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The Influence of Material Roughness on Perceived Gloss and Color Appearance of Graphical Generated Faces

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Abstract

The human face is an essential stimulus in our social life and occupies a large proportion of digital content. The perceptual appearance of faces is important in computer vision, psychology, digital media, and related fields. Various structural and color features of faces have been studied over the years. However, the study of perceptual glossiness of faces and its influence on facial skin color appearance is very limited. This study investigates the relationship between perceived glossiness of facial skin, skin roughness, and perceptual color attributes. Psychophysical studies were conducted to model perceptual gloss and its effects on the perceived color appearance of faces. The investigation was carried out across varying roughness levels and skin tones. The results indicated that facial gloss influenced the perceived lightness of the facial skin, a phenomenon not observed to the same extent in non-face objects included in the experiment. The effect on lightness could partially be explained by a strategy of discounting specular components for surface color perception. Observers tended to focus on the brightest regions of the objects while avoiding specular highlights to infer color attributes. The current findings provide insights into understanding visual appearance characteristics of face and non-face objects and will be useful for accurate gloss and color reproduction of graphical generated faces.

Introduction

Face perception is an essential part of our social life. We regularly parse information about faces to distinguish familiar from unfamiliar people, and to make inferences about social characteristics like age, sex, personality, and emotion ([4], [31]). Face perception is particularly salient early on, starting from infants recognizing their mother ([14]). Human face processing continues to become more specialized relative to many other kinds of visual stimuli, likely because of the heightened ecological value of face information ([15]). Several facial surface properties have prominent roles in face processing, including skin color and gloss([21], [23], [13]). Neurophysiological evidence has shown dissociated neural pathways for processing faces separate from other types of objects, and that color perception of faces is impacted more by memory color than other objects ([9]), further indicating that color perception is uniquely sensitive for processing faces. Skin appearance (including both gloss and color) is determined largely by several biophysical properties, including hydration, sebum, erythema, carotenoids, hemoglobin and melanin ([26], [20], [19]). These substances in the skin vary according to an individual's genetic characteristics, but can also vary considerably due to changes in health, diet, emotion, and environmental factors. Aside from naturalistic face processing, facial stimuli occupy a large proportion of digital content, such as gaming, graphics, and other visual media. Because color appearance is critical for face perception, it is important to better understand how material properties of digitally rendered faces influences their color appearance. In the current work, we focus on the interplay between material surface roughness, perceived gloss, and color appearance for digital faces, as well as for non-face objects.

Perceived gloss is largely attributed to specular reflection. In reflection models, modulating refractive index, Fresnel reflection, and roughness can vary different gloss attributes, such as specular gloss, contrast gloss, sheen at grazing angles, haze, distinctness of reflected image gloss, and absence of surface texture gloss ([5], [12]). These parameters are sufficient to represent and reproduce gloss for most materials. However, skin has particularly complex optical properties. The layers of skin include the air-oil layer; the outer layer, which is translucent and partially reflects incident light; and the epidermis and dermis, which absorb and scatter light, causing it to exit in random directions. Therefore, skin reflection involves surface and subsurface reflection ([18], [27]). Existing studies generally concerning face gloss do not capture the complex optical properties of skin, including physical parameters like skin roughness. The proposed research uses physically-based rendering techniques to to investigate how skin roughness, varying across diverse human skin tones, influences perceived gloss and color appearance.

Moreover, the visual characteristics of materials depend on their optical properties. Gloss and color are among the most critical material attributes, each having a perceptual influence on the other ([11]). For instance, lighter-colored surfaces tend to appear less glossy than darker ones ([12], [6], [24]), and glossy surfaces often appear more chromatic and darker than matte surfaces due to the concentration of light at the specular reflection ([1], [3], [7]). Additionally, a steeper luminance gradient makes diffuse areas appear darker ([17]), and perceived lightness is impact more by diffuse reflection than by spatial average reflection ([29], [25]). Finally, perceived gloss relies on visual cues that also affect color perception. The dependence of perceived saturation and value on the linear combination of specular coverage and the inverse of perceived gloss increases with the surface orientation of the stimuli. The specular component of reflection on relief-shaped surfaces can complicate the separation of diffuse and specular highlights, thereby affecting color appearance ([10]). While these studies used physical or rendered objects as stimuli, mechanisms relevant to face perception have been generally overlooked. The proposed research addresses this gap by examining how gloss influences color perception specifically for faces, relative to non-face objects.

In summary, various factors, including material optical properties, physiological aspects, and perceptual mechanisms, contribute to gloss perception and color appearance for both face and non-face objects. Previous research has modeled perceptual gloss and has demonstrated the influence of perceived gloss on color perception, particularly for non-face objects. However, there is a shortage of studies modeling perceptual gloss and exploring gloss and color perception interactions for faces, whose uniqueness lies in skin optical properties, sensory and cognitive mechanisms in skin and face perception, and distinct neural pathways for face processing from other objects. This study aims to fill this gap by investigating the specific effects of gloss on color perception in faces. The study explores how roughness and gloss affect perceived lightness and chroma, via physically-based rendering to simulate skin composition and structure. The research also aims to investigate whether facial skin exhibits unique perceptual behaviors due to the geometric shape of faces. Accordingly, the present study aims to investigate the impact of gloss on color appearance (i.e., lightness and chroma), and determine the degree to which this influence differences between facial and non-facial objects.

Figure 1: Tone-mapped low dynamic range image of background. A high dynamic range image was used in rendering.

Experiment

A preliminary experiment demonstrated the exponential relationship between the roughness in microfacet distribution function and perceived gloss in facial objects (Figure 2). The resulting linear regression model is employed in this experiment to generate perceptually linear-spaced stimuli. The present experiment is designed to investigate the influence of perceived gloss on the color appearance of faces. Previous research has shown that the representation and recognition of faces involve different neural processing pathways and cognitive factors compared to other objects ([9]). Accordingly, two additional non-face object shapes are included to determine if perceived gloss affects the color appearance of non-face objects in the same way. The experiment is conducted for four different baseline skin color types.

Methods

The experiment employs a 'method of adjustment' experimental methodology. Observers were presented with a single 3D object on the left side of the screen and asked to match the color appearance of a uniform color patch displayed on the right side of the screen. A GUI for a sample trial is shown in Figure 3. The experiment included a total of 84 3D object stimuli, consisting of 3 different shapes, 4 baseline skin color types, and 7 perceptual gloss levels, as illustrated in Figure 4. For the color appearance matching task, observers adjusted the lightness and chroma of the color patch. It was expected that varying levels of gloss would influence the perceived color appearance of the objects, particularly in terms of lightness. Additionally, we investigated whether this influence varied depending on the object's shape and baseline color.

Stimuli

The experiment contains 84 stimuli. On the left side of the experimental interface, an object image would appear with a randomly selected shape (face, sphere, or blob), baseline color type ('lightest', light', 'dark', 'darkest'), and gloss level (7 total levels). The geometric shape of the face providing surface normals is the initial model of FaceBuilder ([16]), which is a gender-neutral 3D face model without textures and shadings. To render images, a physically based ray-tracing algorithm is used. To illuminate the environment, an image based lighting techniques is utilized, with a high dynamic range image shown in Figure 1. The material optical properties were also defined by bidirectional scattering surface reflectance distribution function (BSSRDF). In this study, skin BSSRDF was estimated with a given diffuse scattering coefficient, transmission coefficient (set to 1), microfacet roughness, refractive index (set to 1.55), and the mean free path (0.0013 0.0009 0.0006 for RGB channels). The mean free path, the mean distance of light path in the medium before scattering is the reciprocal of attenuation coefficient, ranging from 0 to 1. We additionally chose to include the sphere-shaped object to represent a simple geometric shape with smooth, predictable material and light interactions. The blob-shaped object was chosen to represent a more complex shape with less predictable light interaction (edges and contours similar to a face), but with less familiarity and social relevance than a face. The 7 gloss levels of the objects were determined by the roughness function established in a preliminary experiment, so the roughness values used in the experiment increase approximately linearly with perceived gloss (Figure 2). The gloss levels used represent ranges of perceived gloss from 0.2 to 0.7 with the interval of 0.08. The base four skin colors were selected through clustering the Pantone SkinTone Guide ([22]) color sets (measured with an i1-pro spectrophotometer), using the k-means clustering algorithm. From the resulted eight cluster centers, four representative and distinct colors were chosen. The selected skin colors had CIELAB values of: Lightest [39.93, 6.69, 6.21], Light [37.25, 5.96, 8.74], Dark [31.09, 5.78, 8.05], and Darkest [28.83, 4.07, 5.15]. It should be noted that the colors values are from the final renderings. The colors selected from the clustering results and used as the diffuse RGB parameters do not exactly match the final renderings, as the rendering process involves additional parameters beyond diffuse characteristics. The final stimuli colors are labeled 'Lightest', 'Light', 'Dark', and 'Darkest' to indicate relative lightness differences, but do not correspond to any specific skin typology (e.g., Fitzpatrick, Monk).

Procedure

Fifteen observers participated in the experiment (age from 25-50, 9 females and 6 males, expert color science observers, all have normal or correct to normal vision acuity, and normal color

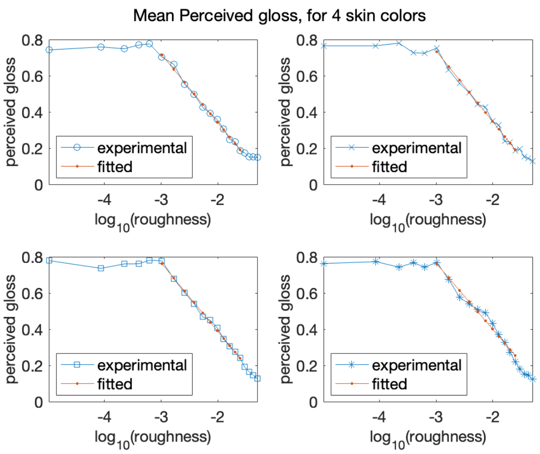


Figure 2: linear fitting to the relationship between mean perceived gloss and logarithm of roughness. From top-left to bottom-right, 4 plots are for 4 color types: 'lightest', 'light', 'dark', and 'darkest'.

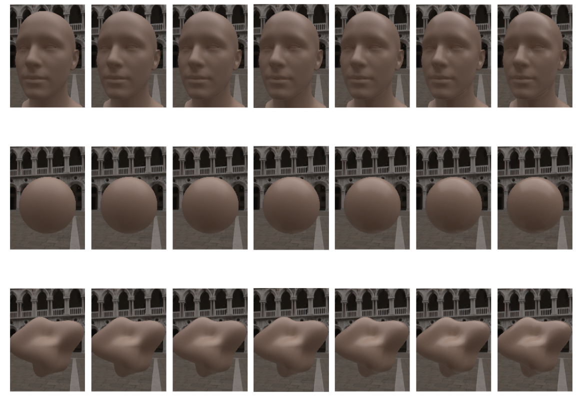


Figure 4: Example stimuli used in the experiment. Face, sphere, and blob-shaped objects with 7 gloss levels, for the 'Light' color type.

vision). One object target image was displayed on the left side of the screen for each trial. This target image had a randomly selected shape type, baseline color type, and gloss level. The color patch was displayed on the right side of the screen simultaneously. Observers were asked to adjust the color of the patch to match the target's surface color. The color patches were able to be adjusted by observers using a keyboard along dimensions of lightness (CIELAB L*, using up/down keys) and chroma (CIELAB C*, using left/right keys). The initial colors of the patch were those extracted from a point-sample of the forehead region of the rendered face images with 0 roughness. These point-samples were selected as they did not include either specular highlights or shadows, and were judged by the authors as having the most diffuse area of the images. This initial color could be adjusted to either increase or decrease along the L* and C* dimensions independently, and the step size of each adjustment (key press) was 1 unit for each dimension (Figure 3, 4). The full adjustment range was ±20 L* and ±10 C* of the initial color of patches. The responses included the final CIELAB L*, C*, a*, and b* values of the color patch, as well as the L* and C* indices (representing the steps of L* and C* adjustment, respectively). Each observer completed a trial for each combination of target shape type (3), baseline color type (4), and gloss level (7), for a total of 84 trials. The monitor was calibrated to the sRGB color profile with D65 white points (luminance: $100 cd/m^2$) with primaries R(0.64, 0.33), G(0.3, 0.6), and B(0.15, 0.06) in CIExy.

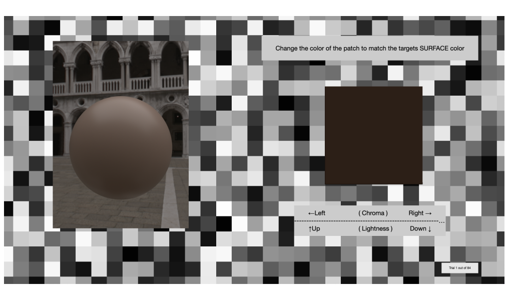


Figure 3: GUI for an example trial from the experiment

Results and Discussion

The L* and C* indices were used in the subsequent analyses. These indices represent a 1-unit step change of lightness and chroma adjustment made by observers, respectively. The analyses were conducted using these indices in order to normalize the adjustment responses, so that relative changes along these dimensions could be compared across the different color types. The initial, point-sample colors (starting points in the experiment) had an L* index of 21 and a C* index of 11, which are indices at the center of adjusting matrices. Therefore, indices above (or below) these values represent an increase (or decrease) in lightness and chroma adjustments made to the color patches to match the target object.

Linear mixed-effect models with random participant slopes and intercepts were used to evaluate the effects of gloss level (7 levels of a continuous predictor), shape type (3 factors; faces, spheres, blobs), color type (4 factors, 'lightest', 'light', 'dark', 'darkest'), and their interactions, on adjusted L* and C* indices. We report the results from the statistical analyses separately for lightness and chroma adjustments. Reported values are returned from F statistics ([2]). The responses of lightness and chroma adjustment are also predicted using linear models in R ([28]).

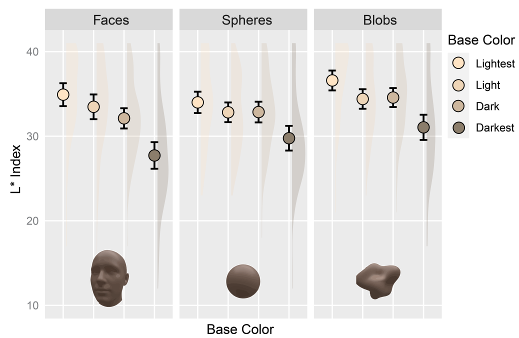
Lightness Adjustment

There was a significant main effect of gloss level on lightness adjustment, F(1,14)=14.54, p=0.002, indicating that perceived lightness generally decreased as gloss increased (B=-0.91, SE=0.24). The main effect of shape type did not reach statistical significance, F(2,13)=3.21, p=0.074. However, followup t-tests indicated that faces (M=32.1, SE=0.83) were generally perceived as darker than blobs (M=34.2, SE=0.66), t(14)=3.46, p=0.004, but not spheres (M=32.4, SE=0.81), t(14)=0.42, p=0.68. There was a significant main effect of color type on lightness adjustments, F(3,12)=10.07, p=0.001. Generally, participants increased lightness more for 'lightest' colors (M=35.2, SE=0.65), followed by 'light' (M=33.6, SE=0.66), 'dark' (M=33.2, SE=0.70), and 'darkest' (M=29.5, SE=1.03) color types. All pairwise differences among the color types were significant ($ps < 0.005$), except for the difference between 'light' and 'dark', t(14)=1.21, p=0.248

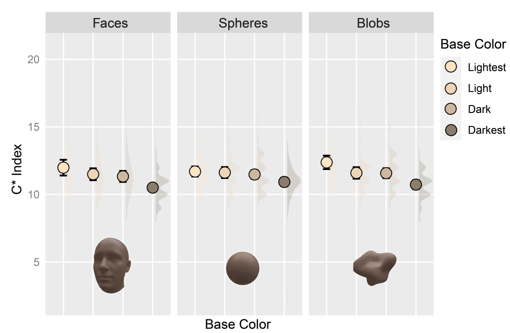
(Figure 5a, 6).

There was also a significant gloss level and shape type interaction, F(2,13)=4.052, p=0.043, indicating that the influence of gloss on lightness varied as a function of shape type. Perceived lightness decreased as gloss increased for face-shaped objects (B=-0.55, SE=0.13), t(14)=4.29, $p < 0.001$, but this pattern was not statistically significant for spheres (B=-0.13, SE=0.12), t(14)=1.12, p=0.28, or blobs (B=-0.15, SE=0.12), t(14)=1.21, p=0.25 (Figure 6 and 7).

There were no statistically significant interactions between gloss level and color type, F(3,12)=1.27, p=0.33, between shape type and color type, F(6,9)=1.32, p=0.34, or the three-way interaction among them, F(6,9)=0.74, p=0.63 (Figure 7).



(a)



(b)

Figure 5: The mean (circles) of L* and C* index for various shape and color types; Error bars represent standard error. Distributions represent the frequency of L* or C* index of individual responses.

Chroma Adjustment

Our analysis also shows that there is no significant effect of gloss level (F(1,14)=0.01, p=0.92) and shape type (F(2,13)=1.32, p=0.30) on chroma adjustments. But a significant main effect on chroma, F(3,12)=3.56, p=0.047, due to color type is observed. Generally, perceived chroma decreased from 'lightest' (M=12.0, SE=0.31), to 'light' (M=11.6, SE=0.22), 'dark' (M=11.5, SE=0.21), and 'darkest' (M=10.7, SE=0.14) color types. All pairwise differences among the color types were significant ($ps < 0.013$), except for the difference between 'light' and 'dark', t(14)=1.10, p=0.288 (Figure 5b). Moreover, no statistically significant two-way or three-way interactions was observed among these variables ($ps > 0.41$) (Figure 5b).

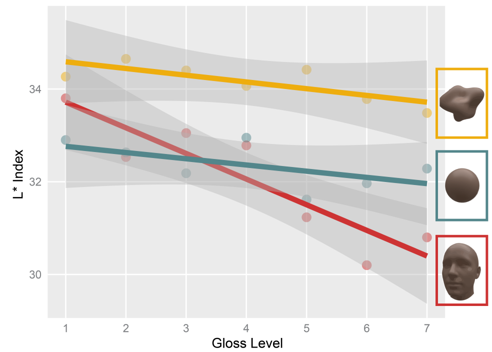


Figure 6: predicted L* (lines) and mean of responses (dots) for 3 shapes, as a function of gloss level. Shaded area represents 95% confidence intervals. Observers' perceptions of surface lightness generally decreased as gloss increased. This pattern was particularly pronounced for face-shaped objects.

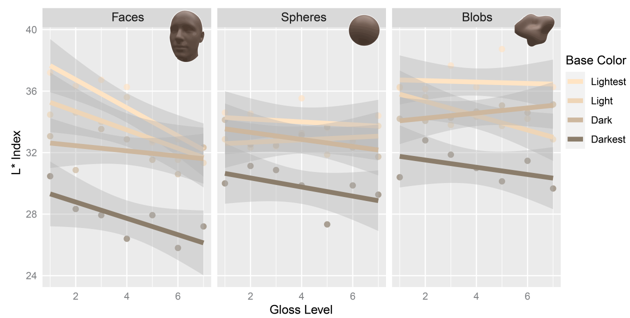


Figure 7: predicted L* index (lines) and mean responses (dots) for 4 color types, and 3 shapes, as a function of gloss level. On average, observers increased lightness more in order from 'lightest' to 'darkest' color types. These differences are larger for faces relative to other shapes.

Image Color Analysis

In addition to gloss level analysis on color appearance, we explored whether observer color adjustments corresponded to systematic patterns among regions of the images themselves. To do this, we identified the image pixels that comprised CIELAB values having small color differences ($\Delta E \leq 5$) from the average CIELAB values of observers responses. These pixels are shown in color, with pixels outside of this range colored gray, in Figure 8. For each shape in each gloss level, ΔE is computed and averaged across the 4 color types, such that the images shown identify the objects' regions-of-interest, rather than the precise color of each object. This analysis speculates about the strategy observers might have used to determine their representative color matches, however it is worth noting that their decisions may not have been determined according to specific areas of the objects necessarily. Additional data such as from eye-tracking or pixel-selection methods in future work may be needed to confirm these strategies. Because perceived chroma was not impacted by changes in gloss, this section focuses on discussions regarding perceptions of object lightness. These analyses indicate that the image areas containing similar colors as observer responses are largely near the edges surrounding the specular highlight, suggesting that observers tended to use the brightest region of the objects (but excluding the highlight area) when judging colors of the surfaces. This strategy likely becomes easier as objects become more glossy, as the specular highlight edge becomes more defined. This possibility is likely supported by the general decrease in lightness adjustments as gloss increased, as highlight regions are more likely to be avoided and considered distinct from perceptions of the surface color. The colored area is larger when gloss level decreases for spheres and blobs but not faces (Figure 8). This indicates that the area representing surface colors by observers is larger with decreasing gloss, possibly because the boundary between diffuse reflection and specular highlight is less sharp for more matte surfaces. It has been previously shown that perceived lightness of objects was determined by diffuse reflection instead of mean lightness of the objects ([29], [8]), and that observers judge the lightness of a object according to the area neighboring the highlight region ([8]), which is supported in the current work.

Figure 8: Image analysis corresponding to observer color matches. Top-rows: pixels containing color values within $\Delta E \leq 5$ from mean observer responses are shown, with all other pixels colored gray. Bottom-rows: original images for reference. Images increase in gloss from left-to-right. Note: images for only one color type are shown, but these include spatial areas corresponding to $\Delta E \leq 5$ averaged across all color types.

General Discussion

Color appearance is indispensible in face processing and social perception. In digital graphics, faces are rendered by simulating light interactions with material properties like roughness, affecting gloss and color perception. Understanding how these material properties influence color appearance, especially in faces, is crucial for improving interactions with digital characters in applications, such as gaming and animation.

The current study utilised the relationship between material roughness and perceived gloss in face rendering for 4 skin color types, to explore the influence of perceived gloss on color appearance for faces, and non-face objects, having different baseline colors. Notably, we found that perceptions of object lightness decreased as gloss increased, but that this pattern was most evident for face-shaped objects, supporting the notion that processing of facial stimuli operates in different ways than other kinds of objects, most likely because faces are particularly familiar and contain important social information, relative to abstract shapes. Additionally, we did not find evidence that perceptions of chroma were impacted by gloss, and therefore we will focus the discussion on perceptions of lightness.

Previous research has demonstrated that the effect of gloss on color of an object depends on the perceptual separability of the specular highlight from the diffuse area. People tend to ignore specular highlights when identifying surface body color ([29]). It could also be the case that specular highlights are misattributed to diffuse areas when surface colors are lighter and more matte. Consequently, the perceived color of matte and lighter surfaces are expected to have higher perceived lightness than more glossy surfaces ([10]). These expectations were largely supported by the current findings, as perceived lightness generally decreased as gloss increased. Further, our image color analyses indicate that the image areas containing similar colors as observer responses were largely near the edges surrounding the specular highlight, suggesting that observers tended to use the brightest region of the objects (while excluding the highlight area) when judging colors of the surfaces. This strategy likely becomes easier as objects become more glossy, as the specular highlight edge becomes more defined. Conversely, highlight regions for more matte objects are more difficult to avoid, becoming less distinct from perceptions of the surface color. However, discounting the highlights can only partially explain this strategy, as it appears that the color matches still included some highlight information, rather than darker, more diffuse areas of the objects.

For the effect of color types on lightness adjustment, the significant difference between 'lightest' and 'light' and between 'dark' and 'darkest' indicate observers exaggerate lightness adjustments with increasing skin luminance. However, there was no significant shape type by color type interaction on lightness adjustment, indicating that this exaggeration happened for all shapes. The lightness differences between 'lightest' and 'light', 'dark' and 'darkest' are smaller than the difference between 'light' and 'dark'. However, the visual difference between 'light' and 'dark' is approximately equal to the base lightness difference. The other color type pairs ('lightest' and 'light', 'dark' and 'darkest') have larger visual lightness differences than base lightness difference(Figure 5a). A similar pattern occurs in chroma adjustment responses. The reasons for these visual difference patterns in lightness and chroma responses found in the study should be further investigated by future work.

The current study has limitations that future work could address. Future research could improve the realism of facial skin simulations by using actual optical parameters, such as wavelength-dependent refractive indices for the epidermis and dermis. Additionally, faces were rendered without realistic textures (e.g., eyes, hair) to facilitate comparisons with non-face objects, but it would be valuable to assess the findings with more realistic faces. While material roughness was the primary input used to generate perceptions of gloss, there are several other dimension that would impact gloss and color appearance which were not evaluated in the current work (e.g., distinctness of image and contrast gloss are function of diffuse reflectance component, the energy of specular component and the spread of specular lobe, of Ward's model ([6])). In addition, the skin color selection was based on the measured reflectance of the printed Pantone skin set. However, the printed color set may be less representative that real human skin measurement databases ([30]). Further, this approach summarizes spectral data with RGB values to represent skin color, which certainly impacts how skin material would interact in a light simulation.

Conclusion

The present study conducted experiments to evaluate the relationships among material roughness, perceived gloss, and color appearance, for faces and non-face objects having 4 baseline skin tones . The results indicated that perceived lightness (but not chroma) was influenced by gloss, which was most notable on face-shaped stimuli. We also speculate that people tended to judge surface color by largely (but not entirely) discounting specular highlights. The current work demonstrates the value of evaluating the influence of material properties on color appearance for digitally rendered objects, and particularly highlights the need to consider face stimuli independent of other kinds of objects.

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