Effect of material perception on mode of color appearance

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The mode of color appearance (mode) is a concept suggesting that variations in a medium that emits, transmits, or reflects light can cause differences in color appearance. For example, the same light beams that appear brown (or gray) when reflected from a given object surface may appear orange (or white) when emitted from a light source. The present study investigated the relationships between material perception and perceived mode, especially in terms of luminosity. In the experiment, a rotating spheroid was presented with surrounds of various luminance levels. The surface texture of the spheroid was either matte gray (three surface reflectance levels) or one of two fabrics. The participants were asked to evaluate the luminosity (mode) and perceived reflectance of the object. The results show that the mode perception is clearly different from the lightness perception. The luminosity was fit with a linear function of the lightness scale in CIE (Commission Internationale de l’Eclairage) L* value of the object surface, unless the material of the surface was identifiable. To conclude, the luminosity (mode) perception can be strongly affected by the material percept, and the luminosity perception of the same object can vary when its surface property is ambiguous.

Introduction

The mode of color appearance (mode) is a concept proposed by Katz (1935). The essential idea is that the color appearance of identical beams of light can seem to differ when the rays are emitted from, reflected on, or transmitted through various materials. For example, a ray that appears brown may be reflected from an object surface, but the same ray often appears orange when it comes from a light-emitting medium such as a flashlight. A similar phenomenon can occur for gray. Gray and brown are perceptible only from an object (i.e., reflecting) surface, not from a light source. Such differences in color appearance according to the mode are considered to be one of the causes of occasional mismatches in color appearance in digital publishing procedures, when printed material and digital drafts on the computer screen are compared (Brown & Fairchild, 1996; Henley & Fairchild, 2000; Katoh, Nakabayashi, Ito, & Ohno, 1998).

Studies on the mode have focused mainly on the effects of spatial arrangement around the test stimulus and relative luminance among the objects in the scene. The point of transition in the mode (between the surface- and luminous-color modes), called the luminosity limit or threshold, has been studied primarily in terms of lightness and color constancy (Bonato & Gilchrist, 1994, 1999; Gelb, 1929/1938; Gilchrist, 1977, 1994; Gilchrist et al., 1999; Okajima & Ikeda, 1991; Shinoda, Uchikawa, & Ikeda, 1993; Speigle & Brainard, 1996; Uchikawa, Koida, Meguro, Yamauchi, & Kuriki, 2001; Yamauchi & Uchikawa, 2005). In these studies, the mode was manipulated by varying the relative intensity of the light between the surrounds and the test light. Typically, test stimuli presented in a dark surround appear self-luminous, and test stimuli in a lit environment with various surrounding objects appear to be reflecting surfaces. The Gelb effect is one of the consequences of such a perception of the luminous mode, as evidenced by an isolated color chip illuminated by a hidden spotlight in the dark (Gelb, 1929/1938). Our previous study reported that the luminosity threshold is determined by brightness, not luminance, when the test stimuli are chromatic (Uchikawa et al., 2001). We measured the luminosity threshold for monochromatic light as a function of the wavelength and reported that the luminosity threshold was determined by a brightness sensitivity function rather than a luminance sensitivity function—V(λ)—in each participant.

The original concept of the mode of color appearance was proposed in relation to the final material that released the ray that enters the observer’s eye, in the context of a scene incorporating multiple reflecting objects, including transparent or translucent materials. The present study is a first step in studying the mechanisms behind the mode of color appearance by investigating the relationships between the perceived mode and the material perception. In particular, the perception of the transition between the surface-color...
and luminous-color modes was evaluated through a psychophysical experiment in which participants viewed objects with various surface textures generated as computer graphics.

**Experiment 1: Main experiment**

**Method**

**Apparatus**

A traditional experiment for luminosity threshold analysis was conducted by varying illuminant conditions or the luminance of the surround stimuli (Kuriki & Uchikawa, 1996; Okajima & Ikeda, 1991; Shinoda et al., 1993). However, the luminances of conventional computer displays, such as cathode ray tube (CRT) or liquid crystal display, are not suitable for the presentation of complete darkness on the screen. CRT and liquid crystal display screens faintly emit light even when black areas (R, G, and B = 0, 0, and 0, respectively; where R, G, and B denotes digital value for red, green, and blue color primaries, respectively), are presented on the screen. This incomplete darkness in the surround may cause failure or lead to incompleteness as regards the presentation of a test stimulus with luminous-color mode. However, the recent invention of organic electroluminescent or organic light-emitting diode (OLED) displays has enabled us to present a very low level dark area while retaining the same highest luminance as conventional displays. For example, the relative strength between the highest and lowest luminances on the screen can be 10^7 for OLED displays, whereas it can be 10^3 for common displays and 10^4 for projectors (Ito, Ogawa, & Sunaga, 2013). Therefore, to enable the darkest possible surround, an OLED display (PVM-2541, Sony, Tokyo, Japan) was used in this study. The monitor was placed in an otherwise completely dark room and was carefully calibrated using a general method described elsewhere (Cowan, 1983) with a spectrophotometer (SR-UL1R, Topcon, Tokyo, Japan) that guarantees measurements at the minimum luminance level of 0.01 cd/m^2. The highest luminance of the display was 154 cd/m^2, while the lowest luminance was less than 0.01 cd/m^2. The highest lightness surface for normalizing the lightness scale in CIE (Commission Internationale de l’Eclairage) L* was set to 100 cd/m^2 of equal energy white (x,y = 0.333, 0.333) in CIE xy color space, such that a specular highlight would have CIE L* larger than 100.

**Stimulus**

To give some indication of the object material perception to the participants, three-dimensional computer graphics were generated (LightWave 10, NewTek, San Antonio, TX). The main stimulus was a spheroid, producing a circle as its front view, and the side view constituted a vertically elongated oval with an aspect ratio of 1:1.5. First, a sphere was modeled with 4,902 points of mesh frame; a circular dissection, which included the diameter and the center of the sphere, was modeled with 100 points equally spaced along the circumference, corresponding to an angular step of 3.6° between adjacent points. The spheroid was modeled by squashing the sphere along the radius in the depth direction. A white parallel light “100%” (in the software parameter scale) was casting in the virtual space from the upper left (45° azimuth and 45° elevation) direction in front of the spheroid in addition to a “10%” (in the software parameter scale) of uniform ambient illumination (Figure 1). The background was rendered in the same virtual space with a matte and flat surface without color, facing the participant’s viewpoint, with a uniform scattering reflectance. The parameters used for the image rendering are summarized in Table 1.

The background surface was placed far behind the spheroid so that the shadow cast by the spheroid would not appear in the generated image. The size of each frame was 1920 × 1080 pixels.

There were six surface-property conditions for the spheroid. These included three lightness levels of uniform gray matte surface and two textured surfaces mapped with organic cotton and suede fabrics (Figure 2A, B). In addition, to confirm whether any statistical cues in the spheroid with the organic cotton surface affected the result, a control measurement was made with a spheroid mapped with a texture constructed by shuffling the positions of all the pixels in the image while retaining the combination of the RGB values in each pixel (Figure 2C).
The random shuffling of the image pixels deteriorated the texture of the woven fabric, but mean, variance, and skewness in the luminance and chromaticity of the overall image were preserved. The uniform matte surface was not colored (i.e., gray) and had CIE $L^*$ (hereafter, $L^*$) values of 30, 60, and 80 at the center of the spheroid when its front was facing the participant (original position). The center spot on the screen (diameter $\frac{1}{8}$ visual angle) was used for the photometric measurement because this spot included no specular highlight or shading in the original position. Surfaces with fabric textures had approximately the same $L^*$ of 60 at the center of the spheroid in the original position: $L^* = 60.6$ for organic cotton (original and shuffled) and $L^* = 62.2$ for suede tan. See Supplementary Movies S1 and S2 for organic cotton and suede tan stimuli, respectively, in a dark surround.

The stimuli around $L^* = 60$ were used to compare the effects of the different textured surfaces. The uniform matte surface with $L^*$ values of 30, 60, and 80 was used to test the effects of the object reflectance (luminance), while the background level was set to $L^* = 0$, 30, 50, or 70 on the screen. See Supplemental Movie S3 for the lightest matte gray stimulus ($L^* = 80$) in a dark surround.

Each stimulus was a movie of 60 frames with 2-s duration at a frame rate of 30 frames/s. During this time, the spheroid made a $360^\circ$ turn around the vertical axis centered at the origin of the spheroid in either the clockwise or counterclockwise direction. This rotational motion was introduced to prevent any misperception of undulation or dimple-like modulation in the object shape that could be perceived particularly from the organic cotton and suede tan textures on the spheroid surface.

**Procedure**

The participants were asked to evaluate the mode of color appearance in terms of self-luminosity (hereafter referred to as luminosity or mode) and the lightness of the object surface. To ensure the criterion for the mode evaluation, the participants were asked to watch two movies as samples of two mode value extremes. The spheroid stimulus examples for the zero and 10 modes were the spheroid with organic cotton texture on the lightest background and the spheroid with uniform matte gray of the highest $L^*$ in the dark, respectively.

After each participant confirmed the zero and 10 mode evaluations, they proceeded to the trials. There were 24 conditions (movies) incorporated into each session as combinations of four surround and six texture conditions. After watching each movie, the participants were asked to evaluate the mode and lightness of the spheroid appearance.

In the mode judgment, the participants were told to report the approximate level of self-luminosity in comparison with the two samples shown at the beginning of each session. In the lightness judgment, they were told to report the perceived level of reflectance, as if estimating the gray level of a piece of fabric.

![Fabric images mapped on the spheroid surface.](https://jov.arvojournals.org/pdfaccess.ashx?url=/data/journals/jov/934120/)

According to the difference in color calibration, the appearance may differ from the actual images used for the experiment. The two fabrics (organic cotton and suede tan) were obtained from a copyright-free photographic library, and the shuffled image was created by randomly relocating the positions of all the pixels in the organic cotton image. The reflectance parameter for the spheroids with these textures was fixed at 100% (see Table 1).

![Figure 2. Fabric images mapped on the spheroid surface.](https://jov.arvojournals.org/pdfaccess.ashx?url=/data/journals/jov/934120/)

The random shuffling of the image pixels deteriorated the texture of the woven fabric, but mean, variance, and skewness in the luminance and chromaticity of the overall image were preserved. The uniform matte surface was not colored (i.e., gray) and had CIE $L^*$ (hereafter, $L^*$) values of 30, 60, and 80 at the center of the spheroid when its front was facing the participant (original position). The center spot on the screen (diameter $\frac{1}{8}$ visual angle) was used for the photometric measurement because this spot included no specular highlight or shading in the original position. Surfaces with fabric textures had approximately the same $L^*$ of 60 at the center of the spheroid in the original position: $L^* = 60.6$ for organic cotton (original and shuffled) and $L^* = 62.2$ for suede tan. See Supplementary Movies S1 and S2 for organic cotton and suede tan stimuli, respectively, in a dark surround.

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### Table 1. Parameters for rendering spheres.

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<th>Parameter name</th>
<th>Organic cotton (original and shuffled) and suede tan</th>
<th>Uniform matte gray</th>
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<tr>
<td>Reflectance (%)</td>
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<td>Specular reflection (%)</td>
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<td>Transparency (%)</td>
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<td>0</td>
</tr>
<tr>
<td>Texture mapping</td>
<td>Yes</td>
<td>No</td>
</tr>
</tbody>
</table>

Notes: *a* Parameter names are translated from those in the Japanese revision of the software. Exact names can be different in other versions in other languages. *b* Reflectance implies the relative efficiency of reflectance defined by another parameter. For spheroids with texture mapping, 100% reflectance implies that the mapped image completely affected the relative strength of the light reflected on the spheroid surface, whereas reflectance was manipulated for the gray spheroids to vary the intensity of reflected light.
Results

Consistency of mode evaluations

To examine the consistency of the mode evaluations among the participants, Pearson’s correlation coefficients were calculated between one participant (S1) and the other six participants. The correlation coefficients were no smaller than 0.61 (mean ±1 SD = 0.71 ± 0.075), and the correlation coefficient analysis (the null hypothesis was zero correlation) revealed that they were correlated with statistical significance: for the smallest correlation coefficient, \( t(22) = 3.88, p < 0.001 \); on average, \( t(22) = 5.47, p < 0.00005 \). Therefore, the mode evaluations in this study were reliably consistent among the participants.

The effect of the stimulus presentation order was also tested. The participants’ mode evaluations were plotted as a function of the stimulus presentation order (see Supplementary Figure S1 for details), which showed no obvious trend. In addition, Table 2 shows a significant positive correlation between the two sessions of luminosity (mode) judgments in each participant, \( t(22) > 4.47, p < 0.0005 \). Therefore, it is unlikely that the experience of watching other stimuli did not affect the results.

Effects of surface material

Figure 3 shows the results of the mode and lightness evaluations, indicated by filled and open symbols, respectively. Three clusters of four linked symbols

![Figure 3](https://jov.arvojournals.org/pdfaccess.ashx?url=/data/journals/jov/934120/ on 10/24/2018)
represent different surface property conditions. In the current comparisons, the clusters represent the results for the spheres with (from left to right) the organic cotton and suede tan fabric textures and the uniform matte surface. The differences among the four linked symbols represent the differences in the background luminance level: from left to right, 0, 30, 50, and 70 in the CIE $L^*$, respectively. The vertical axis indicates the estimated magnitude of the mode and lightness levels in arbitrary units. For the lightness, the vertical-axis value of 10 represents the highest lightness. For the mode (luminosity) evaluation, the zero value represents the object surface and 10 represents the mode perceived from a bright sphere in complete darkness, shown at the beginning of the session as one of the sample movies.

As can be seen in Figure 3, the evaluations of the mode and lightness differed clearly. According to the two-way ANOVA with a Greenhouse-Geisser correction (object texture × surround), independently applied to the mode and lightness results, two main effects were statistically significant regarding the mode evaluations—texture: $F(1.26, 7.55) = 102.6, p < 0.001$; background $L^*$: $F(1.98, 11.9) = 4.44, p < 0.05$—but the background $L^*$ was the only significant factor in the lightness evaluations, $F(1.8, 10.8) = 11.0, p < 0.005$. Interactions were significant for both the mode, $F(2.97, 17.8) = 3.26, p < 0.05$, and lightness, $F(2.08, 12.5) = 5.41, p < 0.05$, evaluations.

The results of post hoc analyses on the mode were as follows. The luminosity (mode) judgments among the three materials were significantly different: organic cotton < suede tan < matte gray, all $t(6) > 7.99, p < 0.0005$. For the effect of background luminance, the surround effect was significant for suede tan and matte gray, both $F(3, 18) > 3.88, p < 0.05$. This implies that the simultaneous contrast effect existed for the luminosity (mode) judgment; it also implies consistency with the previous studies, in which mode of color appearance was manipulated by the luminance contrast with the surrounds (Okajima & Ikeda, 1991; Yamauchi & Uchikawa, 2000). For the lightness judgments, the results of post hoc analysis showed a significant effect of the background for the matte gray surround, $F(3, 18) = 9.41, p < 0.001$.

The three textures in this comparison differed in terms of perceptibility of the object material. After the session, all participants reported that they clearly recognized the spheroid texture as being fabric when it was presented with the organic cotton texture. No participants recognized any material in the uniform matte surface case, probably because the surface appeared overly smooth in the image. However, for the spheroid with the suede tan texture, four out of seven participants reported it as being a velvet-like fabric. The mode evaluation was in the intermediate level for the organic cotton and uniform gray textures. This implies that the three surface textures used in this study differed mainly in terms of object identification. The effect of perceptibility on the material property was more explicitly examined in Experiment 2.

**Confirmation of fabric texture perception**

It has been reported that statistical profiles of images can affect the evaluation of object surface property (Motoyoshi, Nishida, Sharan, & Adelson, 2007). To confirm whether image statistics (e.g., mean, variance, and skewness) affected the mode evaluations, we measured mode and lightness evaluations for a spheroid with the shuffled image of the organic cotton texture under four surround conditions. The random shuffling of the image pixels preserved mean, variance, and skewness in the luminance and chromaticity of the overall image, but the spatial frequency spectrum was significantly affected. Figure 4 shows a comparison between the results for the original and shuffled images of the organic cotton texture (left and center clusters) and the uniform gray surface (right) with $L^* = 60$. The mode evaluation results for the spheroid with a shuffled image are clearly different from the original data, whereas the lightness evaluation was not affected by the texture, as was observed in the results presented in Figure 3.

For the mode evaluations, the two-way ANOVA with a Greenhouse-Geisser correction detected significant texture effects, $F(1.12, 6.7) = 140.7, p < 0.0001$, and marginal surround effect, $F(2.16, 13.0) = 3.50, p = 0.0580$, and interaction, $F(2.71, 12.3) = 3.15, p = 0.0757$. The result of the two-way ANOVA on lightness detected the main effects of surround, $F(1.87, 11.2) = 10.5, p < 0.005$, and interaction, $F(2.09, 12.5) = 6.19, p < 0.05$, but, again, the effects of variations in texture...
were not significant, \( F(1.07, 6.44) = 0.123, p = 0.755 \). However, the results of the post hoc analysis on the mode evaluation revealed that the differences between the original and shuffled images were statistically significant, \( t(6) = 11.7, p < 0.0001 \). This implies that the mode evaluation was not determined simply by the image statistics (Motoyoshi et al., 2007).

For the mode evaluations, the impact of the surround was statistically significant only for surfaces whose properties were not clearly identifiable, namely matte gray and shuffled organic cotton. The result of the post hoc analysis on the mode evaluations indicated that the interaction was significant only for the surround effects in the shuffled texture case, \( F(1.68, 10.11) = 9.41, p < 0.005 \), and had a marginal effect in the matte gray case, \( F(2.26, 13.6) = 2.73, p = 0.0961 \).

The trend in Figures 3 and 4 implies that the surround luminance affects the evaluation of luminosity in such a way that it increases under darker surrounds. This is consistent with the conventional approach to manipulating the mode using the surround luminance (Kuriki & Uchikawa, 1996; Okajima & Ikeda, 1991; Uchikawa et al., 1993). For the lightness evaluations, such an effect implies a simple lightness contrast with the surround or induction effects from the surround. In addition, for the lightness evaluations, the main effect of the surround \( L^* \), \( F(1.87, 11.24) = 10.5, p < 0.005 \), and the interactions between the material and the surround effects, \( F(2.09, 12.54) = 6.19, p < 0.05 \), were significant. According to the post hoc analysis, the effect was significant regarding the surround \( L^* \) in the shuffled texture case, \( F(2.38, 14.28) = 4.93, p < 0.05 \), and the matte gray texture sample, \( F(1.68, 10.11) = 9.42, p < 0.001 \).

**Effects of object reflectance**

Figure 5 shows the mode and lightness evaluation for spheroids with different object surface reflectance values, represented by three clusters (CIE \( L^* = 30 \), left; \( L^* = 60 \), center; and \( L^* = 80 \), right), when measured at the center spot of the stimulus in which no highlight or shadow was included. The stimulus \( L^* \) level affected the mode and lightness evaluations, but the trends of the two evaluations did not differ significantly. For both the luminosity (mode) and lightness judgments, the effect of the background \( L^* \) was present as the simultaneous contrast, but its magnitude was different between the spheroid \( L^* \)s. According to the two-factor ANOVA with a Greenhouse-Geisser correction, the effects of the spheroid \( L^* \) on the mode evaluation, \( F(1.08, 6.47) = 12.1, p < 0.05 \), and lightness evaluation, \( F(1.24, 7.42) = 75.3, p < 0.0001 \), were both significant. However, the effects of the background \( L^* \) was marginally significant regarding the mode evaluation, \( F(1.99, 12.0) = 3.45, p = 0.0656 \), but was significant in the lightness judgments, \( F(2.03, 12.2) = 9.07, p < 0.005 \). The interaction between the spheroid and the background \( L^* \)s was significant in terms of lightness evaluation, \( F(3.17, 19.0) = 3.99, p < 0.05 \), and had a marginally significant effect on the mode evaluation, \( F(3.59, 21.5) = 2.40, p = 0.0874 \). The small decline in the perceived mode and lightness evaluations with background \( L^* \) implies, again, the effect of simultaneous contrast.

**Mode and lightness evaluations as a function of spheroid \( L^* \)**

Figure 6A and B shows the mode and lightness evaluations, averaged across four background conditions and seven participants, respectively, as functions of the \( L^* \) at the center spot for the photometric measurement on the spheroid surface. As clearly seen, the mode and lightness evaluations can be fit with a linear function of object surface luminance (in CIE \( L^* \)).

Apart from the objects with material perception in all of the participants (organic cotton) and in about half of the participants (suede tan). The correlation coefficient for the lightness evaluation was \( \rho = 0.997 \), including all material surfaces, but for the mode evaluation the correlation coefficient was obviously higher when the two fabric surfaces (organic cotton and suede tan) were excluded (\( \rho = 0.966 \)) as opposed to when they were included (\( \rho = 0.205 \)).

**Experiment 2: Effect of material perceptibility**

The results so far suggest that the variability of mode and lightness judgments with surround conditions seems to depend on the perceptibility of the object
material. To confirm this point, the participants were asked to report the material perception verbally and rated the convincingness for the stimuli used in the present study.

Method

Six participants conducted this experiment; all participants experienced the luminosity and lightness rating experiment more than 6 months before this session. Each participant provided the verbal report and rating only once for each of the 24 stimuli. The participants were asked to report in words the estimated material of the spheroid and to rate the convincingness of the material estimation on a scale of 0 (no convincingness) to 10 (highly convincing).

Results

All participants’ data are shown in Table 3. It became clear that not all the participants used an identical name on reporting the material of the stimuli. However, the answers for the organic cotton stimulus were quite similar among the participants. All six participants reported the organic cotton stimulus as a kind of fabric with a rough texture. For the suede tan stimulus, participants S4 and S6 reported it as a kind of textile, participants S1 and S2 reported it as a material like marble stone, and participants S3 and S5 reported it as a kind of object made of wood. All participants perceived the stimuli as object surfaces with some solid texture but never perceived them as light sources such as fluorescent lamps. For matte gray stimuli, all the dark, middle, and light surfaces were reported as different categories of objects, which suggests the ambiguity of the material perception from the matte gray surfaces.

The convincingness ratings were then compared quantitatively among the materials. Figure 7 shows the results of the mean value for each material, derived after transforming to z scores for each participant. The organic cotton and suede tan textures obtained outstanding high scores in terms of the convincingness. According to the two-factors ANOVA with a Greenhouse-Geisser correction (material × background), only the effect of material was statistically significant, $F(2.08, 10.4) = 13.5, p < 0.005$. The multiple comparisons were conducted between the materials as a post hoc analysis, and the significant differences are shown with asterisks in Figure 7. This result supports the hypothesis that the convincingness of the material perception affected the results of the luminosity (mode) judgment.

Experiment 3: Mode evaluation with respect to the luminosity threshold

The present study used two reference stimuli to equate the criteria across the participants. However, it was not clear whether the sample for the 10 rating reached the luminosity threshold because a uniform spheroid stimulus with shading was used and because we experienced in a previous study that shading could cause reduction in the perceived luminosity (Kuriki & Uchikawa, 1996). To confirm the degree of luminosity for the sample for 10 in the main experiment, the absolute scale judgment was conducted for some stimuli including the light-gray spheroid stimulus, which displays CIE $L^* = 90$ at the center of the spheroid.
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<td>Frisk</td>
<td>3</td>
<td>plastic</td>
<td>2</td>
<td>fluorescent lamp</td>
<td>2</td>
<td>translucent stone</td>
<td>3</td>
<td>plaster</td>
<td>2</td>
<td></td>
<td></td>
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<tr>
<td>matte light gray</td>
<td>70</td>
<td>Frisk</td>
<td>1</td>
<td>paper clay</td>
<td>3</td>
<td>soft rubber ball</td>
<td>5</td>
<td>wood craft</td>
<td>5</td>
<td>stone</td>
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<tr>
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<td>7</td>
<td>fabric</td>
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<td>hemp</td>
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<td>canvas</td>
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<td>hemp</td>
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<td>canvas</td>
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<td>fabric</td>
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<td>hemp</td>
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<td>4</td>
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<td>9</td>
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<td>5</td>
<td>T-shirts cloth</td>
<td>5</td>
<td>wood</td>
<td>5.5</td>
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<td>stone1</td>
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<td>wood</td>
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<td>T-shirts cloth</td>
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<td>wood table</td>
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<td>velvet</td>
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<td>stone1</td>
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<td>rubber</td>
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<td>T-shirts cloth</td>
<td>6</td>
<td>wood table</td>
<td>7</td>
<td>velvet</td>
<td>8</td>
</tr>
<tr>
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<td>4</td>
<td>stone1</td>
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<td>polished wood ball</td>
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<td>T-shirts cloth</td>
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<td>wood</td>
<td>3</td>
<td>sand</td>
<td>2</td>
<td>wood</td>
<td>4</td>
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<td>1</td>
<td>sand box</td>
<td>3</td>
<td>sand paper</td>
<td>2</td>
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</tbody>
</table>

Table 3. Material perception and convincingness. Notes: *C.I.: Convincingness index; 1“marble chocolate”: a chocolate-based snack coated with glossy candy; 2“Frisk”: a name of mint candy with matte white surface, looks like pills.
Method

Five participants, who also took part in the main experiment, were asked to make the judgment. They were shown three types of stimuli on the completely dark background screen: a flat uniform white circle without shading, a matte light-gray spheroid, and a spheroid with organic cotton texture. The flat uniform white stimulus had a diameter of 5.2° in visual angle—the same as the largest diameter of the spheroids—and was used to confirm the mode for stimulus without a three-dimensional structure. The participants were asked to rate the object surface by zero and the lower limit of self-luminous mode by 100 based on each participant’s criterion. The numbers between zero and 100 correspond to the transition mode; a rating larger than zero implies an appearance similar to fluorescence but not yet self-luminous. The rating of 100 corresponds to the appearance for the lower boundary of the self-luminous mode. The participants repeated the rating five times in a random order.

Results

The light-gray spheroid with a uniform matte surface, which was used as the sample for the mode rating of 10 in the main experiment, was rated as 63.0 on average, with a standard error of 11.7. The results for all the three stimuli are summarized in Table 4.

The uniform flat (two-dimensional) white surface was estimated as self-luminous; the rating was higher than the luminosity threshold after a paired two-tailed t test against 100, t(24) = 3.80, p < 0.0005. The rating for the spheroid with the organic cotton texture was not significantly different from zero, t(24) = 1.42, p = 0.082. Therefore, the judgment of the mode rating in the main experiment did not reach the luminosity threshold, and the uniform matte gray surfaces were evaluated as in the transition mode between the surface and luminous modes (Yamauchi & Uchikawa, 2000) in most cases. Since the average of the actual luminosity (mode) rating for the light-gray spheroid in the dark background was 8.5, the value 10 can be estimated to correspond to approximately 74% between the surface mode and the luminosity threshold.

Experiment 4: Achromatic color naming

To confirm whether the participants were really judging the mode of color appearance, the participants were tested on whether they named the stimuli with colors in surface mode among achromatic hues (i.e., gray and black) when they were forced to name them black, gray, or white. If the luminosity judgments were based on the mode of color appearance, the use of color names characteristic to surface colors would have positive correlations.

Method

Five participants conducted the naming session; all participants had conducted the main experiment. Each participant conducted a single run. Participants were shown the same stimuli used in the main experiment.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Uniform flat white (two-dimensional)</th>
<th>Matte light-gray spheroid (three-dimensional)</th>
<th>Organic cotton spheroid (three-dimensional)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rated valuea (M ± SEM)</td>
<td>116.8 ± 9.2</td>
<td>63.0 ± 11.7</td>
<td>0.36 ± 0.4</td>
</tr>
</tbody>
</table>

Table 4. Absolute judgment of the mode of color appearance. Notes: aValues zero and 100 correspond to surface mode and luminosity threshold, respectively.
with four background conditions, and they were asked to categorize each stimulus as black, gray, or white.

Results

The results are shown in Figure 8. First, the results of naming for the stimulus set used in Figure 3 are shown in Figure 8A. This particular set was chosen because it was the most representative result of this study. Also, the luminance of the spheroid is approximately in the middle of the background luminance range; the background conditions could cause changes in the perceived mode of color appearance.

Figure 8A shows the averaged use of each color term in each stimulus, averaged across the participants. Although the luminance of the stimulus is almost the same (around $L^* = 60$ at the center spot of the sphere), the result of naming was clearly different among the three objects. The stimuli with fabric textures showed a higher percentage of naming with gray, especially for the lower surround $L^*$s, in which it is possible for the spheroid to appear more luminous if only the combination of the spheroid and the surround $L^*$s determines the mode of color appearance. In contrast, the use of gray for the matte gray spheroid reached nearly 50% and 100% for the stimulus conditions with a similar ($L^* = 50$) or
brighter \((L^* = 70)\) background, respectively. This trend clearly indicates that the change in the mode of color appearance occurred by the presence of a uniform gray surround, which is consistent with the results shown in Figure 3. To evaluate this trend with a quantitative measure, color-naming points were assigned arbitrarily to each color name (e.g., 9, 5, and 1 for white, gray, and black, respectively). The correlation coefficient was calculated between the points for color categories (Figure 8A) versus luminosity judgments (Figure 3) after converting both data sets to \(z\) scores in each participant. As shown in Figure 8B, two measures were positively correlated with a statistical significance: across all five participants, \(\rho = 0.709, t(58) = 10.8, p < 0.0001\). The results of the same analysis with the color-naming points on three lightness levels of matte gray stimuli are shown in Figure 8C. Likewise, positive correlation was observed with a statistical significance: across all five participants, \(\rho = 0.710, t(58) = 10.9, p < 0.0001\). Therefore, the participants could have been judging the mode of color appearance in the main experiment.

**General discussion**

The comparison of the effects of object texture (Figures 3 and 4) on the evaluations revealed that the material property strongly affected the mode of color appearance evaluation, although it did not affect the lightness evaluation. This result clearly demonstrates the differences between the mechanisms for mode and lightness evaluations. The control experiment with shuffled pixel texture also revealed that the mode evaluations were not based on the image statistics of the texture, such as variance or skewness. In addition, the differences between the mode evaluations for the organic cotton and suede tan surfaces revealed that the identification of the object surface property is strongly related to the mode of color appearance.

This is consistent with our informal observations in previous studies on the mode of color appearance using actual color chips. In these studies, when a very tiny surface undulation or a small scratch was visible on the surface of a color chip, it had a strong percept as an object surface and never appeared as being self-luminous. This held even when the color chip was presented in complete darkness with an intense hidden illuminant (Kuriki & Uchikawa, 1996). In such a scenario, color constancy holds regardless of the presenting surround. To cope with this issue, the researchers had to position the color chip at a distant location so that any minute evidence regarding the object surface became invisible to the participant (Kuriki & Uchikawa, 1996; Uchikawa et al., 1993).

Such efforts were aimed at increasing the ambiguity of the surface property because the researchers at the time already knew implicitly that the mode evaluation for the color chips would be fixed to surface mode once the participant disambiguated the material surface property. The present study confirmed this informal observation from a different perspective.

The mode evaluation for the suede tan surface was not as compelling as that for the organic cotton in the present study. One of the reasons for this was that the fidelity of the computer graphics rendering did not replicate the velvet-like surface as perfectly as it replicated the cotton material. A fabric with short fibers should vary its reflectance in accordance with the angular relationships of the viewpoint, illuminant, and surface normal directions because the light reflected at the short fibers, which are densely packed on the surface, varies with these angular relationships. The computer graphics used in the present study rendered the suede tan surface simply by mapping a two-dimensional image, and the fidelity was not as perfect as rendering changes in reflected light with short fibers. The image quality could be improved by using more sophisticated algorithms that trace the paths of the rays reflected from each short fiber. However, the primary purpose of the present study was not the perfect replication of the appearance of the suede tan texture. The incompleteness of the fabric percept from the suede tan stimulus has rather led us to the inference that the clarity of recognition for the surface property could affect the evaluation of luminosity (Figures 3 and 4).

Another possible argument on the experimental setup pertains to the use of an OLED display in this study. Because every kind of computer display emits light, it is inevitable that the participants were facing a light-emitting device. Therefore, whether the participants perceived surface mode on the computer screen is a crucial problem. However, from the reasons described below, we consider that the use of display itself is not a critical problem when investigating the mode of color appearance. Based on our previous study on color naming for stimuli on a CRT screen (Uchikawa, Kuriki, & Shinoda, 1993), we know that computer screens that emit light can be recognized in object color mode. Our study revealed that when the participants were shown stimuli with the same chromaticity but with or without a gray background, the participants’ color-naming result varied for gray and brown; the stimuli appeared only dark white or orange when the surround was black. In fact, it is quite obvious that we perceive object surface images (e.g., wood surface) on computer screens. Also, as the Gelb effect nicely demonstrates, the object surface could appear self-luminous when it is illuminated with a strong projection light and the surround is completely black. We used the OLED...
display because it can produce a very dark surround: The maximum contrast was about 1:10 (Ito et al., 2013). Therefore, the device for the stimulus presentation is not the only factor that determines the perceived mode of color appearance, and we consider that the use of the computer screen itself is not a critical problem. However, a control experiment using real object stimuli was not conducted in the present study, and the reproducibility of the results across different stimulus media is not confirmed in the present study. Therefore, it must be remarked that not all of the results in the present study can be directly applicable to phenomena in the real world.

Since the organic cotton stimulus was shown at the beginning of each session as one of the two samples for the luminosity judgment, it is possible to argue that the luminosity judgment was simply a consequence of the match-to-sample evaluations. However, because about half of the participants reported the suede tan stimulus as surface (i.e., zero) and the other participants reported that the suede tan stimulus appeared to have a fabric texture or not, it is possible to consider that the participants did not simply conduct match-to-sample evaluations. To reject the possibility of the above-mentioned concern, an additional informal observation was conducted in which a stimulus with a wood-surface texture with coarse wood grain, which was clearly visible on the screen, was evaluated for luminosity. Three participants in the main experiment contributed to this observation. The wood-surface stimulus was tested only with a dark background, but all participants reported the wood-surface stimulus as zero luminosity (i.e., object surface).

In addition, a comparison between the luminosity judgments and color-naming results (Figure 8) showed that the participants made judgment based on mode of color appearance. Especially for the transition of color naming from white to gray for the matte gray stimulus with the change in background luminance, it is quite likely that the mode of color appearance was changing. In fact, the mode judgment for matte gray in Figure 3 changed with statistical significance. This trend is consistent between Experiments 1 and 3. The increase in the gray response in the matte gray stimulus and the emergence of the black response in the suede tan stimulus (Figure 8A) with the background intensity (i.e., $L^*$) can be considered additional evidence for the changes in the mode of color appearance with background. Therefore, the participants can be considered to not do match-to-sample evaluations in the main experiment, and their mode judgments can be considered to be based on the mode of color appearance.

The mode evaluations were a linear function of the spheroid $L^*$ when the fabric texture samples were excluded (Figure 6A). Considering that $L^*$ has a nonlinear transformation from luminance according to the 1/3 power law, $L^*$ can be said to be proportional to the brightness perception. Figure 7A implies that the mode evaluation is proportional to the brightness of the object when the object material is ambiguous. This is consistent with a previous study on the luminosity threshold measured as a function of wavelength (Uchikawa et al., 2001), which demonstrated that the luminosity threshold can be better characterized with the spectral sensitivity function for brightness, not luminance.

### Conclusions

The present study demonstrated the dissociation between the mode of color appearance and lightness when the mode evaluation is conducted between the surface-color and luminous-color modes. The mode evaluation was found to be a linear function of the object surface lightness (CIE $L^*$) for the diffuse component when no distinct pictorial texture cue was found on the object surface to perceive the object material.

**Keywords:** mode of color appearance, material perception, luminosity, lightness, surface texture

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### Footnotes

1. [http://free-texture.net/etc-textures/cotton02.html](http://free-texture.net/etc-textures/cotton02.html)
2. [http://free-texture.net/etc-textures/suede-tan.html](http://free-texture.net/etc-textures/suede-tan.html)


