color reproduction. Color difference formulae are traditionally suited for point colors and mostly intended for small differences, with fewer works exploring the metrics for very large color differences [AATF20]. Color difference for 3D objects remains understudied. The International Commission on Illumination recently pointed out the importance of further research on this topic [Int17]. Current works rely on point spectrophotometric measurements at multiple spatial locations of the 3D object that are later pooled [JCM*21]. However, translucent objects have very large color differences across different points, which will be difficult to pool.

In a yet unpublished study, we conducted psychophysical experiments with a grayscale method to quantify color differences among 3D translucent objects. We rendered images in red, green, and blue hues with spectrally selective absorption and scattering coefficients, producing 3 levels of translucency per hue. Each material was rendered under 4 lighting conditions. The segmented objects were placed on a neutral gray background to prevent observer bias due to the potential simultaneous contrast effect caused by the bright and colourful backgrounds and differences in adaptation conditions. Different translucency levels were compared within the same hue and scene. We used a digital version of the grayscale patches, whose XYZ values were measured on a calibrated display using a spectroradiometer. Euclidean colour difference between each patch and the reference patch was calculated to ensure that the steps were linear. Each pair was assigned a letter from A to G that was later converted to numeric scale of 1-7, and geometric mean over all observers' responses was found to come up with a single value per comparison. The sample comparison pair and the grayscale reference are illustrated in Fig. 4. The experiment was conducted on a color-calibrated display. 23 observers with a median age of 23 participated in the study. 36 flipped pairs and 8 random duplicate comparisons were also shown to measure intra-observer consistency. The root mean square error for flipped pairs was 0.32, and 0.34 for duplicate pairs, which indicates that the order of the pair had little impact, and the observers were highly consistent with their own responses. On the other hand, the variation was relatively large across the observers. The average range of responses for each pair was 4.88 units, and the standard deviation was 1.21 units.

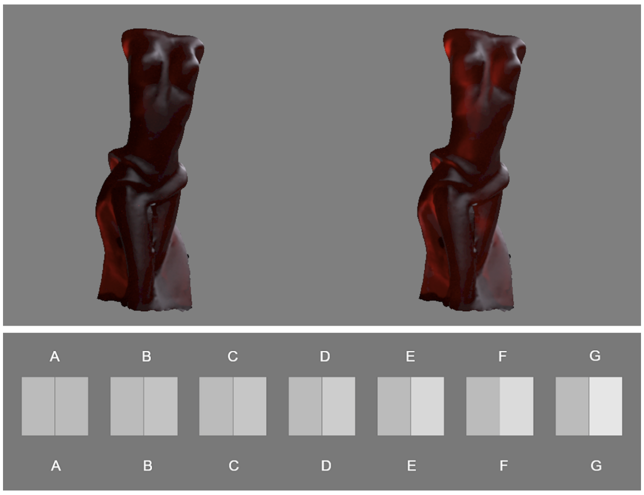

Figure 4: *The task was to compare the color difference between two translucent objects with the grayscale reference.*

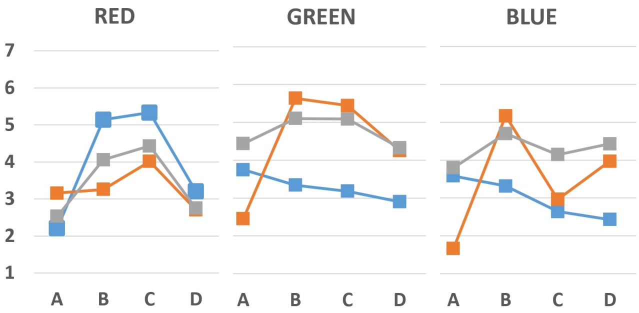

Figure 5: *Perceived color differences for red, green, and blue objects. Scenes A, B, C, and D correspond to Bernhard Vogl's light probe At the Window rotated so to light the object from front (A) and back (B), and Paul Debevec's The Grace Cathedral and The Uffizi Gallery, respectively. Blue curve corresponds to Comparison 1 – between the objects with medium and high opacity; Orange, Comparison 2 – between medium and low opacity; gray, Comparison 3 – between high and low opacity.*

The results substantially differ among the hues (Fig. 5), as well as among the four scenes even when the identical pair is compared. For green and blue objects, the differences are lower and more consistent when more opaque objects are compared and larger when

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objects with more transmission are compared. Also, the differences are usually larger when the objects are lit from behind (scenes B and C). This is consistent with the previous finding that backlight facilitates comparison between translucent objects [GTPH21]. The impact of illumination direction is apparent for Comparison 1 of the red objects, where there is a significant increase in perceived color difference between scenes A and B. Scene C produces high difference, because these objects absorb most of the shorter wavelengths incident from the yellow background, exhibiting strong red highlights shining through.

5. Discussion and Conclusions

There is an increasing need to move from classical colorimetry of uniform patches to understanding color measurement and perception in dynamic 3D scenes. 3D objects have large spatio-temporal variation in color. The color of translucent objects is especially challenging to grasp, since it varies a lot depending on many factors, such as object's thickness, illumination color and direction. Strongly chromatic background or illumination may change the basic color term used to communicate the color of a translucent object. Multiple studies have demonstrated that humans do not simply average the color when picking a single representative color for a 3D object, but their choice is affected by more salient, saturated colors. The first studies indicate that this also applies to translucent objects, where observers systematically overestimate lightness and chroma in comparison with the average color. They rely on saturated areas that result from large amount of subsurface light transport from the background. Color difference between a pair of translucent objects can also significantly vary across conditions, usually being the largest when the objects are back-lit. The spectral power distribution of the lighting plays a big role, since translucent objects have spectrally selective absorption and scattering.

Metrics for very large color differences should be used for translucent objects. Averaging reflectance measurements at multiple spatial locations, which is a common method for opaque objects, may not produce the best results for translucent ones. Instead, the most salient regions for a given observation condition should be detected and measured. Measuring color on flat material samples may not generalize across different shapes and conditions. These aspects need to be incorporated as parametric factors in future color difference formulae that certainly merits future research.

Several significant questions remain that should be disambiguated by future research. First of all, when comparing the colors matched to a given object under different conditions, it is important to verify that the observers recognize given object across these conditions. In other words, future work should explore to what extent material constancy holds for translucent objects, and whether a material is recognized as the same material despite its large color variation across illumination conditions.

Secondly, looking for a single discrete color for a 3D translucent object may not be the viable strategy. It is important to investigate the spread and deviation among all individual matches for a given object to identify the range of colors that represent a given 3D translucent object and to figure out whether these matches fall into a specific shape, such as an ellipse, as in McAdam's seminal color matching experiments [Mac42]. If such regularities are observed, the further question will be whether the size of such shape varies across hues, as it is the case for McAdam's ellipses.

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