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The foundation of a color-chip evaluation system of jadeite-jade green with color difference control of medical device

Ying Guo[1] · Huan Wang[2,1] · Hongmei Du[3]

Abstract Based on the uniform color space International Commission on Illumination (CIE) 1976 L*a*b*, the color green of 728 pieces of jadeite-jade was quantitatively characterized by the spectrophotometer Color i5. The color-chip system of jadeite-jade green with color difference control was then researched. First, with the help of the basic color difference formula, the concentrated plot areas of $L^* \in (35, 55)$, $a^* \in (-30, -45)$, and $b^* \in (0, 35)$ of jadeite-jade color green were taken as the color center, which was in accordance with the CIE standard green ($L^* = 56$, $a^* = -32$, $b^* = 0$) and high chroma green ($L^* = 56$, $a^* = -45$, $b^* = 0$). Second, the total plot areas of $h0 \in (125.21°, 171.10°)$ and $L^* \in (5, 95)$ of jadeite-jade color green were considered as color gamut, which was in accordance with the scope from CIE standard yellowish green to bluish green. In consideration of the color green plot areas of jadeite-jade and China National Standard GB/T 23885–2009 "Jadeite-Jade Grading", $\Delta L^* = 5$, $\Delta a^* = 10$, and $\Delta b^* = 10$ were calculated to form a color-chip system of jadeite-jade color green with $\Delta E^* = 15$ from one chip to another, and 521 chips were then achieved. Color chips were reduced or added for sparse or intense plot points. As a result, the color-chip system was condensed into 126 chips based on lightness and then merged into 19 areas with $\Delta L^* = 5$. With cluster analysis, 126 chips were graded into nine levels. The commercial evaluation of jadeite-jade color green showed that these levels were sequenced from the top quality fancy vivid green to the last faint green. One-way ANOVA verified the reasonability of the nine levels. Fisher discriminant analysis demonstrated that very high accuracy of 99.21 % was achieved, and only one group from 126 groups was misjudged. Thus, based on the statistical analysis of color parameters in the uniform color space, the color-chip evaluation system of jadeite-jade green with color difference control could be used with high accuracy.

✉ Ying Guo
guoyingsci@126.com

[1]   School of Gemology, China University of Geosciences, Beijing 100083, China

[2]   Beijing City of Arts and Crafts Senior Technical School, Beijing 102200, China

[3]   Guangzhou Huadu Bureau of Quality and Technical Supervision, Guangzhou 510800, China

1 Introduction

Jadeite-jade is considered the king of jades, and a tiny color difference can cause an enormous
change in its value; thus, the evaluation of jadeite-jade mainly focuses on the color green quality
[6, 24]. The China National Standard GB/T 23885–2009 "Jadeite-Jade Grading," which was
published in 2009 and used from 2010, provides a definite standard of jadeite-jade color green
grading, but some deficiencies in practice have still been reported. The color matching method is
used to evaluate grade color, particularly in several industries of printing, textile, and construction;
and some color cards are used in jewelry, such as Gem Set and Gem Dialogue [12, 19, 20].
However, these two jewelry color matching systems of green jadeite-jade color evaluation have
certain defects. The shape of Gem Set color cards is simple round, which is similar to round
brilliant cut facet stones but completely different from the shape of cabochon stones. Moreover,
the shape of Gem Set color cards cannot reveal the tiny color difference in good quality green of
jadeite-jade. Given the plastic cards, the luster of Gem Dialogue cannot match the luster of most
gemstones, such as jadeite-jade. Furthermore, the matching results from Gem Dialogue cannot be
compared quantitatively with any other popular color system, such as the Munsell color matching
system and International Commission on Illumination (CIE) 1976 L*a*b* uniform color system.
In addition, the multiformity of matching results is its Achilles' heel. These two color card systems
of gemstone evaluation lack practicality and pertinence. Therefore, scientific, rational, objective,
practical, and specialized green color quality evaluating and grading systems are urgently needed.

2 Samples and experiments

A total of 728 pieces polished cabochon jadeite-jade with smooth surface, fine texture, and
high purity were selected as samples. All these gemstones were from 6 mm × 7 mm × 5 mm to
10 mm × 12 mm × 8 mm, which were below the upper limit of China National Standard
(50 mm × 30 mm × 50 mm), and they displayed an even color ranging from bluish green to
vivid green to yellowish green, with continuous changes in color shade and depth.

Based on the uniform color space of CIE 1976 L*a*b*, spectrophotometer Color i5 was
used to collect reflective signals from the jadeite-jade surface via the integrating sphere. Test
conditions were as follows: specular component excluded, light source of D_{65} [4, 18, 21],
spectral range of 360–750 nm, measurement time < 2.5 s (flash and data acquisition), wave-
length interval of 10 nm, voltage of 240 V, and current of 50–60HZ.

3 Results

3.1 Quantitative analysis of color green

All 728 pieces of jadeite-jade color green were plotted in the uniform color space CIE
1976 L*a*b* [23,25]. Most of the jadeite-jade color was concentrated in the area of yellowish
green with medium-low lightness, and no blue tone.

3.2 Color-chip system

3.2.1 Color center of color-chip system

Jadeite-jade color green was concentrated in the areas of L*∈(35, 55), a*∈(−50, −10), b*∈(5, 35) in the uniform color space. Considering the CIE recommended standard green (L* = 56, a* = −32, b* = 0) and high chroma green (L* = 56, a* = −45, b* = 0), the concentrated plot areas L*∈(35, 55), a*∈(−30, −45), and b*∈(0, 35) of jadeite-jade color green were the color center, which was in accordance with the CIE standard green (L* = 56, a* = −32, b* = 0) and high chroma green (L* = 56, a* = −45, b* = 0), as shown in Fig. 1.

3.2.2 Color gamut of color-chip system

First, the color tone was scoped into the area from the CIE recommended standard yellowish green (h0 = 127.57) to bluish green (h0 = 214.51). Second, the lightness was scoped into the area of L*∈(5, 95), which excluded the white end (L* = 100) and black end (L* = 0) of lightness as shown in Fig. 2. According to the 728 pieces of color green plots and China National Standard GB/T 23885–2009 "Jadeite-Jade Grading," it was condensed into a narrow color gamut h0∈(125.21°, 171.10°) and subdivided into three color tone areas, namely, green, green (yellow), and green (blue).

3.2.3 Color difference in color-chip system

To accurately and rapidly evaluate the color green of jadeite-jade, the basic color difference formula $\Delta E_{ab}^* = [(\Delta L^*)2 + (\Delta a^*)2 + (\Delta b^*)2]^{1/2}$ was used in the uniform color space CIE 1976 L*a*b*. Considering that the human eye can distinguish the color tolerance range, the color difference from one piece of color chip to another adjacent one was confirmed as $\Delta E_{ab}^* \geq 15$, which is human visual perception that can easily distinguish the difference between every two pieces of color chips [11, 22].

To establish a uniform chromatic color-chip system, considering the relatively independent lightness scale and simplified calculation, $\Delta E^* = 15$ is recommended. Subsequently, 3D coordinates of uniform color space $\Delta L^* = 5$, $\Delta a^* = 10$, and $\Delta b^* = 10$ should be considered. The 3D uniform color space, which was centered as

Fig. 1 Color green plots of jadeite-jade in the uniform color space CIE 1976 L*a*b* L*∈(5.64, 64.17), h0∈(125.21°, 171.10°), C*∈(10.53, 85.89), a*∈(−69.87, −6.17), b*∈(1.63, 49.94)
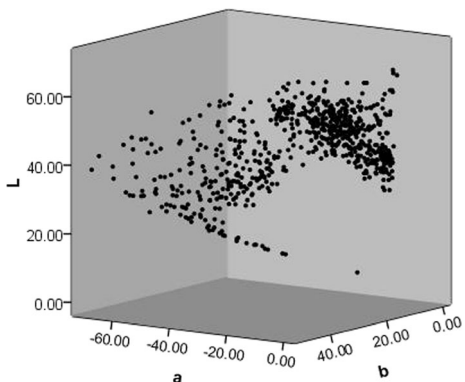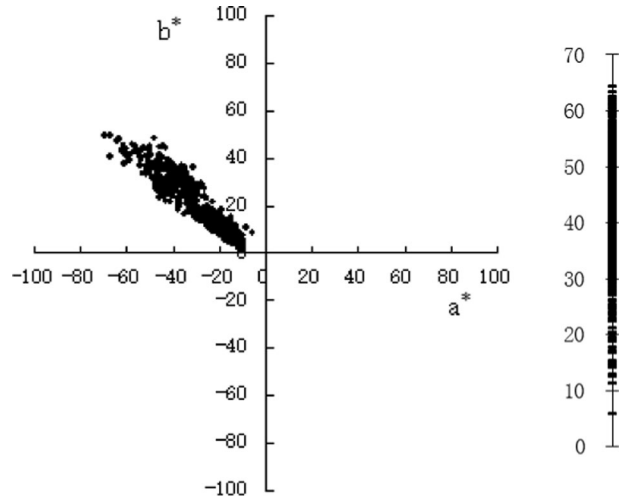
Fig. 2 Chromaticity and lightness plots of jadeite-jade's green in the uniform color space CIE 1976 L*a*b*

green, was segmented into 15 units for color tolerance to form a continuous module. The color of each regional center of 15 units was based on the average color of its unit, resulting in the color of the color chip.

The color-chip system was divided into 19 green regions from $L^* = 5$ to $L^* = 95$ as $\Delta L^* = 5$, and subdivided into 521 green regions as $\Delta a^* = 10$ and $\Delta b^* = 10$. Each region represented one color chip, and the results are shown in Table 1.

3.3 Simplified color-chip system

Combined with the theory of color system and the tested values of jadeite-jade green, 728 pieces of samples were classified into 19 regions, which were divided by lightness from $\Delta L^* = 5$, as shown in Fig. 3.

Furthermore, each lightness region was plotted with chromaticity coordinates.

Table 1 Nineteen regions of color-chip system classified by $\Delta L^* = 5$, $\Delta a^* = 10$, and $\Delta b^* = 10$ from $L^* \in (5, 95)$

L^*	Pieces	L^*	Pieces
5	1	55	63
10	3	60	49
15	6	65	37
20	13	70	28
25	20	75	20
30	28	80	13
35	37	85	6
40	49	90	3
45	63	95	1
50	81	—	—

521 Pieces
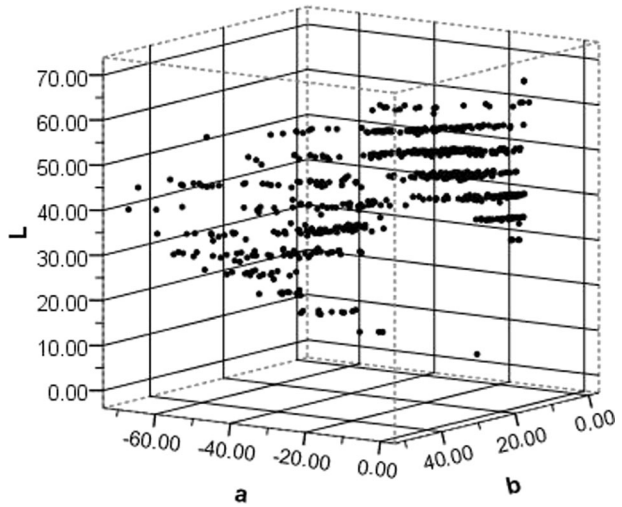
Most color chips of jadeite-jade color green were plotted into six areas of $L^* = 30$, $L^* = 35$, $L^* = 40$, $L^* = 45$, $L^* = 50$, and $L^* = 55$. The results revealed that the green of jadeite-jade had medium lightness and low to medium chroma in each lightness region. The results are shown in Fig. 4.

The experimental data revealed that further improvement of the theoretical system should be executed. Color chips were reduced or added for sparse or intense plot areas to simplify the color-chip system, as shown in Fig. 5.

First, areas covered by green were selected, and 122 pieces of color chips were received (Fig. 6). Second, the jadeite-jade green plot areas of $L^* = 70$, $L^* = 75$, $L^* = 80$, $L^* = 85$, $L^* = 90$, and $L^* = 95$ were incorporated equidifferently into three areas of $L^* = 75$, $L^* = 85$, and $L^* = 95$. Given that the chroma of high lightness of $L^* = 95$ was too low to color white, the other two regions of $L^* = 75$ and $L^* = 85$ were reserved. Finally, in these two regions, color chips were received from equidifferent calculations of four areas with chromatic coordinates of (85, −20, 10), (75, −40, 20), (75, −20, 30), and (75, −20, 10). A total of 126 pieces of color chips were achieved.

Fig. 4 Chromaticity plots of jadeite-jade (L* = 35)
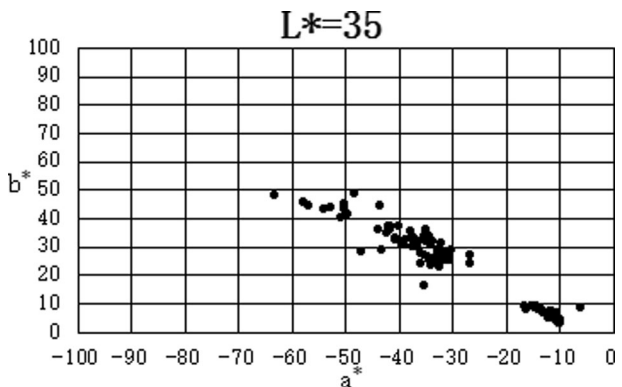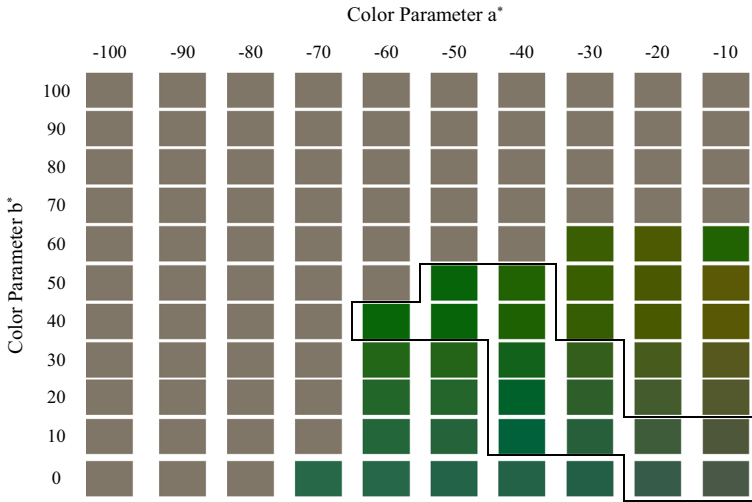
Fig. 5 Chromatic plots of jadeite-jade color green in the lightness region of L* = 35

3.4 Quality evaluation of jadeite-jade color-chip system

3.4.1 Color chips classified by cluster analysis

The quality evaluation of jadeite-jade color green classifies similar color appearances into the same category with the same value, and grades these categories from top quality to the end. Clustering analysis in statistics is an exploratory analysis; it can classify jadeite-jade color green from the color characteristics, even with existing classification criteria [1,9]. Clustering analysis can classify color automatically and rapidly according to the color. Therefore, fast clustering analysis was adopted because numerous jadeite-jade samples were measured and

Fig. 6 Fifteen color chips of jadeite-jade in the lightness region of L*=35, which are selected from 39 plot areas

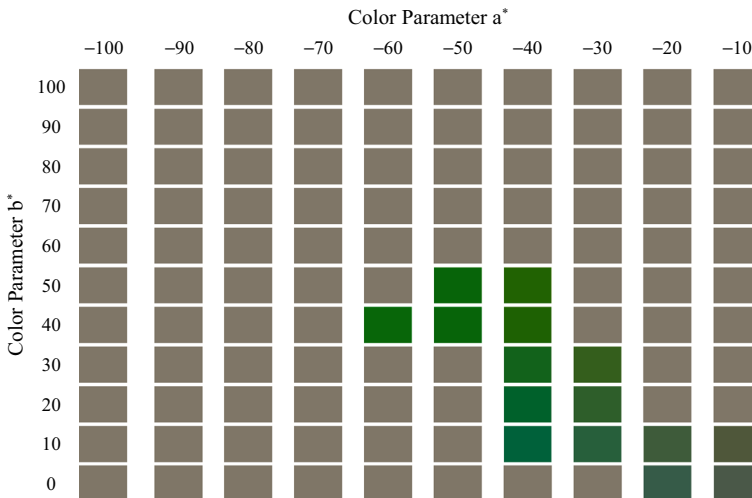calculated. The international quality evaluation system of monochromatic gemstones, such as fancy color diamond and sapphire [3,10], states that 126 color chips of jadeite-jade color green can be graded into nine levels based on sample's L^* and C^*.

However, these 126 color chips could not cover all the color green of jadeite-jade, and grading all colors from color parameters using clustering analysis is impossible. Discriminant analysis can be considered to grade color quality, particularly those colors not studied by cluster analysis. Compared with cluster analysis, discriminant analysis can classify those colors with unknown quality levels using only a certain index.

In the uniform color space CIE 1976 $L^*a^*b^*$, and with the help of software SPSS16.0, K-Means cluster analysis was used to grade color green into nine levels from 126 color chips [10]. The results of one-way ANOVA are shown in Table 2.

For the chromatic coordinates of L^*, a^*, and b^*, each p was lower than 0.01, which revealed that these nine levels were significantly different from one another. Furthermore, the results indicated that K-Means cluster analysis was a reasonable and successful method that yielded perfect results. The results are shown in Table 3.

3.4.2 Quality evaluation of nine levels of color chips

The computer simulating colors according to the results of clustering analysis are listed in Table 5. The highest quality green of jadeite-jade was graded in level 4, which is named "Fancy Vivid Green" because of its medium lightness and large chroma, showing the best visual appearance. When a^* and b^* decreased, the chroma fell correspondingly, so the colors were graded into the next level, namely, level 5, which is named "Fancy Intense Green." With the continuous reduction in L^*, a^*, and b^*, the next level following level 5 was level 3, which is named "Fancy Green." The last level was level 8, with the worst color compared with other levels, and it is named "Faint Green."

Considering both jadeite-jade color quality and its value, the nine levels should be sequenced from the best to worst with decreasing quality. The results are shown in Table 5.

3.4.3 Prediction by fisher linear discriminant

The Fisher linear discriminant model can predict color in the color-chip system, determine the quality of unknown categories of color green, and assess the accuracy of the existing classification results [2,26]. Using SPSS16.0, Fisher linear discriminant analysis was used to discriminate nine levels of jadeite-jade quality, which were graded by cluster analysis. The results are shown in Table 4.

Table 2 ANOVA of nine levels of jadeite-jade color green

	Cluster		Errors		F	P
	Square Mean	Df	Square Mean	df		
L^*	2769.801	8	39.870	117	69.471	0.00[**]
a^*	3912.224	8	41.445	117	94.396	0.00[**]
b^*	2426.090	8	45.164	117	53.718	0.00[**]

significance level is 0.01

Table 3 Function coefficient of Fisher linear discriminant analysis of nine jadeite-jade color quality levels

	Clu-1	Clu-2	Clu-3	Clu-4	Clu-5	Clu-6	Clu-7	Clu-8	Clu-9
L^*	1.981	0.108	0.426	0.933	0.912	1.385	0.970	0.975	1.268
a^*	−0.522	−0.341	−0.923	−1.424	−0.989	−0.331	−0.771	−0.300	−0.874
b^*	0.281	0.188	0.473	0.760	0.750	0.113	0.297	0.138	0.423
Constants	−85.503	−5.967	−31.006	−81.490	−56.733	−43.928	−37.466	−24.127	−57.632

Both coefficient and constant terms of Fisher linear discriminant function of nine levels are listed in Table 4. Nine discriminant functions were then calculated as follows:

$$F_1 = 1.981L^* - 0.522a^* + 0.281b^* - 85.503$$
$$F_2 = 0.108L^* - 0.341a^* + 0.188b^* - 5.967$$
$$F_3 = 0.426L^* - 0.923a^* + 0.473b^* - 31.006$$
$$F_4 = 0.933L^* - 1.424a^* + 0.760b^* - 81.490$$
$$F_5 = 0.912L^* - 0.989a^* + 0.750b^* - 56.733$$
$$F_6 = 1.385L^* - 0.331a^* + 0.113b^* - 43.928$$
$$F_7 = 0.970L^* - 0.771a^* + 0.297b^* - 37.466$$
$$F_8 = 0.975L^* - 0.300a^* + 0.138b^* - 24.127$$
$$F_9 = 1.286L^* - 0.874a^* + 0.423b^* - 57.632$$

When color chips were classified, all color values of L^*, a^*, b^* were taken into the above nine functions. Their function values were then compared, and the biggest one revealed its attribution. The verified discrimination results of 126 color chips of jadeite-jade color green are shown in Table 5.

The diagonal line from the upper-left to the bottom-right shows the correct prediction of the number. The remaining is error prediction. From all 126 color chips, only one group was wrong. The total accuracy was as high as 99.21 %, reaching the goal of ideal prediction accuracy. The only wrong predicted color resulted from class 5, which had discriminant analysis values of $F_5 = 23.654$ and $F_7 = 23.674$. Thus, the color was located at the boundary of these two areas, resulting in wrong prediction.

Table 4 Verified results of discriminant analysis

		Prediction cluster members									Sum.
		1	2	3	4	5	6	7	8	9	
Initial members of 9 categories	1	4	0	0	0	0	0	0	0	0	4
	2	0	2	0	0	0	0	0	0	0	2
	3	0	0	15	0	0	0	1	0	0	16
	4	0	0	0	16	0	0	0	0	0	16
	5	0	0	0	0	22	0	0	0	0	22
	6	0	0	0	2	0	19	0	0	0	19
	7	0	0	0	0	0	0	14	0	0	14
	8	0	0	0	0	0	0	0	17	0	17
	9	0	0	0	0	0	0	0	0	16	16

A total of 125 pieces of jadeite-jade color green are predicted correctly

Table 5 K-Means cluster analysis and quality evaluation of color chips of jadeite-jade color green

	Level	Color	Abb.	Quality		Cluster Center	Simulation color
				L*	C*		
Clu-1 (N=4)	No. 7	Light	L	Hi.	Lo.	L*=77.50 a*=−25.00 b*=17.50	
Clu-2 (N=2)	No. 5	Fancy Dark	FDa	Lo.	Lo.	L*=5.00 a*=−15.00 b*=10.00	
Clu-3 (N=16)	No. 3	Fancy	Fy	Me.	Me.	L*=18.75 a*=−40.62 b*=25.62	
Clu-4 (N=16)	No. 1	Fancy Vivid	FV	Me.	Hi.	L*=40.00 a*=−63.12 b*=41.25	
Clu-5 (N=22)	No. 2	Fancy Intense	FI	Me.	Hi.	L*=38.64 a*=−45.00 b*=39.09	
Clu-6 (N=19)	No. 8	Very Light	VL	Hi.	Lo.	L*=55.79 a*=−15.79 b*=8.42	
Clu-7 (N=14)	No. 4	Fancy Deep	FDe	Lo.	Me.	L*=40.00 a*=−34.29 b*=17.86	
Clu-8 (N=17)	No. 9	Faint	Ft	Hi.	Lo.	L*=39.41 a*=−14.12 b*=8.82	
Clu-9 (N=16)	No. 5	Fancy Light	FL	Hi.	Lo.	L*=52.19 a*=−39.38 b*=24.38	

Lo. means Low, Me. means medium, Hi. means high

4 Conclusion

1. Based on the uniform color space CIE 1976 $L^*a^*b^*$, the color-chip system of jadeite-jade green with color difference control was formed.

   a. The concentrated plot areas of $L^* \in (35, 55)$, $a^* \in (-30, -45)$, and $b^* \in (0, 35)$ of jadeite-jade color green were taken as the color center, which was in accordance with the CIE standard green ($L^* = 56$, $a^* = -32$, $b^* = 0$) and high chroma green ($L^* = 56$, $a^* = -45$, $b^* = 0$);

   b. The total plot areas of $h_0 \in (125.21°, 171.10°)$ and $L^* \in (5.64, 64.17)$ of jadeite-jade color green were used as the color gamut, which was in accordance with the scope from the CIE standard yellowish green to bluish green;

   c. $\Delta L^* = 5$, $\Delta a^* = 10$, and $\Delta b^* = 10$ were calculated to form a color-chip system of jadeite-jade color green with $\Delta E^* = 15$ from one to another, and 521 chips were then achieved.

2. Color chips were reduced or added to adjust plot point intensity. As a result, the color-chip system was condensed into 126 chips based on lightness, which was merged into 19 areas with $\Delta L^* = 5$.

3. With cluster analysis, 126 chips were graded into nine levels. Combined with the commercial evaluation of jadeite-jade color green, these levels were sequenced from the top quality fancy vivid green to the last faint green. Fisher discriminant analysis verified that only one group from 126 groups was misjudged, and the total accuracy was very high at 99.21 %. In future, this research result may improve some other vision related research [2,5,7,8,13–17,27–30].

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Ying Guo is a native Chinese. He is a researcher of Minerology and Gemology, an associated professor at School of Gemology, China University of Geosciences (Beijing). He mainly focuses on data acquisition and

storage of colorimetry, data compression, intelligent testing technology, micro & nano sensor and testing technology, etc. In recent years, he has completed several projects and published 51 research papers.

Huan Wang is a native Chinese. She is a teacher of Beijing City of Arts and Crafts Senior Technical School. She mainly focuses on data acquisition and storage of colorimetry, data compression, intelligent testing technology, micro & nano sensor and testing technology, etc. In recent years, She has completed several projects and published 2 research papers.

HongMei Du is a native Chinese. She is a researcher of Guangzhou Huadu Bureau of Quality and Technical Supervision. She mainly focuses on data acquisition and storage of colorimetry, data compression, intelligent testing technology, micro & nano sensor and testing technology, etc. In recent years, She has completed several projects and published 5 research papers.