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RESEARCH ARTICLE

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Investigation on new color depth formulas

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Abstract

Color depth is difficult to evaluate; however, it plays an important role in the assessments of color fastness, dyeing properties, and so on. The subjective evaluation of color depth is prone to be affected by people, environment, etc. As for objective evaluation, there are more than 10 formulas, which confuses the user. In this study, a theoretically designed new formula is inspected through 18195 chips with 24 grades of color depth from the SINO COLOR BOOK, with the help of four preferable objective evaluation formulas. The specimens were measured using an X-Rite Color i7 spectrophotometer, and all their depth values were calculated and statistically analyzed by programming MATLAB. Of the five formulas, the new formula yields the best outcome of variance coefficients (CVs) but the worst linearity, with a correlation coefficient $R = 0.976$. It was then theoretically revised to two other formulas, one obtains the highest linearity ($R = 0.9997$) and the third CV, and the other gains the second linearity ($R = 0.9984$) and the second CV among the seven formulas. Besides, the three new formulas are not as sensitive as the others to the changes of Hue and Chroma. In general, the new revised formulas show potential and need to be further evaluated.

KEYWORDS
color depth, dyestuff, equi-depth, formula, SINO COLOR BOOK

1 | INTRODUCTION

1.1 | Significance of color depth

The color depth of fabric is generally considered to have three major roles[1-3]: First, it determines the strength and the cost of dyestuffs. Second, it is the foundation of evaluating dyes' color fastness. Third, it is used to characterize and appraise the quality of the dyeing process adopted in the indexes of build-up, migration, etc. Based on previous studies, we believe that at least two more functions can be added to color depth. Fourth, it is very helpful for appraising the depth of colored fabric to improve the technology of dyestuffs, process, fibrous materials' dyeability, and so on. For example, some special dyes and fabrics, such as black dyes,[4] polyester fabrics,[5] silk fabrics,[6] and microfiber fabrics,[7] are not easy to be dyed deeply. In this case, the color depth index can be used to investigate the techniques for deepening the color. Fifth, it is also important for color recipe and computer color matching.

1.2 | Evaluation and formulas of color depth

There are some definitions for color depth. The American Association of Textile Chemists and Colorists[8] (AATCC) defines color depth as the departure of a colored object from white and is frequently associated with either the concentration or efficiency of a colorant. The International Standards Organization[9] (ISO) defines color depth as a color quality that is primarily associated with an increase in the quantity of colorant present, all other conditions (substrate, colorant[s], application method, and viewing conditions) remaining the same.

Then, how do we characterize and evaluate the color depth of dyed fabrics? Traditionally, people are accustomed to adopting a subjective evaluation, that is, judging the depth of color by visual estimation under standard geometric conditions according to observer's experience and Standard Depth Scales. As we all know, subjective evaluation may easily be affected by many factors. What is worse is that Standard Depth Scales are very rare nowadays.

Experts have conducted much research to develop objective evaluation equations. Since the 1950s, more than 10 formulas have been proposed. Among them, the most used or mentioned are listed chronologically as follows: Godlove formula,[10] Rabe-Koch formula,[11] Gall formula,[12] Taylor formula,[3] Kubelka-Munk formula,[13,14] Integ formula,[15,16] Kazushige Teraji formula,[17,18] ISO formula (Christ Formula),[19,20] Sato formula,[21,22] Hawkyard formula,[1,23] and WSI formula.[2,24] Besides, in Reference [25], Berns added more meaning and characters to CIE1976L*a*b* Color Space; among them, a color depth direction and index were also put forward. We use this index as the Berns Formula in this study, which in fact is not a formula intentionally established for evaluating color depth but happens to be great for this purpose.

Every formula has its advantages and disadvantages. When we needed a color depth index in our previous study, we were confused with different outcomes from different formulas and found that many people also misapply some formulas, especially the Kubelka-Munk formula due to its simple and convenient advantages. When we cannot clearly see through the formulas and do not know which formula should be chosen, we try to develop a new one. Fortunately, we did not find the Berns formula before our exploration; otherwise, we may have adopted this formula and would not have the chance to share our formula here. We are also very excited to find that color depth is still important and is considered by great color scientists like Prof. Berns.

Based on basic color theories and referring the Integ formula and others, we designed a color depth formula theoretically and reduced it to a surprisingly simple form as shown in Equation (1),[26] named the Yang formula for convenience of expression. For pure white, YCD = 0; for pure black, YCD = 100. The higher the YCD value of a color presents, the deeper it is.

$$\mathrm{YCD} = 100 \times \left(1 - \frac{X_{\mathrm{sp}} + Y_{\mathrm{sp}} + Z_{\mathrm{sp}}}{X_{\mathrm{w}} + Y_{\mathrm{w}} + Z_{\mathrm{w}}}\right) \tag{1}$$

where YCD is "Yang formula for color depth", which stands for the color depth calculated using the Yang formula; X_{sp}, Y_{sp}, Z_{sp} are the tristimulus values of the test sample; and X_{w}, Y_{w}, Z_{w} are the tristimulus values of pure white or ideal white.

In order to inspect the effect of the newly designed Yang formula, four preferable formulas are utilized in this investigation as references; they are Godlove formula, Rabe-Koch formula, Sato formula, and Berns formula, which are the best performers among the above 12 color depth formulas according to our previous study[27] and are given as follows:

1. Godlove formula

$$A = \left[16(10 - V)^2 + C^2\right]^{\frac{1}{2}} + 0.025 \times C \times \Delta H_{10\mathrm{PB}} \tag{2}$$

where A is abbreviation of "apparent strength" and represents the color depth calculated by the Godlove formula; C refers to Munsell Chroma of the color; V is its Munsell Value; and $\Delta H_{10\mathrm{PB}}$ is the least number of hue steps from 10 PB on the Munsell 100-step scale.[10]

2. Rabe-Koch formula

$$\theta = \frac{10 - 1.2D}{9} S + 1.06D \tag{3-1}$$

$$D = 10 - 6.1723 \times \lg\left(40.7 \frac{Y}{Y_0} + 1\right) \tag{3-2}$$

where θ is depth of shade; D and S are the darkness degree and saturation of DIN system; Y is the luminous reflectance of the surface color; and Y_0 is the maximum possible luminous reflectance at the same color point.[11]

3. Sato formula

$$D = \left(100 - L^*\right) + (0.1 + \Delta h_{290}/360) \times (1 - \Delta h_{290}/360) \times C^* \tag{4}$$

$$0 \le h \le 110^\circ, \quad \Delta h_{290} = h + 70^\circ$$

$$110^\circ \le h \le 290^\circ, \quad \Delta h_{290} = 290^\circ - h$$

$$290^\circ \le h, \quad \Delta h_{290} = h - 290^\circ$$

where D is the color depth; Δh_{290} is CIELAB metric hue-angle difference from h = 290°; and L^*, C^*, and h are the lightness, chroma, and hue angle of color in CIELAB, respectively.[21,22]

4. Berns formula

$$D_{ab} = \sqrt{\left(100 - L^*\right)^2 + (a^*)^2 + \left(b^*\right)^2} \tag{5}$$

where D_{ab} represents color depth; $L^*$is lightness of CIELAB ; and a^*, b^* are the rectangular coordinates of CIELAB.[25]

2 | EXPERIMENTAL

2.1 | Specimen

In this study, 18195 chips from the SINO COLOR BOOK (SCB) are taken as the specimens. SCB is a color book published in 1999 by Taiwan Textile Institute with Mr. Xu Yunpeng as the chief editor. Mr. Xu had more than 20 years of dyeing experience in factory at that time and had been conducting color research and application. His innovation "Color Check List to Display Color System" is patented[28,29] in China, the United States, the United Kingdom, Japan, Taiwan, and so on. SCB is a manifestation of his patent. The 18195 chips in SCB are pure polyester fabrics dyed with excellent light fastness and durability.

SCB's color solid is characterized by three dimensions of hue angle (*H*), chroma (*C*), and depth (*D*), as shown in Figure 1.

SCB's hue circle is based on the dye mixing principle, that is, yellow can be mixed with red to produce orange, red can be mixed with blue to produce purple, and blue and yellow can be mixed to produce green, thereby creating a perfect 360° hue circle of yellow, orange, red, purple, blue, and green as shown in Figure 1A. Hue angle is the angle of a color with yellow (0°).

Chroma is the visual perception of yellow, orange, red, purple, blue, and green. Depth is the sensation of the quantity of the color. The vertical axis (shown in Figure 1A) stands for the standard gray (SG) of different depths; and the top is ideal white with $D = 0$, and the bottom is ideal black with $D = 100$. The lower the position is, the deeper the chip is and the higher its *D* value is. Every cross section of its color solid or each hue plane in SCB has the same color depth, forming an equi-depth plane, and the farther the color chip from SG at the center, the higher chroma the chip has.

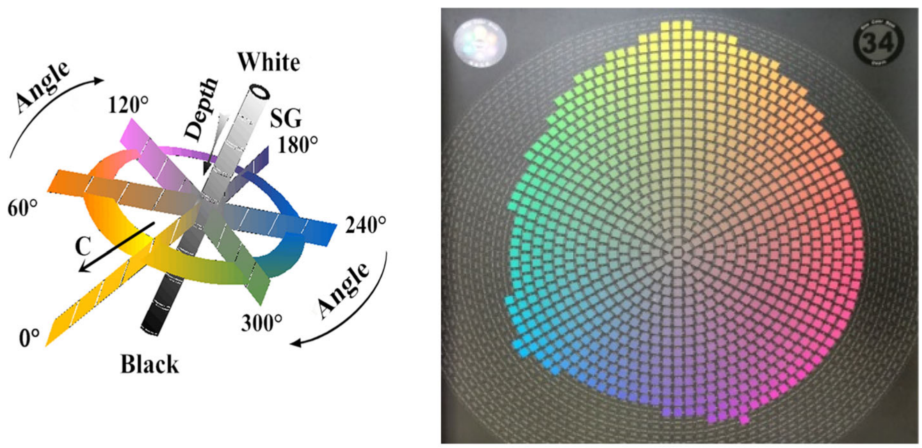
The SGs are uniformly distributed on the vertical axis according to their depths. In order to achieve the equi-depth on each hue sheet, the central SG determines the depth of all of the color chips on the hue sheet and is obtained by mixing together any three, or multiples of three, colors positioned at equidistance along the same hue circle. The distance between the central SG and any hue circle shall be equal at any hue angle. Hue circles of the same chroma also have the same value, and the distance between its hues must be uniform and identical in their visual perception.[29] Figure 1B displays a hue sheet with equi-depth, where all the chips on it have a depth of 34 ($D = 34$). The 18195 chips in SCB are arranged from D12 to D58 at two intervals, forming 24 grades of depth and constructing 24 equi-depth planes.

2.2 | Color measurement

An X-Rite Color i7 Spectrophotometer is used to measure all the 18195 chips in SCB. Each chip is measured three

TABLE 1 The conditions of color measuring

Measurement conditions	
Geometric condition	*d*/8°
Standard observer	10°
Lighting source	Pulsed xenon
Illuminant	D_{65}
Spectrum range	360-750 nm
Wavelength interval	10 nm
Aperture	6 mm
Environment	Room temperature



(A) A sketch of SCB's color solid (B) A picture of the hue sheet ($D = 34$) in SCB

FIGURE 1 SINO COLOR BOOK. A, A sketch of SCB's color solid. B, A picture of the hue sheet ($D = 34$) in SCB times with specular component included and then averaged. Other test conditions are listed in Table 1.

3 | RESULTS AND DISCUSSION

3.1 | Relationship of SCB's depth and Munsell-V

As we know, the Munsell Color System is widely accepted in the world as it was based on rigorous measurements of human subjective visual responses to color and on a firm experimental scientific basis. Munsell pursued "perceived equidistance" for his Munsell Color System, and even though it is not totally isovisual, it is still regarded as a relatively uniform system, especially the Munsell Values.

Therefore, we use the Munsell Value (abbreviated as Munsell-V) to check the perceived uniformity of SCB's depth (noted as SCB-D). SCB-Ds of the SGs and their Munsell-Vs were taken to draw a scatter diagram and then make a fitting. A linearity relationship between them is presented, with the correlation coefficient (R) being 0.9973, shown in Figure 2A, which means the depth grades of SCB are perceptually uniform. At the same time, it can be seen that the *D*s of the SGs higher than 50 are relatively not as ideal as the lower *D*s. Taking only the *D*s from D12 to D48 to fit a line, the result is depicted in Figure 2B, which gives a straight line with $R = 0.9994$. Hence, the equidistance of SCB depth is acceptable.

3.2 | Results of five formulas

All the 18195 chips in SCB are utilized to compute their color depths by the five formulas of Godlove, Rabe-Koch, Sato, Berns, and Yang separately. The results are exhibited in Figures 3 and 4, and Table 2.

3.3 | Discussion

Figure 3 shows the averages and the SDs (the error bars) of the color depths calculated by the five formulas. Obviously, all of them increase regularly and reasonably, with the increase in SCB-Ds. The Rabe-Koch formula seems to have excellent linearity, while the Yang formula seems more curved than the other four formulas, which are proved by the correlation coefficients (Rs) between them and the SCB-Ds.

Figure 4 displays the coefficients of variations (CVs) of the color depths of each equi-depth plane computed by the five formulas. Usually, the smaller the CV value is, the better the performance of the formula or the samples. From this

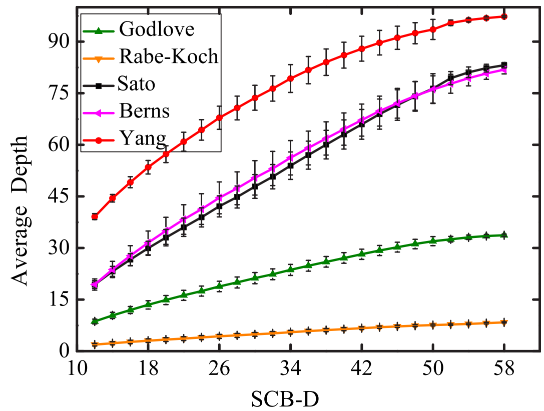


FIGURE 3 The depths of 24 equi-depth planes in SCB computed by five formulas. SCB, SINO COLOR BOOK

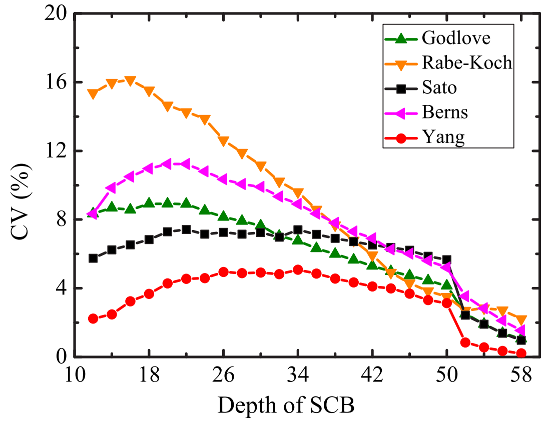
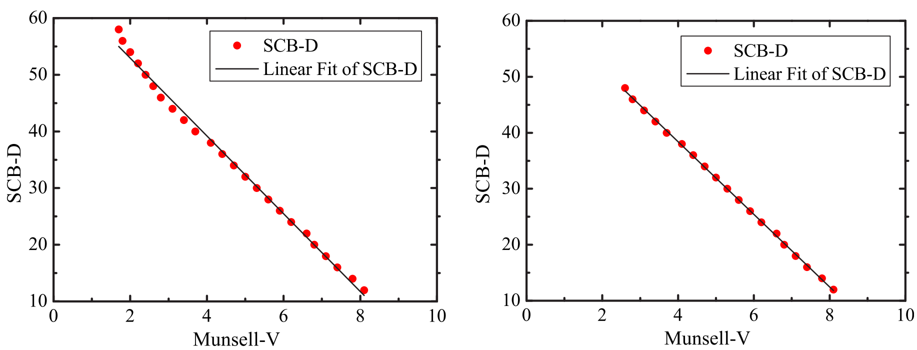


FIGURE 4 CVs of the depths of 24 equi-depth planes in SCB computed by five formulas. CVs, coefficients of variations; SCB, SINO COLOR BOOK



(A) From D12 to D58 (R=0.9973)

(B) From D12 to D48 (R=0.9994)

FIGURE 2 The relationship of SCB-D and Munsell-V basing on SG chips in SCB. A, From D12 to D58 ($R = 0.9973$). B, From D12 to D48 ($R = 0.9994$). SCB, SINO COLOR BOOK; SCB-D, SCB's depth; SG, standard gray

TABLE 2 The CVs of color depths of 24 equi-depth planes in SCB computed by five formulas (the number in parentheses after the CVs represents its rank number in the row)

SCB		Coefficients of variation (%)				
Depth	Amount	Godlove	Rabe-Koch	Sato	Berns	Yang
12	146	8.34 (3)	15.38 (5)	5.75 (2)	8.33 (4)	2.23 (1)
14	278	8.68 (3)	15.98 (5)	6.24 (2)	9.84 (4)	2.48 (1)
16	407	8.57 (3)	16.14 (5)	6.53 (2)	10.50 (4)	3.24 (1)
18	522	8.92 (3)	15.52 (5)	6.83 (2)	10.96 (4)	3.67 (1)
20	629	8.92 (3)	14.66 (5)	7.29 (2)	11.23 (4)	4.28 (1)
22	727	8.91 (3)	14.26 (5)	7.42 (2)	11.23 (4)	4.55 (1)
24	796	8.51 (3)	13.88 (5)	7.15 (2)	10.80 (4)	4.59 (1)
26	858	8.14 (3)	12.63 (5)	7.26 (2)	10.34 (4)	4.95 (1)
28	909	7.91 (3)	11.90 (5)	7.15 (2)	10.06 (4)	4.88 (1)
30	953	7.64 (3)	11.16 (5)	7.24 (2)	9.90 (4)	4.92 (1)
32	978	7.04 (3)	10.22 (5)	6.98 (2)	9.34 (4)	4.82 (1)
34	972	6.77 (2)	9.61 (5)	7.41 (3)	8.90 (4)	5.08 (1)
36	985	6.32 (2)	8.60 (5)	7.14 (3)	8.34 (4)	4.86 (1)
38	990	5.99 (2)	7.68 (5)	6.91 (3)	7.81 (4)	4.56 (1)
40	999	5.65 (2)	6.79 (4)	6.72 (3)	7.30 (5)	4.34 (1)
42	1000	5.30 (2)	5.93 (3)	6.52 (4)	6.90 (5)	4.11 (1)
44	999	4.98 (3)	4.92 (2)	6.38 (5)	6.26 (4)	3.99 (1)
46	991	4.74 (3)	4.30 (2)	6.21 (5)	6.02 (4)	3.69 (1)
48	975	4.45 (3)	3.84 (2)	5.86 (5)	5.60 (4)	3.31 (1)
50	958	4.14 (3)	3.51 (2)	5.66 (5)	5.21 (4)	3.14 (1)
52	632	2.52 (3)	2.70 (4)	2.43 (2)	3.54 (5)	0.84 (1)
54	582	1.92 (3)	2.84 (5)	1.91 (2)	2.83 (4)	0.56 (1)
56	498	1.38 (3)	2.73 (5)	1.38 (2)	2.12 (4)	0.35 (1)
58	411	1.06 (3)	2.22 (5)	0.97 (2)	1.55 (4)	0.21 (1)
Average	**758**	**6.12 (3)**	**9.06 (5)**	**5.89 (2)**	**7.70 (4)**	**3.49 (1)**

Abbreviations: CVs, coefficients of variations; SCB, SINO COLOR BOOK.

aspect, the Yang formula shows the best effect among the five formulas as it can provide a higher differentiation degree than the others. For a clearer demonstration, Table 2 further exhibits all the CVs and their ranks. Apparently, the Yang formula ranks first for every equi-depth plane of SCB. With respect to the Rabe-Koch formula, its CVs almost decline with the increase in D values, which is not expected for evaluation. The more uniform the CVs are, the better the formula or the samples. Referring the other four formulas curves, we derive that the tendency of the Rabe-Koch formula is not caused by the color samples but by its too-low values; for example, its highest depth for D58 is only 8.36.

Observing the curve of the Yang formula in Figure 3 attentively, you will find that it changes to as uniform as the other four, although it is curved, which indicates it indeed demonstrates some regulation of the change of color depth to some extent. Moreover, the Yang formula has the lowest CV, which means a high differentiation degree for different color depths. Therefore, we did not give up and tried to revise the curve to a straight line as higher linearity means better equidistant depth.

4 | EFFECT OF REVISED YANG FORMULA

We revised the Yang formula to increase its linearity. According to colorimetry theories: for ordinary color, the tristimulus X, Y, Z are not isovisual changes, so is not their sum $(X + Y + Z)$ as in Yang formula, but their cube roots are. Therefore, we tried to use square roots and cube roots of X, Y, Z to substitute the X, Y, Z in Equation (1) and then obtained Equation (6). For the convenience of expression, when $n = 2$, we mark the formula as Yang2, and for $n = 3$, we term the formula Yang3. The Yang formula (Equation 1) is a special form of Equation (6) when $n = 1$.

$$\mathrm{YCD}n = 100 \times \left(1 - \frac{\sqrt[n]{X_{\mathrm{sp}}} + \sqrt[n]{Y_{\mathrm{sp}}} + \sqrt[n]{Z_{\mathrm{sp}}}}{\sqrt[n]{X_{\mathrm{w}}} + \sqrt[n]{Y_{\mathrm{w}}} + \sqrt[n]{Z_{\mathrm{w}}}}\right), n = 1, 2, \text{or } 3 \tag{6}$$

Then, formulas Yang2 and Yang3 are used to calculate the depths of the 18195 chips in SCB as well, and the results are depicted in Figures 5 and 6, combined with the previous five formulas together.

As shown in Figure 5, it is clear that linearity of Yang2 and Yang3 improves. Coincidentally, the depths of Yang2 are very close to Sato's and Berns', and there is difficulty distinguishing the three curves. Figure 6 shows that the CVs of Yang2 and Yang3 are both higher than

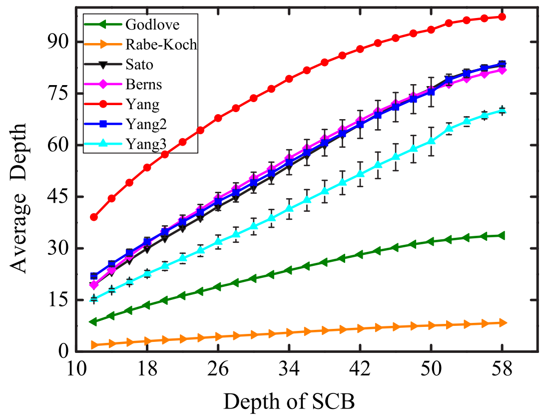


FIGURE 5 The depths of 24 equi-depth plane in SCB computed by seven formulas. SCB, SINO COLOR BOOK

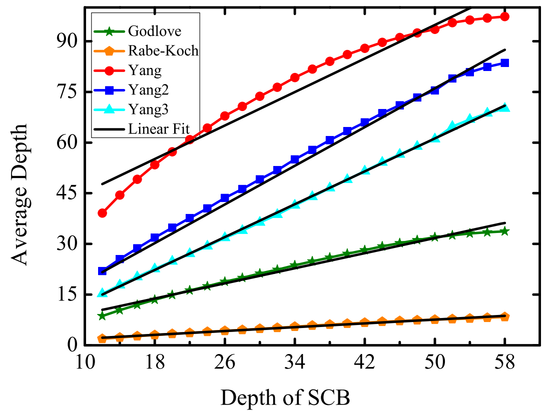


FIGURE 7 The linearity of five formulas (Godlove, Rabe-Koch, Yang, Yang2, Yang3) with the depths of SCB. SCB, SINO COLOR BOOK

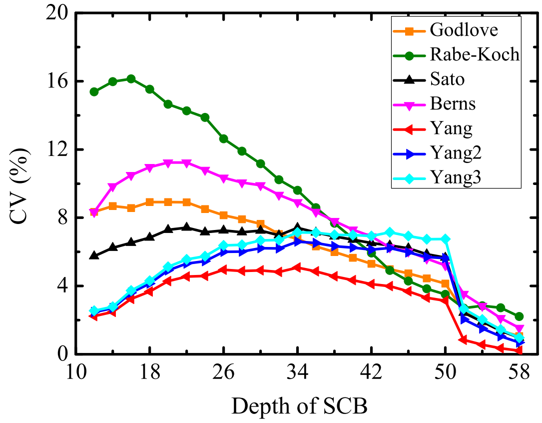


FIGURE 6 CVs of the depths of 24 equi-depth planes in SCB computed by seven formulas. CVs, coefficients of variations; SCB, SINO COLOR BOOK

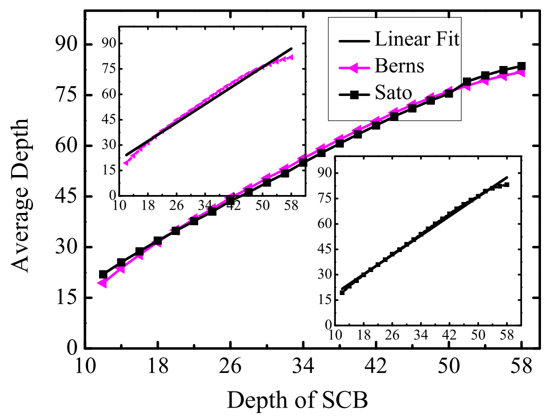
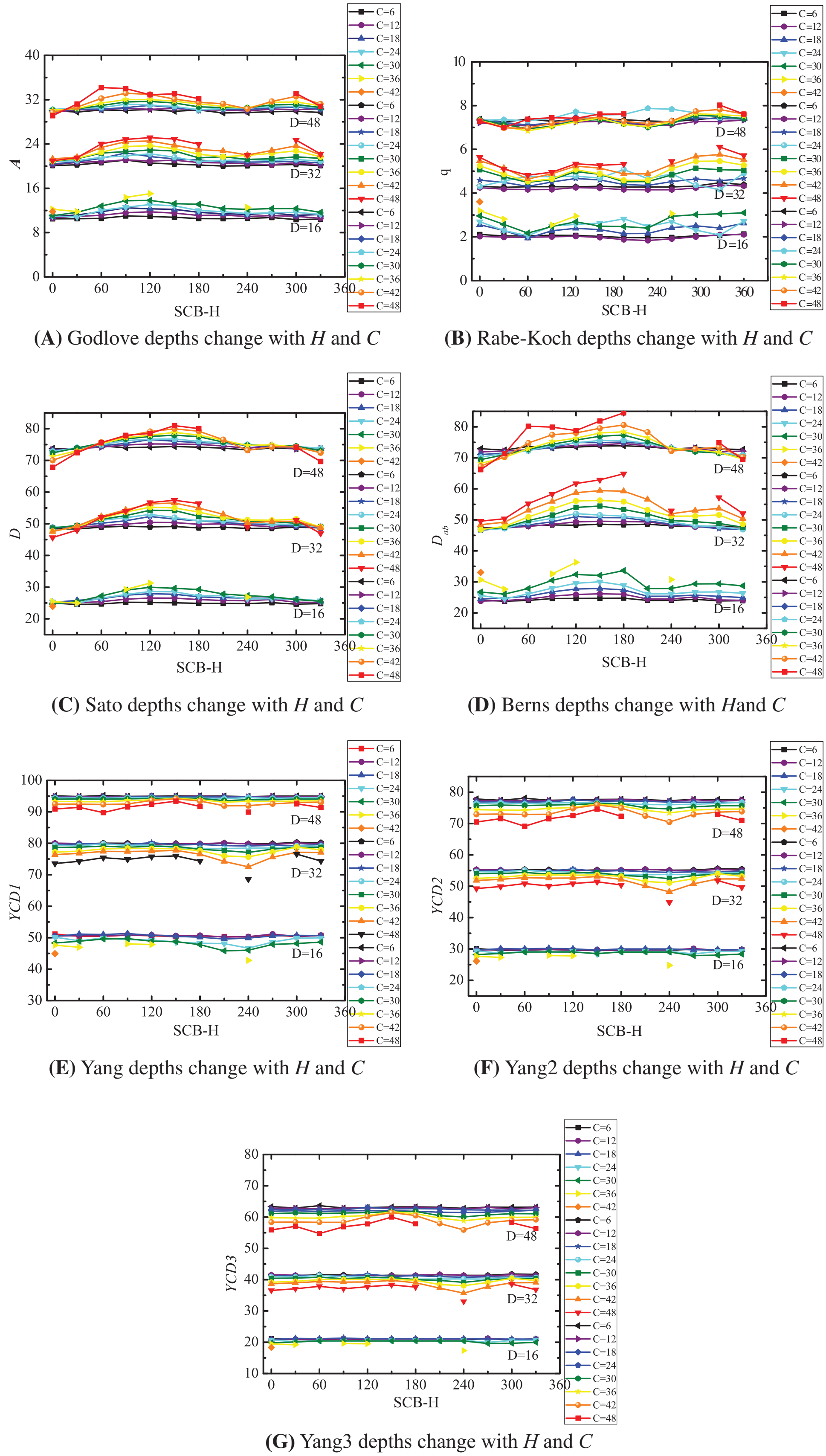


FIGURE 8 The linearity of two formulas (Berns, Sato) with the depths of SCB. SCB, SINO COLOR BOOK

TABLE 3 Ranking of the formulas of color depth according to their linearity and CV values

Formula	Godlove	Rabe-Koch	Sato	Berns	Yang	Yang2	Yang3
R	0.9921	0.9957	0.9976	0.9931	0.9757	0.9984	0.9997
Rank of *R*	6	4	3	5	7	2	1
Average CV (%)	6.12	9.06	5.89	7.70	3.49	4.74	5.24
Rank of average CV	5	7	4	6	1	2	3
Rank sum	11	11	7	11	8	4	4

Abbreviation: CVs, coefficients of variations.



(A) Godlove depths change with *H* and *C*

(B) Rabe-Koch depths change with *H* and *C*

(C) Sato depths change with *H* and *C*

(D) Berns depths change with *H*and *C*

(E) Yang depths change with *H* and *C*

(F) Yang2 depths change with *H* and *C*

(G) Yang3 depths change with *H* and *C*

FIGURE 9 Different depths change with SCB's hue angle and chroma. A, Godlove depths change with *H* and *C*. B, Rabe-Koch depths change with *H* and *C*. C, Sato depths change with *H* and *C*. D, Berns depths change with *H* and *C*. E, Yang depths change with *H* and *C*. F, Yang2 depths change with *H* and *C*. G, Yang3 depths change with *H* and *C*. SCB, SINO COLOR BOOK

Yang's but not higher than the others. In order to assess Yang2 and Yang3 quantitatively, the correlation coefficients (*R*s) of the seven formulas with the SCB-Ds are computed, and the *R*s and the averages of CVs are ranked and then rank summed. All the results are displayed in Table 3.

In Table 3, all the formulas present a higher *R* than 0.97, and these have a very high correlation. The Yang3 formula has the highest *R* (0.9997), showing excellent linearity, and its CV value of 5.24% ranks the third, showing better differentiation ability. The Yang2 formula occupies the second on both *R* and CV averages. While the Yang formula has the lowest linearity and the best CV values, Yang2 and Yang3 together share the best rank sum (the smallest rank sum 4). These indicate that both Yang2 and Yang3 are successful revisions of the Yang formula.

It is now hard to make a choice between Yang2 and Yang3. To yield a more intuitive expression, Figures 7 and 8 depict the curves with the fitted straight lines of the seven formulas. As Yang2's, Sato's, and Berns' color depths are too close, Yang2's results are retained in Figure 7 for comparison with Yang3, Sato's, and Berns' results, shown in Figure 8 separately. From Figure 7, it is obvious that Yang3 is very straight, while Yang2 is slightly curved. In fact, except the Yang3 and Rabe-Koch formulas, all the others are curved to some degree and deviate a little from the straight in the very light and deep areas (the lowest and highest SCB-Ds areas).

Overall, Yang2's mean depth values are similar to Sato's and Berns', and its *R* and CV values are both a little bit better than the four previous formulas; maybe Yang2 is a better choice for balancing the linearity and differentiation ability. While Yang3 is very attractive with regard to linearity, its CVs are also better than those of the other four, although it is just slightly better.

For further comparison, the different depths calculated by the seven formulas are drawn against SCB's hue angle and chroma from three depths of D16, D32, and D48, shown in Figure 9. It can be seen that, relatively, the formulas of Godlove, Sato, Berns, and Rabe-Koch are more sensitive to hue angle and chroma than the three newly designed formulas; the Rabe-Koch and Yang formulas are not uniformly changed with D16, D32, and D48. The Yang2 and Yang3 formulas exhibit relatively more uniform changes along SCB hue angles, chroma, and depth. From for this espect, the revised formulas are still not bad.

Please note that the above results are based on the assumption that the chips on the SCB's equi-depth plane are the same as the human color depth sensation. As SCB has not been authorized as a color depth standard, the degree of coincidence between the SCB-D and each color depth formula does not mean the "better or worse" of the formulas, which is just an inspection for the newly theoretically designed formulas. Factually, every formula has its own properties and serviceability. Due to the limitation of the space, we will not discuss these factors in depth in this paper.

Besides, because the Godlove, Rabe-Koch, and Sato formulas are statistically deduced from physical color samples, their formulas may coincide more with their original samples as judged by experts. Even the Berns formula is also coincide more with its original data, although it is based on CIE's L^*, a^* and b^*, which indeed came from experienced equations of expert statistics between the *XYZ* values and Munsell's *HVC* values. The Sato (from Japan) formula and the three Yang formulas perform better in this study perhaps because the color chips in SCB are produced and checked by Asian experts. We admit that people from different continents have some differences on their eyes, such as the color difference of the iris, why the different of eyes could not affect what we see?

Anyway, because of the SCB's 18195 color chips, the theoretically designed Yang formula has been proved to be adequate, and its revised forms, Yang2 and Yang3, seem to have some potential for assessing color depth. There is no doubt that these new developed formulas need further inspection, and we will conduct more investigations on them.

5 | CONCLUSIONS

A theoretically designed Yang formula is inspected by applying 18195 chips at 24 grades of color depth from a SINO COLOR BOOK along with four main color depth formulas, and then, it is revised based on colorimetry theories, further deriving two other formulas, namely, Yang2 and Yang3. Among the seven formulas, Yang 2 shares the second linearity to SCB-D with R = 0.9983 and the second differentiation degree with average CV = 4.74%; Yang 3 presents the highest linearity with R = 0.9997 and the third CV 5.24%. Compared to Yang's lowest linearity (R = 0.9757) and smallest CV value (average 3.49%), Yang2 and Yang3 can be regarded as successful revisions. In addition, three Yang formulas are not so sensitive to SCB's hue angle and chroma as the other four formulas. As a whole, Yang2 and Yang3 show almost the same potential for color depth characterization and will be further inspected, even though Yang3 is theoretically more reasonable.

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