1. INTRODUCTION

Psychophysical metrics about the relationship between vision, perception and appearance have significantly contributed to industry. As the representative example, the $L^*a^*b^*$ colorimetric system has successfully provided a methodology to quantify the color of prints. It is regarded as one of the uniform color spaces and regarding the uniform and linear correlation with perceived magnitude, it is useful and widely utilized in industry such as the quality control of product color. Thus, the correlation between perception and appearance of common colors, such as red and yellow, have been studied for long time.

On the other hand, the correlation between the perception and appearance of metallic colors, such as gold and silver, is unexpectedly still under study and has been of interest in recent decades [1-8]. For instance, Okajima et al. reported the importance of luminance distribution for metallic recognition [1]. In addition to this, several factors for metallic recognition have been reported such as the specular/diffuse ratio [2, 3], lighting condition [4, 5], surface irregularity [6], shape recognition [7], observation area [8], etc. Although these research studies certainly indicate that the recognition of metallic colors is different from common colors, the prescribed method and index for quantification of metallic image based on perception is not defined, presumably due to the difficulties from said multidimensional recognition factors.

It is a serious issue for players who engage in embellished metallic prints such as designers, printing operators and foil makers. Due to the absence of an appropriate index for quantifying the metallic appearance, many inefficiencies have been caused. That is, designers cannot explain details of their design of metallic prints by a quantitative representation, thus the printing operators cannot choose a suitable foil species for requirement from the designers, etc. The color management of foils has also depended on the visual judgement due to the lack of an index and the dependence has decreased productivity of this market. These inefficiencies have caused time loss and cost and interfered with market expansion. This fact strongly prompted us to study which physical features of metallic prints induce the metallic taste and then construct the index. We now suggest a metallic taste index (MTI) possessing a linear correlation with the perceived magnitude.

To construct the index, we focused on the lightness distribution of the reflection as a feature of the unique metallic appearance. Figure 1 a)-b) shows a comparison of the lightness distribution property between the common colors and metallic colors. Regarding the common colors, almost all the incident light is reflected as diffuse light and the distribution becomes nearly isotropic. On the other hand, the lightness distribution of metallic colors is quite anisotropic, and the incident light is predominantly reflected around specular. This is significantly characteristic for metallic images, and a recent study demonstrated that specular, roughness and
diffusion of the metallic lightness distribution stimulate a specific brain area [9, 10]. Thus, it should be considered for the construction of the index. A diagram of our strategy is shown in Figure 1 c). In this research, the lightness distributions were measured by goniometric spectrocolorimetry [11]. Subsequently, the distribution property was fitted by a Lorentzian curve (Eq. 1) so that the character of the distribution was mathematically explained. Eq. 2 then provided the MTI. The antilogarithm indicates the average lightness concentrated within the width of the half maximum of the specular distribution. The index becomes high if the distribution is sharp and strong, conversely, the index becomes low if the peak possesses a wide skirt.

\[
f_n(\theta) = B + \sum_{i=1}^{n} g_i(\theta), \quad g_i(\theta) = \frac{H_i w_i^2}{W_i^2 + (\theta - \theta_0)^2} \quad (1)
\]

\[
\text{MTI} = \log \left( \frac{\int_{-\infty}^{\infty} f_n(\theta) \, d\theta}{2w_n} \right) \quad (2)
\]

\text{n: Terms of fitting function (= 1 or 2),} \\
\text{B: Baseline,} \\
\text{\theta_0: Peak location,} \\
\text{H: Peak height,} \\
\text{w: Half width of half maximum.}

Furthermore, we demonstrated the threshold between the terms of gloss-metallic, matte-metallic and non-metallic by using the MTI. In the metallic printing market, players often use terms such as Tsuya-Koutaku (gloss-metallic) and Keshi-Koutaku (matte-metallic), but these terms are not clearly defined. Our result of the threshold determination should provide definitions for the terms and contribute to the efficiency improvement of the color management of metallic images.

2. EXPERIMENTAL SECTION

2.1 Materials

2.1.1 Metallic images for magnitude estimation

Ten kinds of metallic images (Image 1–10) were prepared for the magnitude estimation (Table 1).

2.1.2 Metallic images for threshold determination

The mirror-like aluminum deposited film (Image 18) and six kinds of diffusion films were prepared (Table 2).

![Figure 1: Diagrams of lightness distribution of a) common colors and b) metallic colors. c) Concept of quantification for metallic images by lightness distribution.](image)

**Table 1:** Appearance of Images 1–10

| No. | Appearance                      |
|-----|--------------------------------|
| Image 1 | Gray image with slight gloss |
| Image 2 | Gray image with slight gloss and irregularity |
| Image 3 | Blight gray image |
| Image 4 | Mirror-like image with haze |
| Image 5 | Dark mirror-like image |
| Image 6 | Folding-screen-like image |
| Image 7 | Mirror-like image with slight haze |
| Image 8 | Mirror-like image with slight hairline |
| Image 9 | Mirror-like image with orange peel finish |
| Image 10 | Mirror-like image |

**Table 2:** Components of Images 11–26

| No. | Base                           | Haze of diffusion film |
|-----|--------------------------------|------------------------|
| Image 11 | Aluminum deposit film | 92                     |
| Image 12 | Aluminum deposit film | 87                     |
| Image 13 | Aluminum deposit film | 82                     |
| Image 14 | Aluminum deposit film | 67                     |
| Image 15 | Aluminum deposit film | 46                     |
| Image 16 | Aluminum deposit film | 29                     |
| Image 17 | Standard gloss silver foil | –                     |
| Image 18 | Aluminum deposit film | –                     |
| Image 19 | Gold deposit film | 92                     |
| Image 20 | Gold deposit film | 87                     |
| Image 21 | Gold deposit film | 82                     |
| Image 22 | Gold deposit film | 67                     |
| Image 23 | Gold deposit film | 46                     |
| Image 24 | Gold deposit film | 29                     |
| Image 25 | Standard gloss gold foil | –                     |
| Image 26 | Gold deposit film | –                     |
Covering the aluminum deposited film with the diffusion films provided images with several appearances (Images 11-16). Additionally, a standard silver foil image (Image 17) was added. Gold metallic images with several appearances were also prepared to obtain the threshold of the gold (Images 19-26).

2.2 Measurement

2.2.1 Goniometric spectrocolorimetry measurement
Preparation of the samples for the goniometric spectrocolorimetry measurement (Samples 1-26) are shown in Figure 2 a)-b). These samples possess a 15×50 mm metallic area on a 50×50 mm cardboard base. The measurement was carried out by goniometric spectrocolorimetry (Murakami Color Research Laboratory Co., Ltd., GCMS-4) on the metallic area. The lightness distribution from 0 to 50 degrees was obtained at an incident light fixed at -45 degrees. The measurement intervals were 2 degrees and 1 degree for the measurement range from 0 to 30 degrees and from 30 to 50 degrees, respectively. D_50 was selected as the light source condition.

2.2.2 Calculation of MTI
The obtained lightness distributions were fitted by a Lorentzian curve (Eq. 1, n=1) so that the distribution could be mathematically expressed. The fitting curve was estimated by a least square calculation using Excel solver. To briefly confirm the fitting accuracy, the correlation coefficient ($R^2_{fit}$) between the experiment and fitting values was calculated in the range from 0 to 45 degrees. For the $R^2_{fit}$ of less than 0.98 and the skirt of the peak was underrated, fitting with two Lorentzian curves (n=2) was carried out for a precise fitting. Subsequently, Eq. 2 provided the MTI value.

2.2.3 Comparative index
For comparison of the suggested MTI, we calculated the Flop index (Eq. 3) [12], Contrast gloss (Eq. 4) [13], and Specular lightness (Eq. 5) as a comparative index. These $L^*$ values were measured by the goniometric spectrocolorimetry in the same way.

\[
\text{Flop Index} = \frac{2.69 \left( L^*_0 - L^*_{-45} \right)}{L^*_0}^{1.11}
\]  
\[3\]

\[
\text{Contrast Gloss} = \frac{L^*_0}{L^*_{45}}
\]  
\[4\]

\[
\text{Specular Lightness} = L^*_0
\]  
\[5\]

$L^*$: Lightness.
Subscripts show the number of receiver angles.

2.3 Psychophysical experiments
2.3.1 Stimuli
Images 1-26 were masked by a white mask with a 15×15 mm square cutout. Attaching the masked images on circular cylindrical vials provided stimuli for the psychophysical experiment (Stimuli 1-26, Figure 2 c)). Additionally, Stimuli 1’-26’ were prepared using a black mask instead of the white masks (Figure 2 d)). Stimuli 1-10 and Stimuli 11-26 were for the magnitude estimation and threshold determination, respectively.

2.3.2 Observers
Twelve naive observers were assigned. The observers consisted of two males and two females from three generations, i.e., their twenties, thirties and forties.

2.3.3 Magnitude estimation
The observers could freely handle Stimuli 1-10 in the light booth (X-Right, Inc., Judge II) placed in a darkroom and observe the metallic images under the D_50 standard light source. After their observations, they estimated the strength of the metallic taste from zero- (no metallic taste) to ten- (strong metallic taste) points. As references, gray paper and a mirror-like aluminum deposited film were presented as zero- and ten-point references, respectively. After observation of Stimuli 1-10, they repeated the same protocol using the black masked stimuli (Stimuli 1’-10’). The obtained scores were averaged and plotted with the values of the calculated indexes. The correlativity was evaluated by the correlation coefficient ($R^2_{index}$) of the plot.

2.3.4 Threshold determination
The observers could freely handle Stimuli 11-18 in the light booth (X-Right, Inc., Judge QC) placed in a darkroom and observe the metallic images under the D_50 standard light source. After their observations, the observers labeled the stimuli by three terms, non-metallic, matte-metallic and gloss-metallic. The perception probability curve of the gloss-metallic and matte-metallic were then separately calculated by fitting a sigmoid curve as shown by Eq. 6. The thresholds were determined from a middle point location.

\[
s(x) = \frac{1}{1 + \exp \left( a \left( x_0 - x \right) \right)}
\]  
\[6\]

$a$: Steepness,
$x_0$: Middle point location.
Figure 2: Schematic diagrams of preparation of a) Samples 1-10, 17-18, 25-26, b) Samples 11-16, 19-24, c) Stimuli 1-10, 17-18, 25-26, 1’-10’, 17’-18’ and 25’-26’. d) Photograph of stimulus with white and black mask. e) Schematic diagram of preparation of Stimuli 11-16, 19-24, 11’-16’ and 19’-24’. f) Photographs of Stimuli 1-26.
3. RESULTS AND DISCUSSION

3.1 Measurement of lightness distribution

As shown in Figure 3 and Figure 4, goniometric spectrocolorimetry of Images 1-10 afforded the lightness distribution. The shapes of the curves were well fitted by a Lorentzian distribution. Concerning Image 3, fitting with two Lorentzian curves was needed due to the poor fit of the peak skirt area (Figure 4). Figure 6 shows lightness distribution of Images 11-26. The reflection property of all the images was then mathematically explained.

3.2 Magnitude estimation

The obtained perceived magnitude (φ) and calculated values of the indexes are shown in Table 3. From the perceived magnitude, the prepared images seem to be sorted into three categories as low metallic taste (Images 1 and 2, φ=0-3), middle metallic taste (Images 3-5, φ=3-7) and high metallic taste (Images 6-10, φ=7-10). Regarding Images 6-10, the surface finishes, such as orange peel and hairline, were not significantly affected more than expected and all the φ values were greater than seven.
Concerning the Flop index and Contrast gloss, a slight correlation was observed in the low metallic taste domain. However, as shown in Figure 5 a)-b), no obvious correlation could be observed in the high metallic taste domain, and the $R^2_{index}$ were 0.19 and 0.16 (Table 3). The Flop index is mainly utilized for evaluation of the metal flake pigment such as the paint of vehicles. Thus, this index presumably could not be adapted to the high metallic taste image. Alternatively, the Contrast gloss is calculated by dividing $L_{45}^*$ by $L_0^*$ and the value tends to be sensitive to $L_0^*$. Since $L_0^*$ of the high metallic taste images was a variable and independent of the metallic taste, the value was not correlated with the perceived magnitude and is presumably not suitable for evaluation of real metallic images.

For comparing the two indexes, the specular lightness showed a better correction. However, a mismatch was observed in the middle metallic area (Figure 5 c)). In spite of the fact that the metallic taste of Image 3 was obviously lower than those of Images 4 and 5, the specular lightness value of Image 3 was higher than those of Images 4 and 5. The result indicated that the specular lightness overrated the gloss of Image 3 and the metallic taste could not be explained only by the specular intensity. The reasons should be the unique lightness distribution of Image 3. The peak possessed a strong and sharp main peak but also a weak and wide skirt at the bottom of the main peak. This indicated that the gloss contained a secondary component and the secondary broad reflection decreased the metallic taste of Image 3, regardless of the first sharp peak. In that regard, the MTI could reflect the broadness of the secondary specular by a two-peak fitting process and as shown in Figure 5 d), the order between Images 3, 4 and 5 could be identical to the perceived magnitude. Therefore, it possessed a good correlation with the perception from the low to high metallic taste range and high $R^2_{index}$. This result indicated that the suggested MTI linearly correlated with human perception and provided a suitable index for quantifying the metallic taste of the images.

### Table 3: Value of indexes and perceived magnitude

| No | $\varphi$ | Flop index | Contrast gloss | Specular lightness | MTI |
|----|----------|------------|----------------|--------------------|-----|
| 1  | 2.44     | 16.0       | 4.41           | 252.4              | 2.30|
| 2  | 2.88     | 18.2       | 5.29           | 271.2              | 2.33|
| 3  | 4.33     | 21.9       | 15.9           | 738.1              | 2.53|
| 4  | 5.43     | 31.1       | 19.1           | 496.7              | 2.61|
| 5  | 6.14     | 23.8       | 24.2           | 528.6              | 2.66|
| 6  | 7.63     | 45.0       | 367            | 1059               | 2.96|
| 7  | 8.12     | 17.0       | 34.6           | 1026               | 2.94|
| 8  | 8.44     | 7.61       | 19.7           | 1115               | 2.97|
| 9  | 9.10     | 42.3       | 173            | 1126               | 2.96|
| 10 | 9.81     | 38.4       | 146            | 1085               | 2.95|

$R^2_{index}$ | 0.19 | 0.16 | 0.86 | 0.95 |
Furthermore, we confirmed the robustness of the MTI for individual variance. Table 4 shows individual $R^2_{index}$ of the Flop index, Contrast gross, Specular lightness and MTI. Individual $R^2_{index}$ of the MTI were higher than other indexes in every observer. This result suggested the MTI possess high robustness for individual variance.

### 3.3 Threshold determination

We further estimated the perceived thresholds between the gloss-metallic, matte-metallic and non-metallic appearances by using the MTI. The MTI values were calculated from lightness distributions of Images 11-26 shown in Figure 6. The perception probability curve of the gloss-silver is shown as a red line in Figure 7 a). The half-value of the sigmoid curve indicated that the threshold between the gloss-silver and matte-silver was 2.74. Similarly, the blue line in Figure 7 a) shows the perception probability between the matte-silver and non-silver and the threshold was 2.19. Furthermore, the threshold between the gloss-gold, matte-gold and non-gold were estimated to be 2.14 and 2.61, respectively (Figure 7 b)). These results provided a numerical definition to the metallic foil terms such as Tsuya-Gin (gloss-silver), Keshi-Gin (matte-silver), Tsuya-Kin (gloss-gold) and Keshi-Kin (matte-gold).

Concerning difference between threshold of Gloss-silver and Gloss-gold, threshold of Gloss-silver was higher than threshold of Gloss-gold. In this regard, Okajima et al. reported that recognition of Gloss-silver needed more reflectance than Gloss-gold [1]. Our result also indicated similar tendency.

Moreover, we constructed a color space for the metallic images by using the MTI, $a^*$ and $b^*$ values to demonstrate its application for color management. Figure 8 shows the color space. Several terms were used for the appearances of popular gold foils such as Ao-Kin (Cold-gloss-gold) and Aka-Kin (Warm-gloss-gold). Hence, these colors should be numerically defined for color management. The MTI calculation and spectro-photometric analysis of the standard five foils, including Ao-Kin and Aka-Kin, then provided us the color space. The result indicated that the MTI could describe the precise appearance of the metallic foils. Additionally, combining the threshold could enhance the convenience of the color space. The result indicated that the MTI should contribute to color management of metallic images.

#### Table 4: Individual $R^2_{index}$

| Observers | Flop index | Contrast gross | Specular lightness | MTI  |
|-----------|------------|----------------|-------------------|------|
| Observer A| 0.11       | 0.13           | 0.84              | 0.95 |
| Observer B| 0.16       | 0.17           | 0.88              | 0.93 |
| Observer C| 0.18       | 0.12           | 0.87              | 0.88 |
| Observer D| 0.20       | 0.19           | 0.89              | 0.94 |
| Observer E| 0.13       | 0.07           | 0.82              | 0.87 |
| Observer F| 0.22       | 0.24           | 0.78              | 0.94 |
| Observer G| 0.12       | 0.09           | 0.75              | 0.89 |
| Observer H| 0.30       | 0.24           | 0.82              | 0.91 |
| Observer I| 0.34       | 0.27           | 0.81              | 0.90 |
| Observer J| 0.22       | 0.14           | 0.83              | 0.91 |
| Observer K| 0.15       | 0.13           | 0.85              | 0.95 |
| Observer L| 0.11       | 0.11           | 0.76              | 0.88 |
Figure 6: Lightness distributions of Images 11-26. Black and red lines indicate measured curve and fitted curve ($n=1$), respectively.
4. CONCLUSION

In summary, we constructed an index of metallic taste from the lightness distribution of metallic images. It is suggested that the MTI possesses a linear correlation with the perception of metallic taste. Furthermore, the procedure could quantify the metallic taste of images with the unique lightness distribution property such as Image 3. The result indicated that the methodology is versatile for several real metallic images. Although the metallic appearance tends to be already explained by using the specular and diffuse variables, the result also indicated that the appearance of real metallic images could not be quantified by only these two parameters and the shape of the lightness distribution, especially, the peak skirt should be considered for metallic quantification.

Moreover, the threshold between the gloss-metallic, matte-metallic and non-metallic could be clarified by using the MTI. Additionally, the three-dimensional color space consisting the MTI, a* and b* could visualize the precise appearance of metallic foils. This result would provide definition to the terms and be helpful for color management. To the best of our knowledge, a suitable index explaining the strength of the metallic taste of embellished metallic prints does not exist and the absence has restricted the growth of the metallic print market. We hope our results would contribute to support business expansion of the printing market.

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Figure 7: Perception probability curves of a) silver and b) gold. Blue line indicates the threshold between non-metallic and matte-metallic taste. Red line indicates the threshold between matte-metallic and gloss-metallic appearances.

Figure 8: Color space for quantification of metallic images using MTI as z-axis. a* and b* were obtained from specular component include (SCI) measurement of spectrophotometers (KONICA MINOLTA, INC., CM2600d). Red, blue, yellow, dark gray and gray spheres indicate standard Tsuya-Kin (Aka-Kin and Ao-Kin), Keshi-Kin, Tsuya-Gin and Keshi-Gin foils. Red plane indicates average threshold of gloss-silver and gloss-gold. Blue plane indicates average threshold of matte-silver and matte-gold.
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