COLOR NAMING AND CONSTANCY OF 3D TRANSLUCENT OBJECTS

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ABSTRACT

A large body of research on color constancy and naming of colors is based on flat homogeneous patches. Even though recent studies highlight the importance of studying color in context of 3D objects and scenes, they usually address opaque objects only, whereas many objects that we interact with in the real world on a daily basis, such as wax, plastic, or various foodstuff, are translucent. Different amounts of light re-emerge from different parts of the translucent object due to thickness and other geometrical variations, which leads to high spatial variation of color in translucent objects. Little is known about how humans name colors of translucent objects and how constant color is when perceived translucency changes due to illumination direction. In this work, we generated images of chromatic translucent objects with a complex 3D shape and conducted color naming and color matching experiments. Color naming was conducted in two unrelated languages - English and Georgian. We found that the color of the translucent object substantially varies across illumination conditions, and the mean color of the object is a poor predictor of the matched color. Observers usually pick lighter and more chromatic colors than the global average. They prioritize specific spatial regions, whose exact manner remains poorly understood. If the background is highly chromatic, it may affect the hue of the translucent object. The change in illumination conditions did not cause a flip in basic categories in color naming, but we observed several curious exceptions when the background was chromatic. Future works should offer more rigorous quantitative modeling of how optical material properties and shape of the translucent object affect its color variation across the shapes and illumination conditions.

Keywords: color naming, color constancy, translucency, material appearance, perception

INTRODUCTION

Color impacts the perception of translucency [1,2], but little is known about whether the opposite is true. Translucency affects color preferences proposedly because translucent stimuli are associated with ripe fruit and sugar [3]. Certain colorimetric and geometric regularities between the part of the background seen in a plain view and through an overlay are necessary to perceive transparency. This has given rise to color transparency research, which is relatively well-studied [4]. However, highly scattering translucent objects that we encounter daily completely occlude the background [5]. While a substantial part of color science is based on flat homogeneous patches, recent studies show that 3D shape information and interaction with gloss and texture improve color constancy [6,7]. Different authors highlight the importance of studying colors not as isolated points but in context of real-world scenes, objects and materials [8,9]. Giesel and Gegenfurtner [10] studied color matching for real objects and found that humans are good at matching hues, chroma gets affected by lightness, and lightness depends on the brightest areas except specular highlights.

Another important research question is color naming, boundaries among color categories and the linguistic communication of colors [11]. The naming differences among languages [12], persons [13], and their development over time [14] is an active topic of research. However, the research has also mostly been focused on flat homogeneous patches, such as Munsell Sheets of Color [15]. A notable exception is a work by Tanaka *et al.* [16] - however, the work used opaque objects.

Despite advances, the knowledge gaps remain that motivate our research: first, how humans assign representative colors to 3D translucent objects; and second, how constant the color of a translucent object is across different illuminations. Color alone is not enough to convey how objects look, and previous studies show that humans also use gloss- and translucency-related terminology to communicate appearance [17]. High spatial variation of color in translucent objects makes it difficult to quantify it with spot measurements and raises questions about the description of its color [18]. Little is known whether humans can account for shading variations due to the translucency of the object when describing its color (e.g. what would be the color of the objects shown in Figure 1?). Besides, translucency constancy is limited, and illumination geometry significantly affects perceived translucency [5, 19], which on its part may affect color.

To address these questions, we conducted psychophysical experiments. In the first experiment, observers named the color of the overall translucent object; in the second experiment, observers matched the color between a 3D translucent object and a flat homogeneous patch. The objects varied in hue, chromaticity, and degree of translucency, and were placed in different illumination conditions. The objectives of the experiments were to explore: first, how observers assign color names to translucent objects, whether this depends on the degree of translucency and varies across illumination conditions; second, how observers pick the most representative color for the translucent object and whether it can be predicted from global color statistics; third, how constant color of a translucent object is when illumination and geometry change. To the best of our knowledge, this is the first study that investigates color constancy and color naming specifically for 3D translucent objects. Finally, due to the peculiarities of color naming in Georgian and its differences from English [20,21], we decided to conduct naming in two unrelated languages – English (Indo-European) and Georgian (Kartvelian), to analyze the differences between them.

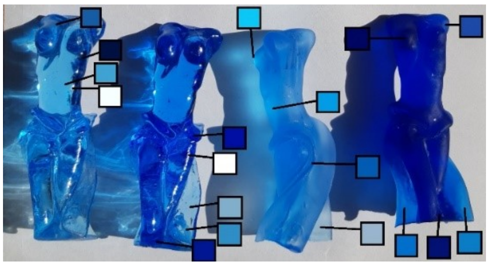

Figure 1. Translucency makes it difficult to measure and describe the color of an object. For instance, which of these point colors best represent the color of the translucent material? The image is reproduced from [22].

METHODOLOGY

Experimental Protocol

We conducted three experiments: Experiment 1 – Color Naming in English, Experiment 1B – Color Naming in Georgian, and Experiment 2 – Color Matching. 48 images of translucent objects were shown one by one. In Experiments 1 and 1B, the observers had to provide a color term in the respective language (English and Georgian). In Experiment 2, both the image and a color picker (implemented with MATLAB's *uisetcolor()*) were displayed. The observers' task was to match a color between the 3D translucent object and a flat homogeneous patch. They were instructed to use the color picker to navigate through the color space and pick one color that best represented the translucent material that the object was made of. They were given unlimited time. Once they were satisfied with the match, they proceeded to the next image. Experiments 1 and 2 were conducted in the same session with the same observers. Color naming in Georgian was conducted independently from the other two experiments.

Stimuli

We used 48 images of translucent objects that varied in hue, degree of translucency, and illumination. We selected a complex 3D shape – a bust figurine from the *Plastique* [23] collection. It includes both thick and thin parts, has both flat and uneven surfaces, and exhibits a broad range of visual cues to translucency. We used 24 synthetic images rendered with Mitsuba Renderer [24] and 24 photographs of real objects from the *Plastique* [23] collection. We rendered materials in 3 hues (red, green, and magenta) with 2 levels of extinction coefficient in 4 different environments. We used Paul Debevec's [25] *The Grace Cathedral* and *The Uffizi Gallery* light probes for a chromatic background and diffuse natural lighting, respectively, and Bernhard Vogl's [26] light probe *At the Window* rotated to two different angles to produce back-lit and front-lit objects. We selected 6 physical objects: blue, yellow-orange, and white-cream, each with 2 levels of translucency, and photographed them four times: front-lit on white and red backgrounds; under dim diffuse lighting; and back-lit with a strong directional light.

Experimental Conditions

Experiments 1 and 2 were conducted on a calibrated display under controlled conditions in a dark room. The 15.8-inch LCD display with a resolution of 3840×2400 was calibrated using a colorimeter to: white point – D65 (x=0.313; y=0.329); Gamma – 2.2; Luminance – 80 cd/m^2. The distance to the display was 50cm. Color naming in Georgian (1B) was conducted online.

Observers

14 observers, 8 male and 6 female, participated in Experiments 1 and 2 with average age of 33.9. All had normal color vision and visual acuity. They were graduate-level students and faculty members with prior knowledge of color science but were naïve to the purpose of the study. All the observers had a good command of English (only 1 was a native speaker). 17 native Georgian speakers took part in Experiment 1B. The majority had no knowledge related to color science and were naïve to the purpose of the study. Their demographic information was not recorded.

Analysis

For color naming, we conducted frequency analysis to identify how color terms vary across illuminations and materials. For the color matching, we are interested in: (1) how the matched color for a given object changes across illumination conditions – for this purpose, we calculate the mean matched color for each condition; (2) which parts of the 3D translucent object the observers rely on when making the match – for this, we calculated the color difference between the mean matched color and each pixel of the object and illustrated as a heatmap. RGB data was converted to CIELAB (D65 white point), and all calculations were performed in CIELAB.

RESULT AND DISCUSSION

Color Naming

Even though color terms in English reflected changes in lightness of basic terms (e.g. "dark red" versus "red"; 1-2 (A-D) in Figure 4), changes in illumination did not usually lead to crossing the categorical boundaries, except for several specific cases. 6A and 6D (Figure 4) were considered purple, but pink in back-lit conditions (6B, 6C). The boundaries of the basic color categories were crossed when a translucent object was placed on a chromatic red background. The object that was consistently labeled as blue (1E, 1F, 1H), became black on a red background (1G). Similarly, the object in 2E, 2F, and 2H was cyan, and was judged inconsistently on the red background (2G) (described as dark gray, black, blue, dark blue, dark green, petrol, and brown by different observers). The objects in 3-4 (E, F, and H) were labeled as yellow and orange by almost half of the observers each. When they were placed on a red background, the majority considered it orange. The objects shown in 5-6 (E-H) were opaquer and less dependent on the conditions. The trends were similar for Georgian too. The confusing object 2G was also described as black, gray, dark green, dark blue, and brown. However, Georgian observers used a broader vocabulary and more non-basic, composite polylexemic color terms. One noticeable difference between English and Georgian was the abundance of reference to commonly translucent objects and materials, such as wax, candle, milk, condensed milk, honey, caramel, amber, ivory, etc.

Color Matching

The first hypothesis was that observers simply spatially average the color of the entire object. Figure 2 illustrates the average color of the object and the average matched color picked by observers (see all images in Figure 4). The observers systematically overestimate lightness and oftentimes chromaticity (e.g. 1C, 2B, 2C, 6B, 6C etc.) – especially for transmissive back-lit (columns B, C, and F) objects. Figure 3 illustrates that the mean difference among matched colors for a given material across lighting conditions is substantial. The illumination condition has more impact on the color of less opaque objects, which is intuitive (cf. 3-4 (A-D), 3-4 (E-H)). There are several instances where change in hue was also observed: e.g., refer to 1G and 2G. In this case, a translucent object, which appears blue in most conditions, is placed on a red background. The blue object absorbs all the spectrum incident from the red background and appears black.

If the observers do not take the average color, it is interesting to investigate which regions they base their judgments on. In Figure 5 we see all images, respective matched colors, and the heatmaps that illustrate the color difference (ΔE CIE76) between the mean matched color and each individual pixel. Even though the shape was identical, the spatial regions that are closer to observers' judgments vary across materials and illumination conditions. In diffuse natural light (column A), the color differences are more evenly distributed but are smallest for vivid highlights of subsurface scattering (A4, A6). When the object is back-lit, the observers interestingly match thin parts of the dress or a flat torso part instead of a thicker and more geometrically complex waist, which appears darker (B, C, F). When the object is lit from front (D and H), observers are able to discount and ignore specular reflections, which is consistent with the previous research [10]. Under dim light observers mostly match the brightest and thin parts (E2) and avoid shadows that are produced if the object is opaque enough (e.g. waist in E1, stomach in E5-6). Black-looking objects placed on a red background appear more homogeneous, while for others, the matched color is closest to the flat chest area, which is lit directly and has no shadows.

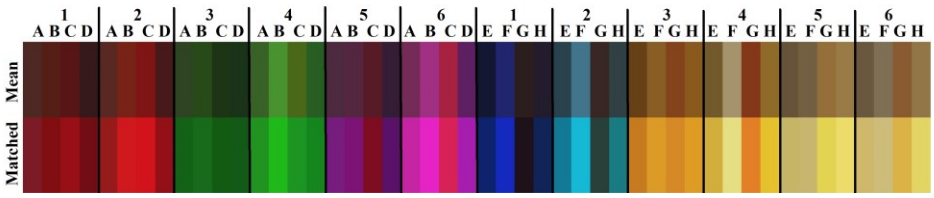

Figure 2. The top row shows the average color of the entire object, while the bottom row shows the matched colors (average). Alphanumeric labels are for reference purposes and will be used throughout the paper.

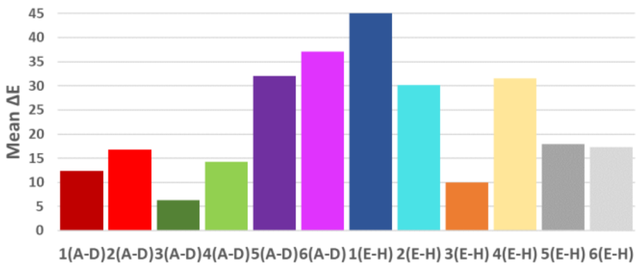

Figure 3. ΔE among matched colors among all conditions for each material.

Discussion

We observed that change in illumination conditions affects the lightness-related label of the color term, but rarely the hue. However, when the background is chromatic, it may still cause to flip hue and cross categorical boundaries – such as, blue becoming black and yellow becoming orange on a red background. This was observed both for English as well as Georgian speakers; however, in Georgian, the reference to translucent objects and materials was abundant. This is

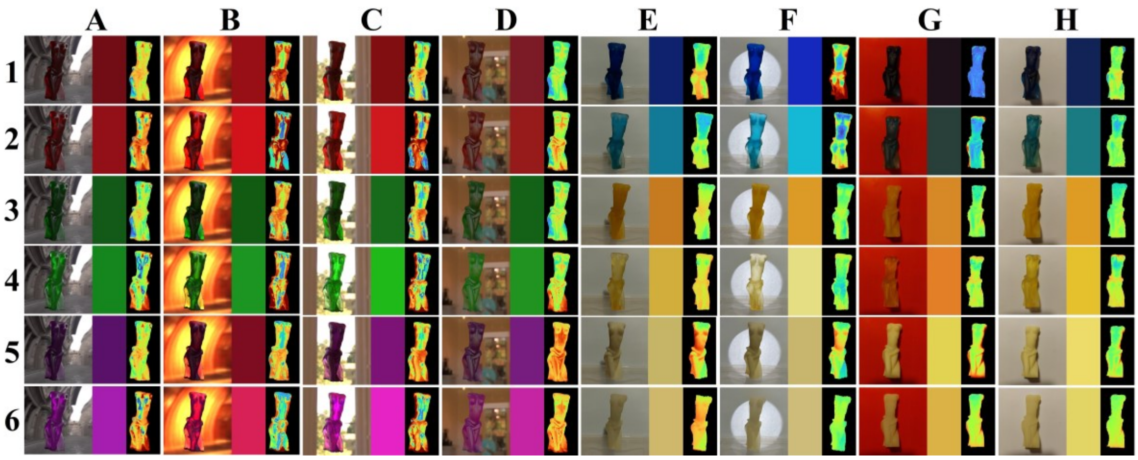

Figure 4. The images with respective matched color and a heatmap, which illustrates differences between matched color and individual pixels (ΔE CIE76). Blue shades correspond to lower color difference, redder shades – to the larger.

an indication that unlike flat homogeneous patches, 3D translucent objects bring material recognition into the color communication. Another explanation is a peculiarity of generating color terms in the Georgian language. Polylexemic composite color terms are broadly used in Georgian. It is very common to produce an intelligible color term by simply putting a noun in the genitive case and adding the suffix *-peri* (lit. "color" in Georgian). Hence, the vocabulary included terms like *tsvilisperi* (color of wax), *rdzisperi* (color of milk) etc. It is also worth mentioning that, unlike English, in the Georgian experiment all participants were native speakers. Future works should include a broader range of colors to measure categorical boundaries among colors, which may be different for translucent objects. Besides, the association between translucent material recognition and color terms certainly merits a future study.

The color constancy of translucent objects seems to be far from perfect. The matched color varies substantially across the conditions, and human observers seemingly do not attempt to discount the effect of light transmission. In comparison with the object's mean color, observers seem to overestimate the lightness and chromaticity. In post-experiment interviews, multiple observers pointed out that thicker parts look "too dark" and are avoided, and that they prefer flat areas. Coincidently, the thickest area near the waist is also geometrically most complex, which produces sharp shadows if the object is opaque enough. Discounting shadows could be an additional explanation of why observers overestimate lightness. Hue shift can be striking where the background is highly chromatic. Future works should provide more rigorous modeling to predict color inconstancy by object's shape and subsurface scattering properties, as well as the illuminant's spectral power distribution and geometry. Our object included areas that were thin enough for the light to shine through. The effect could be smaller for thicker compact objects, such as spheres. Finally, using images inherently limits the realism, which may undermine the color constancy. Future works should use physical objects in real scenes.

CONCLUSION

We conducted color naming and color matching experiments to investigate how translucency affects color. We observed that translucency may affect color terminology if the background is chromatic. We found indications that translucency limits color constancy, human observers do not discount the transmitted light and backlit translucent observers are usually considered lighter. Furthermore, the mean color of the object did not turn out a good predictor of the matched color. Instead of taking a global average, human observers prioritize specific parts of the object. Future works should investigate more robust modeling of how an object's properties impact color constancy and inconstancy thereof.

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