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ORIGINAL ARTICLE

Appearance of Gold, Silver and Copper Colors of Glossy Object Surface

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Abstract: We investigated categorical regions and appearances of gold, silver and copper color, and glossiness for CG spheres with various chromaticities, lightnesses, and contrast glosses. It was found that the chromaticity regions of brown and yellow changed into gold color, those of gray and black into silver color, and a part of brown region changed into copper color with increase of contrast gloss. The magnitude estimates of gold, silver and copper color increased in high saturation chromaticity regions, achromatic regions, and medium saturation regions, respectively as the contrast gloss increased. As lightness levels increase gold and silver color estimates showed almost no change although copper color estimates decreased. It is suggested that the visual system would independently process glossiness and chromaticness of a surface in a lower level, and then, yield appearances of gold, silver and copper colors by combining them in a higher level.

Keywords: *Gold color perception, Glossiness, Color appearance*

1. INTRODUCTION

We perceive various surface colors in our everyday lives. Most previous studies on surface color perception have focused on colors of uniform and matte surfaces. However, we are surrounded by real surfaces with various material properties, such as metal, ceramic, plastic, or glass. The reflectance properties of these surfaces yield various material perceptions, such as glossiness or transparency. In some cases, color names used for surfaces depend on reflectance properties, such as yellow for a mat surface but gold color for a glossy surface, even though the chromaticity of these surfaces is the same. It is necessary to study color appearance of material with non-uniform reflectance in order to fully understand surface color perception [1-3].

There have been growing interest in perception of glossiness. It was shown that physically-defined gloss could not fully explain perceived glossiness [4-6], and that gloss perception was affected by illumination [7-9], shape [10-12], image statistics [13-15], and highlight [13, 16-19]. In most of these studies, achromatic or monochromatic stimuli were used in order to avoid influence of chromaticness.

Only a few studies previously investigated color appearance when a surface had glossiness. Gold, silver or copper colors are good examples that appear only for surfaces with glossiness. These surfaces are called yellow, gray or brown if they are made in the absence of glossiness, but with the same chromaticity [20]. Okazawa et al. [2] investigated categorical color terms used for glossy surfaces. It was found that gold and silver colors had categorical properties appropriate to be included in the basic color terms [21], and that gold and silver colors were more consistently used for surfaces with stronger specular reflectance in a specific region of chromaticity. However, Okazawa et al. could not show continuous change in color appearance in gold and silver color regions since they used monolexemic color naming method. It was also difficult to know effects of lightness on appearances of gold, silver and copper colors in the results of Okazawa et al. [2]. Their stimuli differed in a reflectance property, which combined gloss level (i.e., specular reflectance) and lightness level (i.e., diffuse reflectance), to produce only four stimulus surfaces. Color appearances for glossy surfaces were still not sufficiently clear.

In the present study we aimed at measuring how appearances of gold, silver and copper colors change with contrast gloss, chromaticity and lightness. Observer performed monolexemic color naming to find chromaticity regions of gold, silver and copper colors, and magnitude estimation of the appearances of gold, silver and copper colors and glossiness to reveal how color appearance related to glossiness.

2. METHODS

2.1 Apparatus

We used a 24-inch LCD (Nanao ColorEdge CG242W) monitor with a Macintosh computer (Mac Pro) to present stimuli. Observers binocularly viewed the monitor at a

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viewing distance of 57 cm with their heads fixed on a chin rest. All experiments were performed in a dark room, controlled by Matlab with the Psychophysics Toolbox extensions [22, 23].

2.2 Stimuli

(1) Standard stimulus of golden sphere

We used computer-generated spheres as stimuli with various contrast gloss, lightness, and chromaticity in the experiments. To make the stimuli faithful to real objects we referred to a real golden sphere, which was produced by painting a styrene foam ball of 20 cm diameter with golden acrylic paint (Liquitex, Bright gold). This sphere was illuminated from the upper left at azimuth and elevation angles of 45 degrees with the artificial sunlight lamp (Seric XC-100). Sheets of white drawing paper were placed on a floor and background walls surrounding the sphere. Then, we measured the spectral distribution of the light reflected from the sphere surface using a Photo Research PR-650 spectroradiometer. The front surface image of the sphere was divided into 40 × 40 small regions (one side of 0.5 cm) so that the measurements were carried out at each region of the surface.

The digital photo image of the real golden sphere, taken by a digital camera, was reproduced on the monitor, then, R, G, B values of each of 40 × 40 regions of the photo image were adjusted so that L, M, S values of the photo image became equal to those of the real sphere. We used the spectral fundamental functions proposed by Stockman, MacLeod, and Johnson [24] to calculate L, M, S values. The luminance of the real sphere was linearly compressed into the luminance range of the monitor (compression rate: 1/17) to make the photo image on the monitor, and it was also tone-mapped by a logarithmic function to make the image sufficiently bright. Although luminance of the photo image was different from that of the real sphere, the chromaticities of all regions were equal between the real sphere and the photo image.

We presented both the photo image of the golden sphere and an image rendered by a CG software (LightWave 9.6, NewTec) on a monitor (diameter of image = 7 deg, distance between images = 1 deg). The parameters of the CG software, i.e., diffuse, reflection, specularity, color highlight, glossiness, reflection blurring, light intensity and ambient light intensity, were adjusted by the first author so that appearances of the two images were visually matched as closely as possible (see Appendix). We designated this CG image as the standard stimulus of the golden sphere. This golden sphere looks like G6 stimulus shown in Fig. 1.

(2) Test stimuli

Test stimuli were generated by changing three CG parameters (diffuse, reflection, specularity) from those of the standard stimulus. We used the contrast gloss to specify the stimulus physical gloss. The contrast gloss was defined as a ratio of intensity of specular reflection to that of diffuse reflection. When a light impinges on a surface at 45 degrees the specular reflection is measured at −45 degree direction and the diffuse reflection is measured at normal direction [25]. The diffuse reflection was also used to define lightness. Lightness, which was converted to Munsell Values, was 10 when the diffuse reflectance is 100%. Figure 1 shows contrast gloss (4-6 levels) and lightness (Munsell Values: 3 levels) of the test stimulus (G1 to G15) used in the present experiments. The contrast gloss of the stimulus was chosen so that the stimuli appeared equally different in glossiness at each lightness level. The lightnesses corresponded to 4.6, 5.7 and 6.6. Some examples of the stimulus image are also shown in Fig. 1.

Figure 2 shows 36 chromaticities of the test stimulus in the CIE 1976 (u′, v′) chromaticity diagram. They were

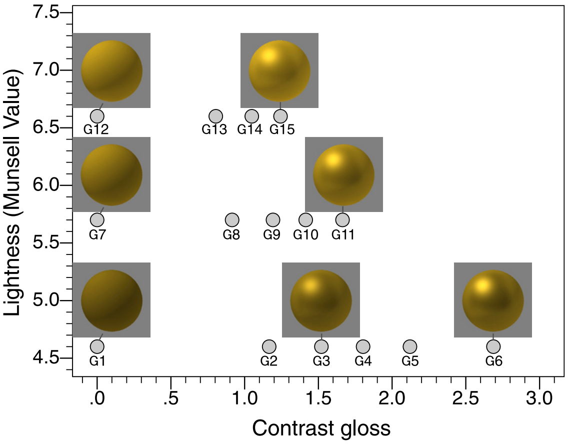


Figure 1: Contrast gloss and lightness of the stimulus used in the present experiment.

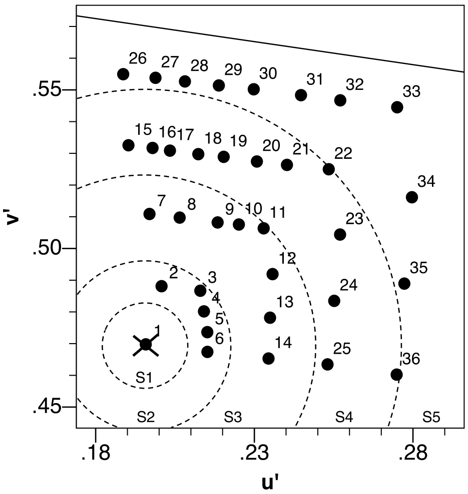


Figure 2: The CIE 1976 (u′, v′) chromaticities (36 points) of the 36 test stimuli.

chosen to cover category areas of gold, silver and copper colors. We assigned 1 to 36 to the test stimuli as chromaticity number. The cross indicates CIE Standard Illuminant D65. We classified chromaticities of the stimuli into five saturation groups (S1 to S5) based on distance from the white point (D65) in order to analyze the effects of saturation of the stimulus. The range of (u′, v′) distance for each saturation group is as follows: S1: −0.0135, S2: 0.0135−0.027, S3: 0.027−0.054, S4: 0.054−0.081, S5: 0.081−. The chromaticity coordinates of the standard stimulus was (u′, v′) = (0.244, 0.529), which was included in S4.

2.3 Procedure

(1) Experiment 1: Color naming

We employed a monolexemic color naming to examine color appearance of the stimuli. In a session, observers adapted to a gray background (52×32 degs, 28.8 cd/m^2, (u′, v′) = (0.196, 0.471)) presented on the monitor for 2 min. Then, a test stimulus (3.8 deg in diameter) was steadily presented on the center of the background. Observers named the stimulus using fourteen color terms, that is, eleven basic color terms (white, black, red, green, blue, yellow, brown, orange, purple, pink, gray) [26] and gold, silver and copper. Observers could move their eyes freely. When observers pressed a button after their responses, the gray background appeared again for 5 sec before the next trial. A test stimulus was chosen at random in a trial. A total of 540 trials were carried out for all test stimuli (15 surface reflectances × 36 chromaticities) in a session. Two sessions were performed for each observer. Observers practiced several trials before starting a session.

(2) Experiment 2: Magnitude estimation of gold, silver and copper colors

Observers estimated strength of gold color of the test stimulus using 0 (no gold color) to 10 (highest strength of gold color, i.e., most typical gold color) point. No reference stimulus was given. Strength of silver and copper color was similarly estimated. The time course of presenting a test stimulus was the same in the color naming procedure. Gold, silver and copper color estimations were carried out for a test stimulus in the same trial. The order of three judgments was not restricted. Observers estimated twice all 540 stimuli in 2 sessions. A decimal point was allowed to estimate strength.

(3) Experiment 3: Magnitude estimation of glossiness

We used G1 and G6 as two reference stimuli with 0 and 10 values of glossiness, respectively. In a trial, after the 2 min adaptation to the gray background, these two reference stimuli were sequentially presented once each with no time limit so that observers could make criteria for glossiness estimate. Then, a test stimulus was presented. Observers estimated the degree of glossiness of the test stimuli using 0 to 10 point. The reference stimuli were presented every 10 trials to keep observer's criterion constant. In a session, all 540 test stimuli were estimated. All observers performed 2 sessions.

2.4 Observers

Four naïve observers (two males and two females, 22-24 years old) participated in all experiments. All observers had normal color vision verified with Ishihara color vision test.

3. RESULTS AND DISCUSSIONS

3.1 Experiment 1: Color naming

Figure 3 (A) and (B) show categorical color regions, obtained in Experiment 1, for all stimuli, G1 to G15. The color terms, used more than 50 percent consensus of all 4 observers, are plotted in the CIE1976 (u′, v′) chromaticity diagram. The color of the symbol represents color category, and the size of the symbol corresponds to the percent usage of the category. Small black points represent positions with no color term. When both of two color terms had 50 percent frequency at the same chromaticity one color term is represented with a small symbol and the other a large symbol. These chromaticity diagrams are located at stimulus positions (closed diamond symbol) in graphs of lightness vs. contrast gloss.

The results show that, at the lowest lightness level, LL = 1, the gold, silver and copper color regions tend to expand as contrast gloss increases in G3 to G6. At the middle lightness level, LL = 2, the gold and silver color regions also expand in G9 to G11, but no copper color region was observed. At the highest lightness level, LL = 3, no gold, no silver except a point in G15 and no copper color regions appeared. Comparing color regions in G3 and G11 at the medium contrast gloss, we can notice that gold and silver color regions do not considerably change but copper color region disappears as lightness increases. Comparing G2, G9 and G15 at the lower contrast gloss, it can be seen that gold and silver color regions exist only at middle lightness level, LL = 2. All observers showed similar changes of gold, silver and copper color regions with contrast gloss and lightness. It is shown in Fig. 3 that as contrast gloss increases the gold color region appears in the brown and yellow regions, the silver color region appears in gray and black regions, and the copper color region appears in the brown regions. It should be noted

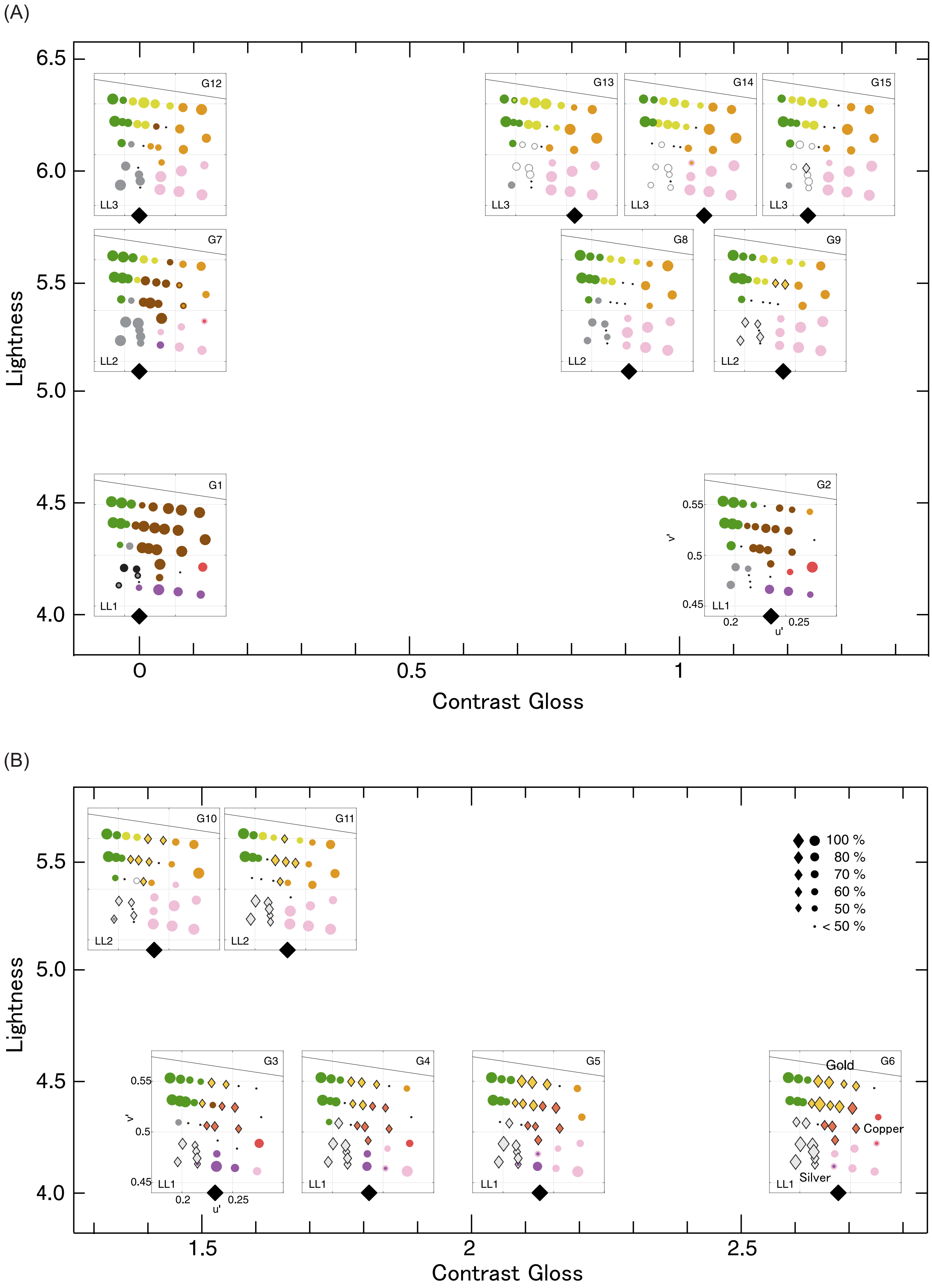


Figure 3: Categorical color regions, obtained in Experiment 1, for all stimuli, (A) G1, 2, 7−9, 12−15, (B) G3−6, 10, 11.

that the gold color region expands into more saturated colors, the silver color region is restricted in less saturated (achromatic) colors, and the copper color region stays in moderately saturated colors. When compared with Okazawa et al. [2], the position of the gold color region obtained in this study is slightly more greenish, and the silver and copper color regions shift slightly in greenish and bluish direction. The reason could be stimulus differences in reflectance properties, shape, and background luminance.

3.2 Experiment 2: Magnitude estimation of gold, silver and copper colors

Figure 4 (A), (B) and (C) show mean magnitude estimates of gold, silver and copper color, respectively, for stimuli with chromaticity having more than 50 percent consensus of any of gold, silver or copper colors in G1 to G15. Chromaticity points are shown with different shapes and shades of symbols in the figures. The chromaticities with the same dominant wavelength are shown with the same shape and shades of symbols. These estimates are separately shown in different saturation groups, S1 to S5.

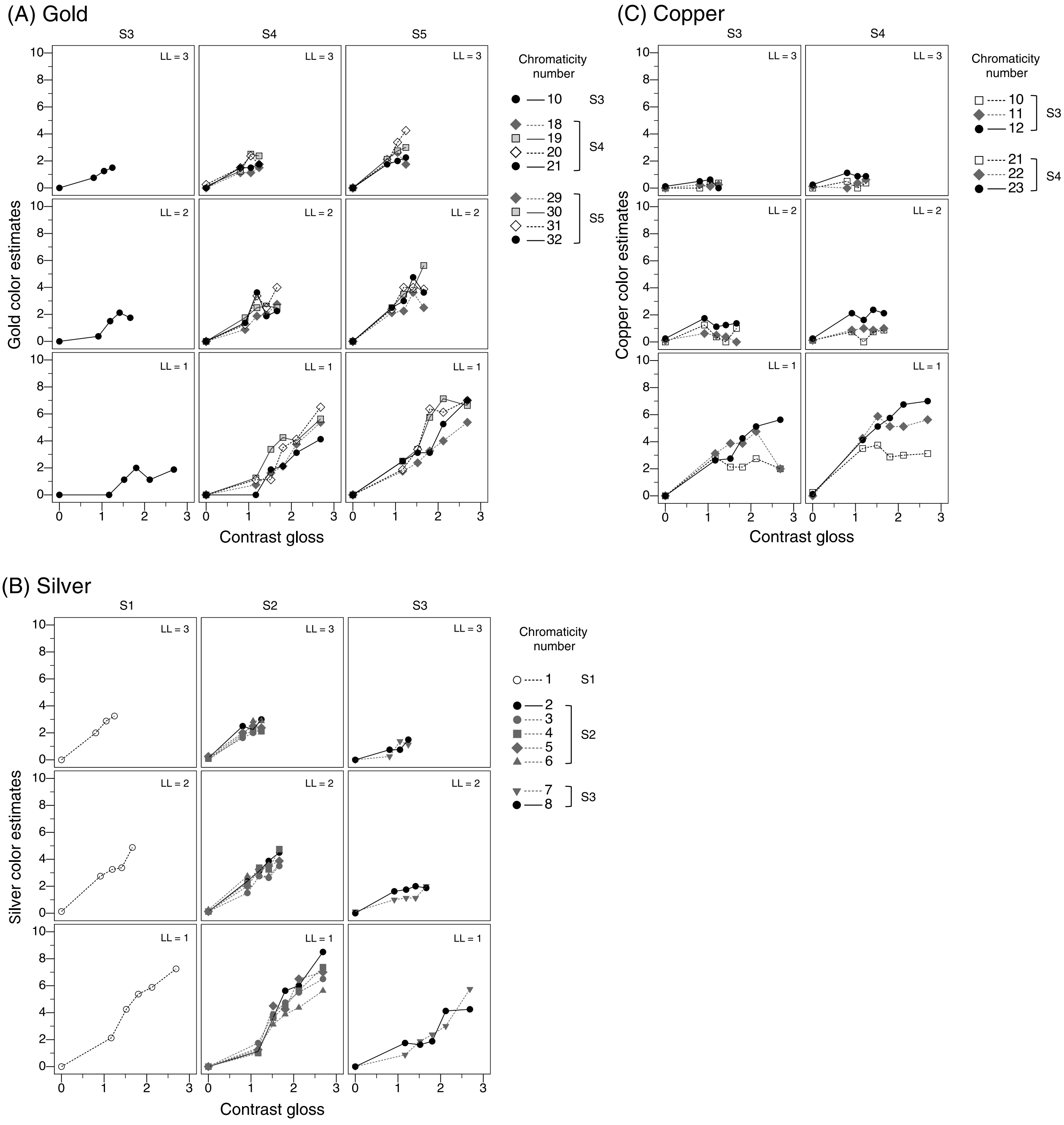


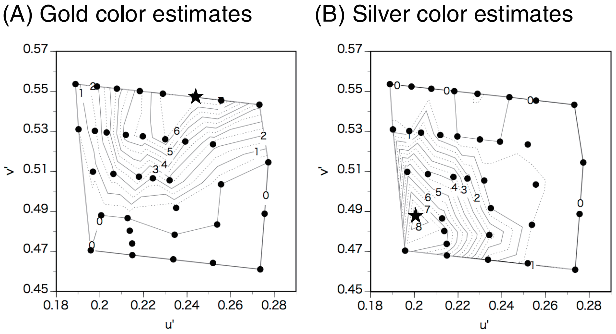
Figure 4: Magnitude estimates of the appearance of gold, silver and copper color plotted as functions of contrast gloss for all observers. (A) gold, (B) silver and (C) copper color.

“LL” refers to lightness level.

In Fig. 4 (A) it can be seen that gold color estimates increase with steeper slopes in S5 at LL1 and LL2 (2-way ANOVA, LL1: F(2,198) = 12.674, $p = 0.000007$, ANCOVA, LL2: F(2,176) = 4.869, $p = 0.0087$, LL3: F(2,140) = 2.264, $p = 0.108$). In Fig. 4 (B) silver color estimates are shown to increase with steeper slopes in S1 at all lightness levels (ANCOVA, LL1: F(2,188) = 8.690, $p = 0.000246$, LL2: F(2,156) = 4.685, $p = 0.0106$, LL3: F(2,124) = 3.664, $p = 0.0284$). In Fig. 4 (C) copper color estimates increase with steeper slopes in S4 at LL1 (ANCOVA, LL1: F(1,141) = 7.539, $p = 0.00682$, LL2: F(1,117) = 1.599, $p = 0.208$, 2-way ANOVA, LL3: F(1,88) = 1.593, $p = 0.21$). They increase more steeply than gold and silver color estimates when the contrast gloss is lower, and then, tend to reach asymptotes when the contrast glosses are higher.

It is noticed in Fig. 4 that gold and silver color estimates showed almost no change in different lightness levels whereas copper color estimates decrease as lightness level increases. This means that lightness per se does not influence gold and silver colors, but strongly affects copper color.

Figure 5 shows contour lines of gold, silver and copper color estimates for G6 in the CIE 1976 (u′, v′) chromaticity diagram. G6 was selected here because all color estimates clearly appeared in G6 (see Fig. 3). Black circle represents chromaticity of the stimulus. The highest estimates were obtained at chromaticity number 31 (gold), 2 (silver) and 23 (copper), shown as star symbols in Fig. 5. We can see in Fig. 5 that gold, silver and copper color estimates change almost isotropically from each highest position (star symbol) in the chromaticity diagram, indicating that these glossy colors vary depending on color difference. It would be suggested that a simple color mechanism yields gold, silver and copper colors by means of putting glossiness on a particular chromaticity. This would explain why these color components are reduced as functions of color difference.


(A) Gold color estimates

(B) Silver color estimates

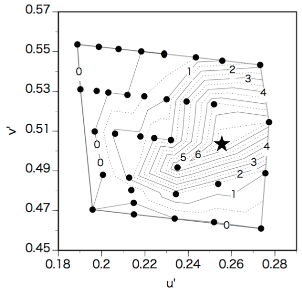

(C) Copper color estimates

Figure 5: Contour plot of (A) gold color estimates, (B) silver color estimates, (C) copper color estimates as a function of CIE 1976 (u′, v′) chromaticity of G6.

3.3 Experiment 3: Magnitude estimation of the glossiness

We found that the chromaticity of the stimulus had no effect on the glossiness estimate at all lightness levels (LL1: F(35, 648) = 0.343, $p = 0.999877$, $p\eta^2 = 0.018$, LL2: F(35,540) = 0.221, $p = 1$, $p\eta^2 = 0.014$, LL3: F(35,432) = 0.346, $p = 0.999852$, $p\eta^2 = 0.027$). Figure 6 (A) shows mean

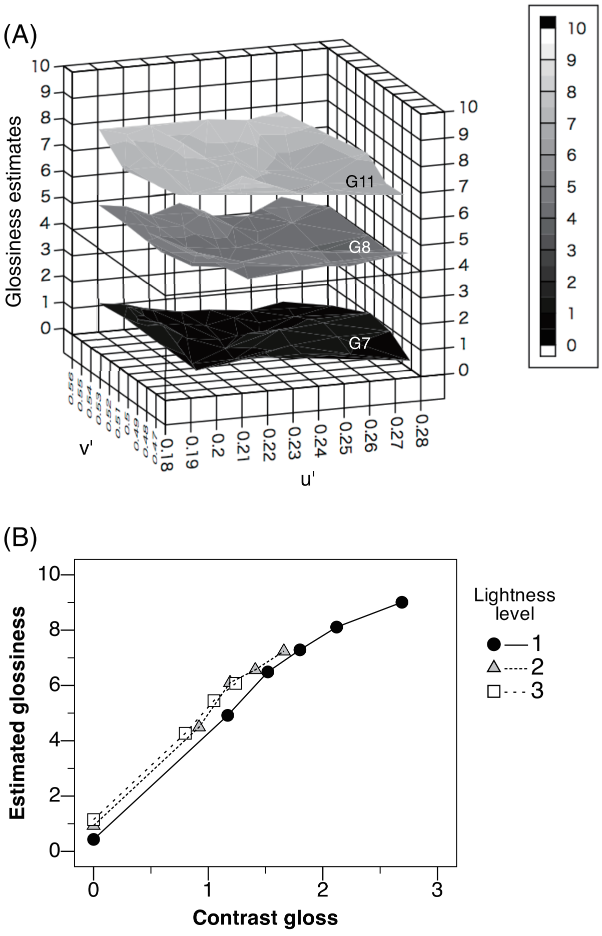


Figure 6: (A) Glossiness estimates plotted as a function of (u′, v′) chromaticity in the condition of lightness level 2 and contrast gloss 0, 0.92, 1.66 (G7, G8, G11).
(B) Glossiness estimates plotted as a function of contrast gloss.

glossiness estimates across all observers plotted on the (u′, v′) chromaticity diagram. We chose G7, G8 and G11 stimuli as examples. Figure 6 (B) shows mean glossiness estimates across all chromaticities as functions of the contrast gloss. The ordinate represents mean estimates of glossiness across all chromaticities for each stimulus of G1−G15. The abscissa represents contrast gloss of the stimulus. Lightness levels are designated with different symbols. It was found that perceived glossiness linearly increased with the contrast gloss, and that it was slightly lower for lightness level LL = 1 than LL = 2 and 3.

4. GENERAL DISCUSSION

In the present study we investigated how gold, silver and copper color changed as physical gloss increased for stimuli with different chromaticity and lightness. In Experiment 1, we found that as the contrast gloss increased brown and yellow changed into gold color, gray and black into silver color, and brown partly into copper color. Gold and silver color regions did not change with lightness although copper color region decreased with increasing lightness. In Experiment 2, we showed that as contrast gloss increased gold color increased in high saturation chromaticity regions, silver color in achromatic regions, and copper color in medium saturation regions. In Experiment 3, it was found that we perceived glossiness of a surface being independent of its chromaticity. These results indicate that the chromaticity and the contrast gloss of the stimulus seem to work independently to yield gold, silver and copper colors. This may suggest that the visual system would process chromaticness and glossiness of a surface in different pathways, then combine them to produce gold, silver or copper color appearance.

We compared the chromaticity of a real gold surface (99.99%) with the chromaticity region of gold color obtained in Fig. 3. The spectral reflectance of specular reflection of the real gold surface was measured for incident light angles of 15, 30, 45, and 60 degree. Figure 7 shows CIE 1976 (u′, v′) chromaticities of the real gold surface illuminated by the CIE standard illuminant D65 and the gold, silver and copper color regions for G6 replotted from Fig. 3. The chromaticities of the real gold are shown with yellow diamonds symbol, and correspond to incident angles of 15, 30, 45, and 60 degree from right to left sides. The red dotted line shows the locus of chromaticity of the real gold. The white diamond symbol represents the chromaticity of D65. Gold, silver and copper region in G6 of Fig. 3 are shown with enclosed regions with yellow, gray and orange colors, respectively. It is clearly shown that the chromaticities of the real gold do not match to the categorical region of gold color. They are close to 9, 20 and 21, less saturated colors than 31 or 32, the gold colors with the highest estimate. Okazawa et al. [2] reported the similar inconsistency between real gold and categorical gold color regions, but they showed that the saturation of a real gold surface increased when more than the second reflections were took into considerations.

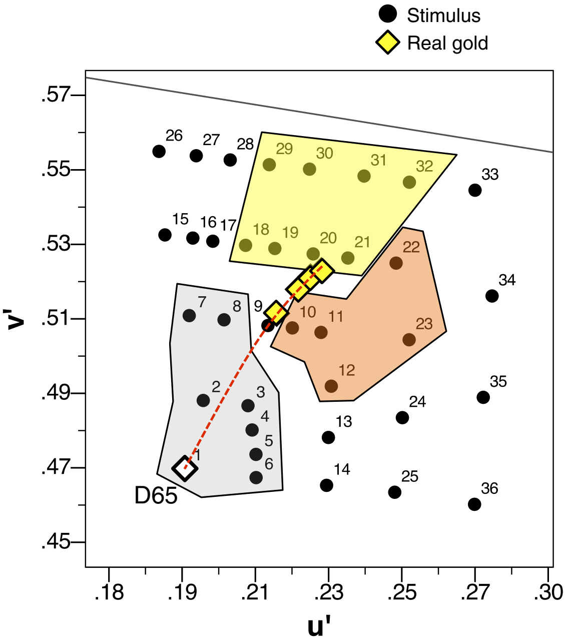


Figure 7: CIE 1976 (u′, v′) chromaticities of the real gold (99.99%) surface illuminated by the CIE standard illuminant D65 and the gold, silver and copper color regions for G6 replotted from Fig. 3.

It would not be necessary that the chromaticity of real gold coincides with that of the highest gold color estimation since gold color appearance would be developed independently of seeing real gold. We speculate that the gold and silver color perception would result from hard-wired mechanisms in the visual system evolutionarily developed to categorize colors in natural environments. There are a number of things or occasions that appear gold or silver color in natural environments. For example, the sunlight reflected from the ocean surface and the moon shining in a night sky appear gold color. When we see a surface of water from grazing angle, it reflects light like a mirror. If surfaces of the sea water ripples, they often appear silver color. There are many fish having silvery shining scales. Materials and phenomena having appearance of gold and silver colors would be so important for human being to survive that color names of gold and silver were assigned as categorical basic names [2].

It should be noted that gold, silver and copper color perception was studied for visual stimuli presented on a monitor in this study as well as most previous studies. In natural scenes, lights reflected from real surfaces are generally much more intense exceeding a dynamic range of a monitor. Therefore, it should be noted that it is crucially important in future studies to use high-dynamic-range displays and real object surfaces to reveal the perceptual mechanism of gold, silver and copper colors. Finally, 4 observers participated in the present study. This number of observers are comparable to previous studies [11, 15, 27, 28], and the individual variations obtained in the present experiments are not large so that it would not be reasonable to suspect validity of our results because of small numbers of observers. However, further studies are needed to confirm the generalizability of our findings.

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APPENDIX

Table 1 shows the controlled parameters and the matched values in the CG software "Lightwave" described in the section of "*Standard stimulus of golden sphere*,". The color (R, G, B values) of the diffuse reflection was determined based on the average chromaticity of the photometric value of our real golden sphere.

Table 1: The controlled parameters and the matched values in the CG software "Lightwave".

Controlled parameters	Matched values (%)
Diffuse	51
Reflection	76
Specularity	13
Color Highlight	100
Glossiness	23
Reflection blurring	50
Light intensity	150
Ambient light intensity	35

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