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Quantification of Faithful "Color Appearance" Reproduction, and Application to New Products

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Abstract

In photographic prints, color reproducibility is an important factor for print quality. For quantification method of color, lightness (CIEL a* b*) and optical density (OD) based on spectral reflectance measurement method (45deg incidence/0deg light reception) is used widely. However, there is often a case that the measured L* a* b* and the result from subjective evaluation does not match depending on observing environment. Therefore we examined new methods to evaluate "color appearance" reproduction, which highly correlated to the subjective evaluation. And we used this new evaluation method to develop the new "imagePROGRAF PRO" series printers, and realized high optical density in black area and wide color gamut.*

1. Introduction

Optical density (OD) and lightness (CIE L*), which are based on spectral reflectance measured at 45deg incidence/0deg light reception, have been used for quantifying the dark area. In glossy print images, however, values of OD and L* have not often been correlated with order of optical density appearance. We explained why they had such a low correlation and suggested a method to quantify optical density appearance [1].

In this study, we also found that another kind of appearance, such as Chroma, had low correlation with color value measured by a 45/0 spectrophotometer.

Therefore we also examined this low correlation and suggested a new quantification method to evaluate such appearance. We defined color reproduction in a viewing environment as "color appearance" in an actual environment as described below.

2. "Color Appearance" in Viewing Environment

"Color appearance" is determined by radius flux [W] in a visual light band directing to an observer, which is reflected and diffused by a sample after emitted from the light source. The radius flux includes two types of power of reflected light; one is reflected only by a sample which the observer catches directly, and the other is reflected by walls before reflected by the sample which the observer catches indirectly. This second type of light is called "the second illuminant". While the direct reflection by a sample includes only diffuse reflection, the indirect reflection from the second illuminant includes both diffuse reflection and specular reflection.

Figure1 shows a schematic diagram of diffuse reflection from the light source and diffuse/specular reflection from the second illuminant. Ld [W/sr/m^2] represents radiance of diffuse reflection which is reflected by the sample from various directions, while Ls [W/sr/m^2] represents radiance of specular reflection which is reflected by the sample from the part of a wall circled in red.

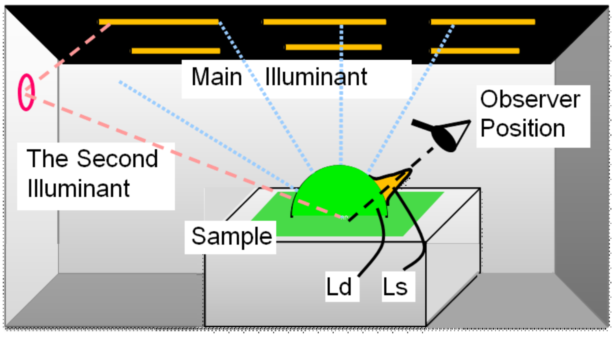

Fig.1 *Relationship between Brightness and "Color Appearance"*

Figure2 shows a schematic diagram of a measurement condition for a conventional 45/0 spectrometer. Conventional 45/0 spectrophotometers measure only diffused light.

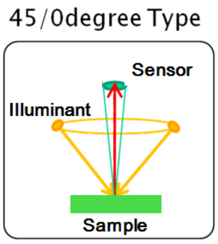

Fig.2 *Measurement Condition for Spectrophotometer*

As stated above, "color appearance" in a viewing environment and color value measured by a 45/0 spectrophotometer handle specular reflection differently. This is why "color appearance" does not always match color value measured by a 45/0 spectrophotometer. In general, saturation of Ld tends to be higher because it is influenced by a coloring layer of colorant. As a main component of Ls is specular reflection, however, saturation of Ls is lower and its hue is usually different from that of Ld.

Consequently, as Ls relates to muddiness while Ld to coloring, "color appearance" is influenced largely by Ls. In particular, dark areas tend to be influenced by Ls easily as Ld is lower in such areas. Therefore, "color appearance" does not always match color value measured by a 45/0 spectrophotometer which measures only diffuse reflection.

3. Problem of Using Current Method

Based on the above background, we made an experiment to verify the low correlation. In this experiment we calculated the coefficient of determination, denoted by R^2, between CIEL*, a*, b* value measured by a 45/0 spectrophotometer and results of the subjective evaluation experiment. We use Chroma, $C^* = (a^{*2} + b^{*2})^{1/2}$, as the index which indicates the correlation between these objective and subjective evaluation.

If R^2 between C* measured by a 45/0 spectrophotometer and vividness evaluated subjectively is nearly 1, we could say "color appearance" matches measured color value.

If R^2 is considerably less than 1, we could say "color appearance" doesn't match the measured color value.

In the subjective evaluation, we used a normalized-rank approach which focuses on vividness. Measurement conditions are indicated in Table 1.

Table 1 Subjective Evaluation

Experimental Approach	Normalized order test, Sort in vivid order 1st 2nd 4th 4th 4th 6th 7th
Subjects	9(Image designer)
Samples	7 Glossycolor samples, 5 Hues groups 1/2/3/4/5 (10cmx10cm size) Total 35samples
Environments	Env.1:WhiteWall 2:GrayWall 3:BlackWall

Fig. 3 shows one of the results: Hue 4 in Environment 1.

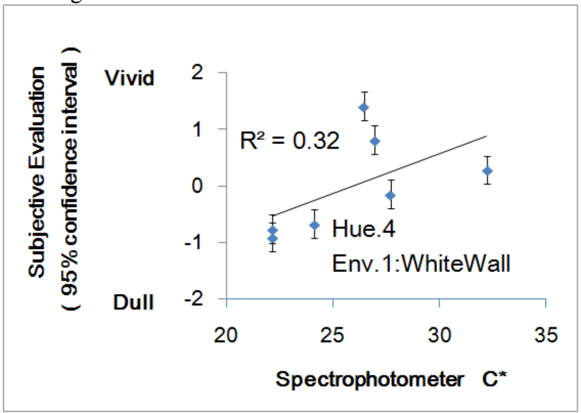

***Fig.3** Correlation between Spectrophotometer and Subjective Evaluation*

As shown in Fig.3, R^2 between C* measured by a 45/0 spectrophotometer and vividness evaluated subjectively was very low at 0.32. We made the same experiments with different 5 hues and got similar results.

4. Proposed Method (1)

Based on the above problem, we installed a spectroradiometer in an observation position and measured the sample for considering both of diffuse and specular reflection which were important for "color appearance". Fig.4 shows the measurement condition of this experiment.

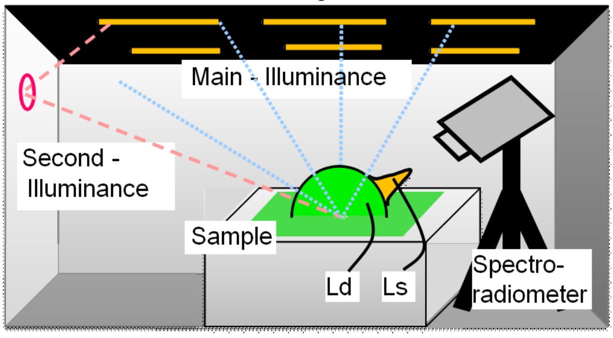

***Fig.4** How to Set Spectroradiometer*

We made an experiment to examine the correlation between this proposed method and "color appearance", likewise the above experiment described in "Section3. Problem of Using Current Method".

If R^2 between C* measured by a spectroradiometer and vividness evaluated subjectively is nearly 1, we could use them alternatively.

We made the experiment in representative 3 types of environments, which are consisted with 3 levels of wall brightness: white, gray, black. Wall brightness is a parameter which corresponds to brightness of the second illuminant. These three environments cover almost all of general photographic observation environments: Black Wall environment for dark art museums and Gray/White Wall environment for general offices and photo exhibits.

Therefore, if each correlation in these three environments is high, we can expect the proposed method is valid in various photographic observation environments.

The result of this experiment is shown in Fig.5.

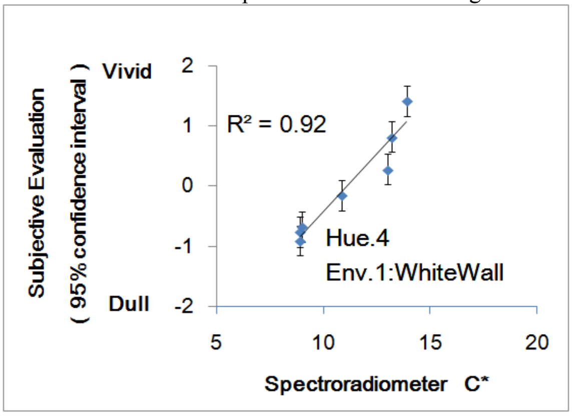

***Fig.5** Correlation between Spectroradiometer and Subjective Evaluation*

Fig.5 shows the result of applying the same condition as the experiment in "Section3. Problem of Using Current Method": Hue 4 in Environment 1: White Wall. R^2 was 0.92 by the proposed method, which is much higher than the result by the current method: $R^2 = 0.32$.

Then we examined the R^2 using other spectrophotometers to compare with the proposed method.

Fig.6 (1), (2), (3) shows the measurement conditions for the compared spectrophotometers. We chose the spectrophotometers in reference to the measurement conditions of standards [2].

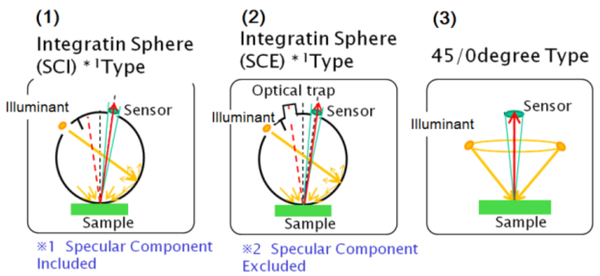

***Fig.6** Measurement Conditions of Spectrophotometers*

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Fig.7 shows the comparison between the results of using the spectroradiometer and using the spectrophotometers. Here, we calculated five values of R^2 using five different hues, and used their average as a representative value.

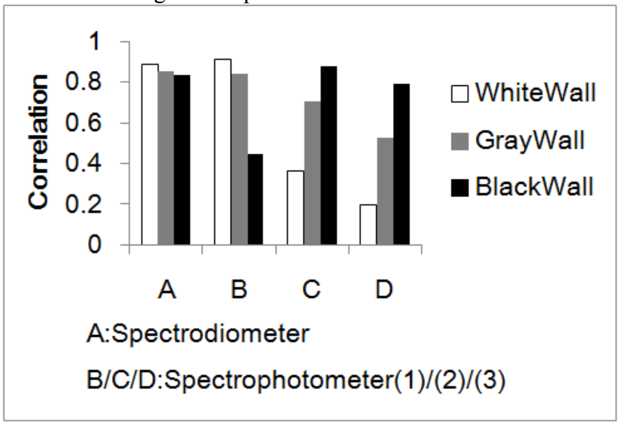

***Fig.7** Correlation of Subjective Evaluation with Spectroradiometer and Spectrophotometers*

Regardless of environments, the correlation using the spectroradiometer is high. However, when we used spectrophotometers, their correlations were different depending on environments.

From these experiments, we confirmed that the proposed method, installing a spectroradiometer in a viewing environment, was effective to evaluate "color appearance."

5. Application to the Products

We applied this new technology to our new professional printer series "imagePROGRAF PRO series"(Fig.8).

***Fig.8** imagePROGRAF PRO-1000*

In imagePROGRAF PRO series we optimized refractive indexes and extinction coefficients of image, which were determined by the surface and inner structure of ink dots. Practically we designed the ink formulation (LUCIA PRO ink) and used OIG System (Optimum Image Generating System) for the image processing method. By controlling both diffused and reflected light, these printers successfully expanded their color reproduction ability and realized high optical density in a viewing environment, which enabled real photo print.

Fig.9 shows color gamut volume of dark area (L* <= 40), which is important for photographic prints, measured by a spectroradiometer.

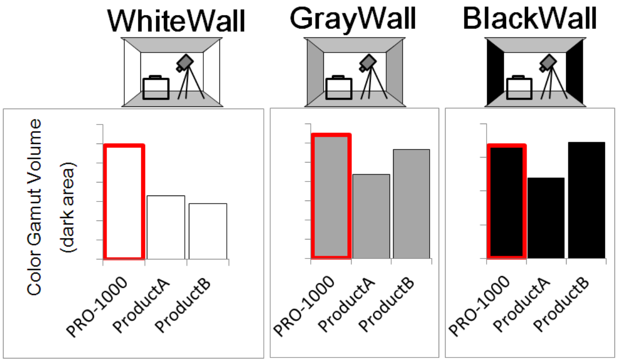

***Fig.9** Color Gamut Volume (L*<=40)*

Comparing to conventional products (Product A and Product B), we can confirm that imagePROGRAF PRO series(PRO-1000) realizes richer color reproduction in various viewing environments. In particular, this series expands color gamut reproduction in White Wall environment.

Fig.10 shows the comparison of whole color gamut in White Wall environment. Fig.10 (a) shows gamuts measured by a 45/0 spectrophotometer and Fig10 (b) shows gamuts measured by a spectroradiometer in the viewing environment, where wire indicates imagePROGRAF PRO series and solid indicates the conventional product B.

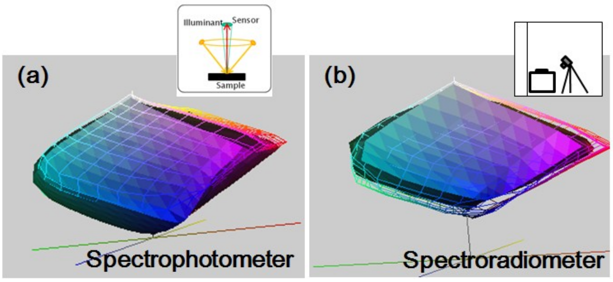

***Fig.10** Color Gamut of Spectrophotometer and Spectroradiometer*

Although imagePROGRAF PRO series has large color gamut volume in a viewing environment, we can't express "color appearance" using a 45/0 spectrophotometer. Using spectroradiometer (b), however, enables us to express "color appearance".

Furthermore, we constructed environments which simulated actual photographic observation environments such as photo museums and photo galleries, and then measured color gamut in each environment using a spectroradiometer.

Fig.11 shows the simulated environments and color gamut in each environment. Fig.11 (a) shows a room where white walls are lightened equally, while Fig.11 (b) shows a room where photographs are lightened mainly by spotlights. The pictures measured by the spectroradiometer are on the right wall. Fig.11 (c) and Fig.11 (d) show each color gamut measured by the spectroradiometer in Fig.11 (a) and Fig.11 (b). The wire indicates imagePROGRAF PRO series and the solid indicates conventional product B, likewise Fig.10.

In comparison with conventional product B, we can confirm that imagePROGRAF PRO series realizes richer color reproduction in various photographic observation environments.

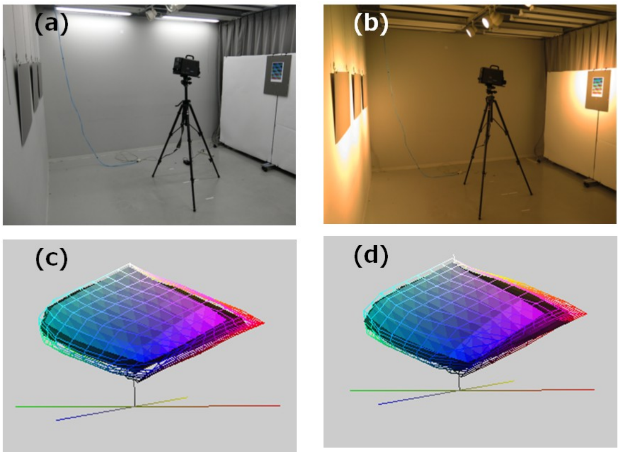

Fig.11 Color Gamut of Spectroradiometer in Simulated Photographic Observation Environments

6. Proposed Method (2)

So far, we have explained our new evaluation technique is effective in obtaining "color appearance" in viewing environments: installing a spectroradiometer in a viewing environment and evaluating light caught by an observer directly. Using this method, however, we always have to reconstruct viewing environments for each measurement. This method requires a heavy workload and is difficult to be reproduced. Therefore, this method still has problems for being used practically to quantify "color appearance", when we need to evaluate different viewing environments or samples.

In this study, we constructed a quantitative model linking "color appearance" for various viewing environments by independently measuring or setting distribution of the light source, position of the second illuminant that specularly reflects to the observation position and BRDF shape of the sample (Fig.12).The detail of its calculation is described in paper [1]. While only Y channel in CIEXYZ is used to obtain black optical density appearance in the previous work, XYZ channels are used to obtain L*a*b* for color appearance in this study.

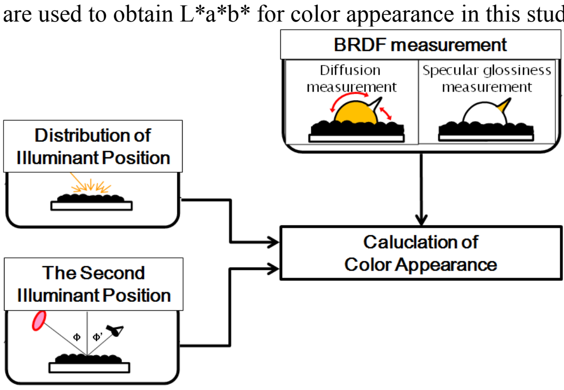

Fig.12 "Color Appearance" Model

Fig.13 shows the verification result of the model. We calculated R^2 between C* calculated by the proposed model (2) and C* measured by the spectroradiometer. For the above calculation, we actually use 2250patchs (125 color patches, which cover whole gamut, were printed by 6 printers and evaluated in 3 viewing environments.)"

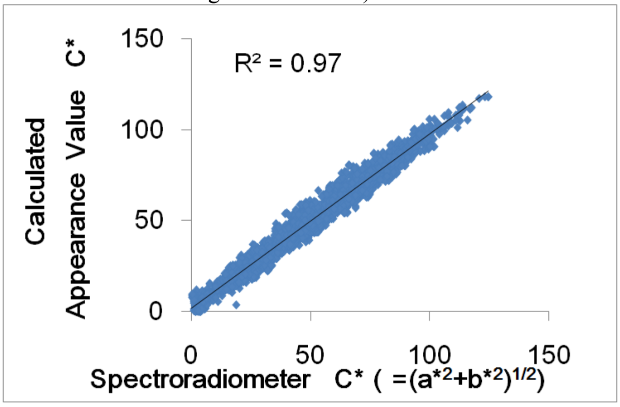

Fig.13 Correlation between Spectroradiometer and "Color Appearance" Model.

As the result was R^2=0.97, which indicates highly correlated, now we can say it is possible to substitute this model for the spectororadiometer. This also indicates that we can obtain "color appearance" in a viewing environment by the proposed model (2) as well as by the spectroradiometer.

From this verification, we found that we could evaluate "color appearance" in any viewing environments by constructing quantitative models with various conditions of the light source distributions and the second illuminant positions.

7. Conclusion

We proposed the quantification methods highly correlated to "color appearance", and applied the methods to our new printers. We keep on establishing user oriented products by applying this quantification method to designs of ink formulation and image processing. And we will contribute to development of the print culture through our products.

References

[1] Tomokazu Yanai, Takumi Kaneko, "A Report about the Quantification of Black Density "Appearance" in the Glossy Print Image", Imaging Conference JAPAN 2015 Fall Meeting,pg.81-84,(2015)

[2] JIS Z 8722 Methods of color measurement – Reflecting and transmitting object, Japanese Standards Association

Author Biography

Takumi Kaneko received his B.E. and M.E. degrees in Physics at the University of Waseda in Japan in 1995 and 1997 respectively. He joined Canon Inc. in 1997 and has been engaged in the development of inkjet printer.

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