Interactions in the Material Appearance of Colored Semi-Opaque 3D Objects Simulated on Generic Computer Displays

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ABSTRACT

This study examined the perception of gloss and color of translucent objects rendered on generic computer displays of remote users. We found critical perceptual interactions between the experiences of gloss and color (lightness and saturation), which might be explained by models that consider chromatic variations in the structure of images.

1 Introduction

In recent years we have seen an unprecedented reliance on the use of visual displays for inferring information about real-world objects (e.g., online shopping, remote communication and remote expression). This reliance on standard consumer-grade displays has been further motivated out of necessity following the restrictions imposed on direct interactions due to COVID-19. In this paper, we examine how virtual objects simulated on remote displays are perceived by users and how different perceptual attributes interact.

The problem proposed above is a direct application of the vision scientist's problem, which is to understand how we perceptually recover information about the physical properties of objects (e.g., 3D shape, gloss, color and opacity) presented either in the real world or virtually on a computer monitor.

Previous studies have proposed a number of image properties that could be used to perceptually infer material properties from images (e.g., Todd & Mingolla, 1983; Motoyoshi et al., 2007; Sharan et al., 2008; Anderson & Kim, 2009; Kim et al., 2011; Kim et al., 2012; Marlow et al., 2012; Marlow & Anderson, 2016; Marlow et al., 2017; Wijntjes & Pont, 2010).

The perception of gloss has been shown in previous studies to depend on the apparent amplitude and sharpness of specular reflections in an image (Marlow & Anderson, 2013). However, other studies have shown that the presence of specular highlights in an image can alter the perceived lightness (Schmid & Anderson, 2014) and color (Honson et al., 2020; Isherwood et al., 2022) of 3D object rendered on standard computer displays. For example, Honson et al. (2020) found that increasing the specular roughness of an opaque bumpy surface caused it to appear less saturated in color and higher in lightness. This finding was also replicated in across surfaces simulated with different chromatic profiles (Isherwood et al., 2021). However, these studies have largely only considered the perception of color in opaque objects.

Some researchers have considered how visual processing of color appears to be important for the perception of translucency in semi-opaque objects (Fleming & Bulthoff, 2005). They found that perceived translucency was observed when color saturation was correlated with luminance, and different qualities of translucency (warm or cool glow) were perceived with positive or negative correlation. This dependence of perceived translucency on the appearance of color suggests that our experience of material properties generally must involve some form of co-interaction within the brain (e.g., between gloss, opacity, and color).

Here, we undertook psychophysical measurements of translucency, gloss, lightness and color saturation in participants who viewed objects on remotely located computer displays. We also analyzed the interactions that occur between these percepts to identify whether there was any evidence for differential encoding of information at low-level and mid-level stages of vision.

2 Experiment

The study was designed with two main phases. The first phase involved stimulus generation and data collection for assessing perceptual interactions between different material properties of 3D objects rendered on computer displays. The second phase involved computational modelling of images to identify image-based cues that might be informative for objectively estimating user experiences of different material properties when viewing these images.

2.1 Participants

Seventeen adult participants were recruited who had normal or corrected normal vision (including color vision). All procedures were approved by the Human Research Ethics Advisory Panel at the University of New South Wales.

2.2 Stimuli

Images of 3D translucent objects were rendered in Blender 3D version 2.92 with bumpy relief generated using cloud-based textures as displacement maps (meso texture size = 0.05 and macro texture size = 1.0). The strength of macro relief was varied over three levels using the displacement mapping tool (0.5, 0.75, 1.0).

The simulated diffuse reflectance these models was defined within HSV color space (hue = 0.301, saturation = 0.972, value = 1.000). To simulate translucency, the principled bidirectional scattering distribution function (BSDF) was used with a subsurface radius of 5.

Specular roughness was systematically varied over 4 levels (0.2, 0.4, 0.6, 0.8), as exemplified in Figure 1 (A-D) for the highest level of gloss. We considered object images with specular amplitude of 0.2 (i.e., specular intensity). The simulated point light source was positioned at an angle of 40° upwards from a distance of approximately 9 m to the surface relative to the viewing axis. The camera was situated at approximately 5 m from the 3D surface. The diameter of the simulated bumpy 3D object was approximately 1 m on average.

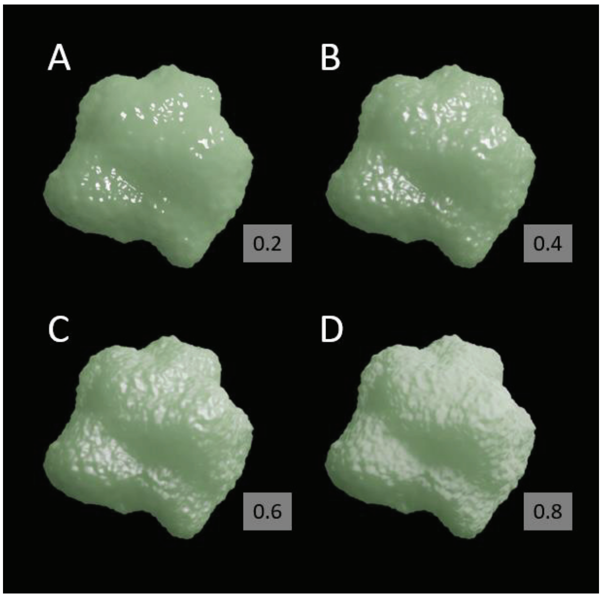

Fig. 1: Sample renderings of objects simulated to have the highest level of macro 3D relief and different levels of specular roughness (A-B: 0.2, 0.4, 0.6, 0.8) as defined using Cycles render in Blender 3D.

2.3 Visual display

Images were uploaded to a temporary location on the web that was remotely accessible through any standard internet browser. There was no restriction imposed on the display that was used. Participants were free to use any desktop monitor that was capable of presenting images at a pre-defined optical height and width.

To configure the size of the screen layout, participants initially placed their student card against the screen and zoomed in and out until the image of a template card rendered on the display roughly matched their own. All brightness and contrast settings were allowed to be varied according to participant preference.

2.4 Procedure

After commencing the experiment, stimulus images were presented in a random order on separate webpages navigated using a [Next >] button. On each page participants were instructed to rate (on 10-point scales):

1. *Transmission*: 0 indicates complete opacity; 10 indicates complete transmission.
2. *Glossiness*: 0 indicates pure matte; 10 indicates pure specular (like a mirror).
3. *Lightness*: 0 indicates black; 10 indicates white (relative to the sample range in Figure 2 below).

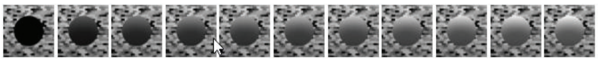

Fig. 2: Lightness rating scale (0-10).

4. *Saturation:* 0 is grey/achromatic and 10 is completely saturated in color (relative to the sample range in Figure 3 below).

Fig. 3: Saturation rating scale (0-10).

After all settings were made on each page and the participant had advanced beyond the final stimulus presentation, a completion message was presented on the screen. An encrypted data string containing all perceptual judgments was then emailed by the participant to the researcher.

2.5 Data analysis

The statistical analysis package R was used to analyze all data collected. One-way repeated measures ANOVAs were used to assess effects of specular roughness on each of the four dependent variables. Relationships between perceptual outcome metrics were examined using intercorrelations. We also performed inter-correlations between perceptual outcome metrics to determine whether there may be any mid-level visual interactions that could explain any perceptual biases.

3 Results

Figure 4 shows the effect of specular roughness and relief height on perceived transmittance, glossiness, lightness, and saturation.

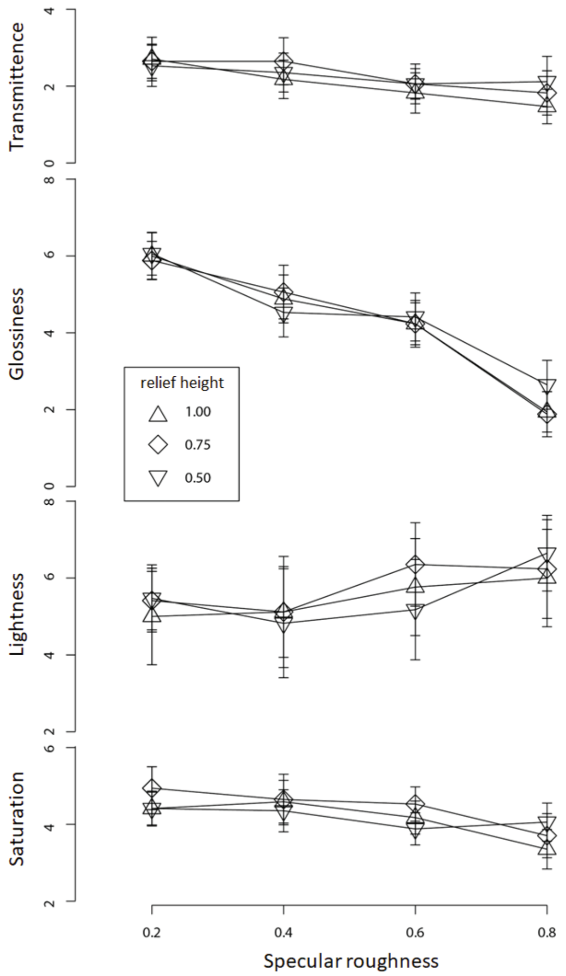

Fig. 4: Mean estimates for each of the four perceptual measures plotted as a function of specular roughness. Separate lines in each set of axes are different macroscopic relief height levels (0.50, 0,75, 1.00). Error bars show standard errors of the mean.

There was no main effect of bumpiness ($F_{2,32} = 1.80$, $p = 0.18$) or specular roughness ($F_{3,48} = 2.51$, $p = 0.07$) on perceived transmittance. There was no interaction effect between bumpiness and specular roughness on perceived transmittance ($F_{6,96} = 0.57$, $p = 0.75$).

There was no significant main effect of bumpiness on perceived glossiness ($F_{2,32} = 0.25$, $p = 0.78$). However, there was a significant main effect of specular roughness on perceived glossiness ($F_{3,48} = 16.20$, $p < 0.001$). There was no interaction effect between bumpiness and specular roughness on perceived glossiness ($F_{6,96} = 0.86$, $p = 0.53$).

There was no significant main effect of bumpiness on perceived lightness ($F_{2,32} = 0.85$, $p = 0.44$). However, there was a significant main effect of specular roughness on perceived lightness ($F_{3,48} = 3.21$, $p < 0.05$). There was no interaction effect between bumpiness and specular roughness on perceived lightness ($F_{6,96} = 0.58$, $p = 0.74$).

There was no significant main effect of bumpiness on perceived color saturation ($F_{2,32} = 0.91$, $p = 0.41$). However, there was a significant main effect of specular roughness on perceived lightness ($F_{3,48} = 2.10$, $p = 0.11$). There was no interaction effect between bumpiness and specular roughness on perceived lightness ($F_{6,96} = 0.72$, $p = 0.63$).

Given the differential effects of specular roughness on different perceptual outcome metrics (i.e., glossiness and lightness), we decided to explore the inter-correlations between them (see Table 1 below). There were significant inter-correlations between all pair-wise comparisons, except between perceived lightness and saturation.

Table 1: Inter-correlation between percepts (df=10; *p<0.05, **p<0.01, ***p<0.001).

Percept	Trans	Gloss	Light	Satur
Trans		+0.85***	-0.58*	+0.82**
Gloss			-0.70*	+0.82**
Light				-0.42
Satur				

Despite the absence of effect of specular roughness on perceived transmittance and color saturation, there was a strong positive inter-correlation between these perceptual outcome metrics ($r = +0.82$, $p < 0.01$). This indicates that objects that appeared to convey greater transmittance of light also tended to appear to have greater overall color saturation, based on our sample of rendered images.

Moreover, we also found there was a strong positive inter-correlation between perceived transmittance and perceived gloss ($r = +0.85$, $p < 0.001$). This correlation appears to indicate that objects that appear glossier also convey greater appearance in the transmittance of light. Objects that appeared glossier also appeared to be darker in albedo and higher in color saturation ($r = -0.82$, $p < 0.05$). However, any potential relationship between lightness and saturation did not reach significance.

4 Discussion

In this study we observed strong effects of specular roughness on the perception of gloss and lightness. Despite the absence of any significant main effects of specular roughness on perceived transmittance and color saturation, we found strong inter-correlations between most of the perceptual outcome metrics.

Although these results may appear to be complex at first to interpret, the effect of specular roughness on perceived lightness is consistent with previous research with colored opaque objects (Honson et al, 2020). The correlation between perceived transmittance and perceived color saturation is also consistent with the findings of other previous research with translucent materials (Fleming et al., 2005). These findings together suggest that processing of color saturation information may be a major contributor for the perception of translucency and may therefore warrant future exploration in greater detail.

For example, using different lighting directions to impose changes in the illuminance flow and subsurface scattering may influence the chromatic properties of the retinal image, and thus, both perceived saturation and transmittance.

The main manipulation of specular roughness exerted very strong effects on perceived gloss by making objects appear more matte, as would be expected due to the decline in sharpness of the specular lobe (Marlow & Anderson, 2013). Detection of specular edge gradients may depend on the activity of low-level visual feature detectors, but may also be encoded by the activity of V1 contour detectors (or beyond). Indeed, it has been shown that perceived gloss declines following adaption to image contours that are spatially oriented in alignment with specular edges (Kim et al., 2016). This could form the basis for mid-level interactions between perceived gloss and perceived lightness.

In this study, increasing specular roughness did not significantly affect perceived saturation nor perceived transmittance. These data together appear to suggest that perceived color saturation and perceived transmittance depend more on perceived gloss than on structure of specular reflections per se. Further research will hopefully provide greater insight into the perceptual mechanisms involved in the processing of these material properties.

5 Conclusions

We examined how remote observers perceive different material properties on standard computer displays that are configured to their working preferences. We were able to replicate some of the findings made by previous researchers using controlled displays. Although we found some seemingly strong perceptual interactions in the experiences of color and opacity, the findings appear to be explainable by differential processing of information concerning the structure of specular highlights and surrounding chromatic image content at low-level and mid-level stages of vision.

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