Relationship between Paper Whiteness and Color Reproduction in Inkjet Printing

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Paper is widely used as a substrate for inkjet printing, where the paper feature heavily impacts the print quality, especially the color reproduction. The unprinted area on paper is visible and applied as a background reflectance for the toner layer. Hence, it is worthwhile to understand the effects of paper whiteness on print color reproduction. In this study, the tested papers were treated with different dyes, which resulted in the change of the paper's optical properties, but not surface roughness. The print density was impacted by the paper whiteness and ISO brightness. The effect of the paper whiteness on the print density is a stronger linear correlation compared to the ISO brightness. Paper whiteness has a positive correlation with the ISO brightness. The print colorimetric values (lightness and chroma values) increased with increasing paper whiteness up to a certain level, after which the paper whiteness did not have a noticeable impact on its print lightness and chroma values. The print color (a* and b* values) was affected by its corresponding paper color.

Keywords: Paper whiteness; Print colorimetrics; Color reproduction; Inkjet printing

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INTRODUCTION

Paper is the most important substrate in ink-jet printing, which is widely used in the home and office globally. Hence, the paper properties, especially optical properties, have attracted more attention from people lately (Moutinho *et al.* 2011).

Paper properties can be grouped into three parts: mechanical properties, structural properties, and optical properties (Juric *et al.* 2013; Hu *et al.* 2016). The mechanical properties play an important role in its runnability and printability (Kasmani *et al.* 2013). The paper structure properties play a factor in determining the interaction between paper and ink and affect the print performance (Corson *et al.* 2004; Arthur *et al.* 2011; Hu *et al.* 2013). Although the paper's optical properties have no bearing on the runnability and print performance, they also have a large impact on the print quality because the paper is visible between the printed area and defines the background reflectance for the toner layer (Ataeefard 2015; Hu *et al.* 2016).

Many researchers have investigated the influence of paper's optical properties on the print quality (Coppel *et al.* 2010; Jurič *et al.* 2013; Ataeefard 2015). However, the effect of the paper whiteness on the color reproduction, which is a significant part of print quality, has been limitedly reported. Some results are ambiguous from previous literature

(Fernandez-Reche *et al.* 2004; Norberg and Andersson 2009; Jurič *et al.* 2013). Jurič *et al.* studied the influences of 10 different commercially coated and uncoated paper optical properties on the color reproduction and found that while the paper brightness and whiteness are in linear correlation to the perceived print quality, the decrease of paper whiteness can also increase the chromaticity of primary colors (Jurič *et al.* 2013). Coppel *et al.* found that the perceived image quality could be improved by increasing the paper whiteness (Coppel *et al.* 2010). Ataeefard (2015) reported that the paper whiteness less affected the optical density, compared to both the roughness and gloss). Norberg and Andersson explored how the paper whiteness impacted the color reproduction quality and found an improved color rendering with increasing whiteness up to a certain level, after which the paper whiteness did not have a noticeable impact in ranking (Norberg and Andersson 2009). Fernandez-Reche *et al.* (2004) found that the color reproduction has no systematic correlation between color reproduction and the colorimetric properties of paper. Perales *et al.* (2009) deemed that the paper colorimetric properties had no clear relationship with the color gamut. In all of these studies, the paper consisted of different types of commercial paper that were manufactured with different methods. The optical properties of these papers were different from each other, meaning that the other properties, such as surface roughness and ink penetration, had been changed. Paper properties, such as roughness, gloss, brightness, opacity, and contact angle of ink on the paper, have a strong effect on the print quality, and these paper properties are highly dependent on each other. A change in one of these parameters will lead to a significant change in the effect of the other paper properties on print quality (Chen *et al.* 2012).

Paper whiteness and/or brightness is affected by the residual lignin in the pulp (Liu *et al.* 2014). To improve the paper whiteness, the pulp should be bleached before manufacturing the paper. In the pulp bleaching process, effluent containing the chlorinated lignin and degraded polyphenolic intermediates can be produced, and many researchers have studied reducing the production of the effluent (Li *et al.* 2015; Nie *et al.* 2015). In addition, the production of high whiteness pulp is very costly. The cost of high whiteness paper also could be increased. Thus, the relationship between paper whiteness and color reproduction should be understood, which would be in favor of paper manufacturers to design an appropriate manufacturing process.

In the present work, the paper was treated with different dyes to change the paper whiteness and/or brightness and reduce the impact of the other properties, such as surface roughness and ink penetration. Then, the treated paper was printed with the same ink-jet printing technology. The print density and colorimetric values of all of the primary colors (cyan, yellow, magenta, and black) were determined to better understand the relationship between color reproduction and paper whiteness.

EXPERIMENTAL

Materials

Commercial ink-jet paper was provided by Chenming Paper Mill (Weifang, China). Three kinds of ink (black, blue, and red) were provided by the Shanghai Ink Factory (Shanghai, China). All the inks are dye-based ink and the solid contents of black, blue, and red ink is 3.81%, 1.08%, and 2.97%, respectively. All the inks were filtered with a 0.22

μm filter membrane, and the filtrate ink was used as the colorant to treat the paper. In addition, the ink colors was chosen according to the Aksoy method (Aksoy *et al*. 2004).

Methods

Treatment of paper and testing

A wire-wound metering rod (OSP-04/250, OSP China) was used to apply filtrate inks (dye solution) evenly to the ink jet paper to obtain the dyed samples with different whiteness. The filtrate inks were diluted, and the concentration of the diluted filtrate inks were shown in Table 1. Sample 1#, 2#, and 3# were treated with the diluted filtrate black, blue, and red inks, respectively. Sample 4# was treated with deionized water. Then the treated paper samples were allowed to dry overnight at room temperature.

Table 1. The L, a*, and b* of the Treated Paper

Sample	Concentration of the diluted filtrate ink mg/ml	*L*	*a**	*b**
1#a	0.254	71.35	0.41	4.42
1#b	0.152	83.15	0.41	3.31
1#c	0.076	91.84	0.22	1.29
2#a	0.108	94.46	0.34	-2.32
2#b	0.043	94.91	0.30	-1.83
2#c	0.022	95.08	0.27	-1.71
2#d	0.002	95.13	0.13	-1.35
3#a	0.119	92.33	8.46	-2.41
3#b	0.059	94.45	3.80	-1.56
3#c	0.006	92.14	1.98	-0.36
4#	0	95.12	0.01	-0.04

The treated paper was measured with an X-rite 530 spectrodensitometer (X-Rite Color Management, Grand Rapids, USA) to obtain *L*, *a**, and *b** values. The whiteness was measured according to the Coppel method (Coppel *et al.* 2010) and calculated as follows, which is dependent upon the *L* and *b** values.

$$W_{CIE} = 2.41L - 4.45b^{*}\big(1 - 0.009(L - 96)\big) - 141.4$$

Paper properties were measured at 23 °C ± 1 °C and 50% ± 2% relative humidity. The PPS roughness, paper gloss, and ISO brightness measurements followed the ISO standard methods ISO 8791-4 (2007), ISO 8254-1 (2009), and ISO 2470-2 (2008), respectively.

As is commonly known, water is the main component of ink-jet printing ink (Lee *et al*. 2005). The contact angle of water on paper was used to characterize the contact angle of ink on the treat paper. The contact angle was measured with contact angle measurement instrument (XG-CAMB1, Xuanyichuangxi Industrial Equipment Co., Ltd, Shanghai, China).

Ink-jet printing procedure and testing

The standard color test sample with different dot area coverage percentages was provided by GATF Company, as shown in Fig. 1. The dot area coverage percentage ranges from 5% to 100% with 5% intervals. The treated paper was printed with a desktop ink-jet printer (Epson Stylus C88+, Seiko Epson Corporation, Nagano, Japan) and utilized all of the primary inks (cyan (C), magenta (M), yellow (Y), and black (B)).

The L, a*, and b* values of the different dot area coverage percentages were measured with an X-rite Eye-One spectrophotometer (X-Rite Color Management, Grand Rapids, USA) under D50 standard illuminant and a 2° standard observer. The print density was also measured with the X-rite Eye-One spectrophotometer.

The yellow, blue, magenta, and black prints of sample 4# were the standard print. The yellow, blue, magenta, and black prints of the other samples were the sample print. In the CIE L, a*, b* system, the CIE color difference was calculated as follows (Hubbe *et al.* 2008),

$$\Delta E = [(L_1 - L_2)^2 + (a_1^* - a_2^*)^2 + (b_1^* - b_2^*)^2]^{0.5}$$

where the subscript 1 refers to the sample data and subscript 2 refers to the standard.

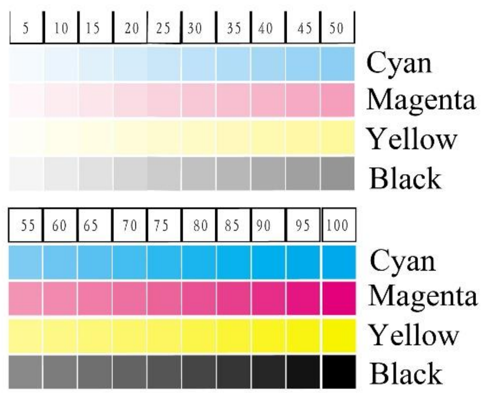

Fig. 1. Standard color testing sample for ink-jet printing; the numbers (*i.e.*, 5, 10, 95, and 100) represent the dot area coverage percentages.

RESULTS AND DISCUSSION

Properties of Treated Paper

The paper properties, such as surface roughness, contact angle of ink on paper, gloss, ISO brightness, and whiteness, were all regarded as influences on the print color reproduction (Chen *et al.* 2012). The paper samples were treated with different concentrations of dyes and the paper properties were tested. The paper surface roughness could affect interaction between paper and ink. The contact angle of ink on the paper was characterized as ink penetration for ink-jet printing. The surface roughness and the contact angle results are shown in Fig. 2(a). The surface roughness were very similar and not heavily affected by the dye treatment. The contact angle of sample 4# was slightly higher than the other samples. The possible reason was that the paper samples were treated with hydrophilic dye, which might decrease the contact angle. But the concentration of the dye solution is very low (less than 0.254 mg/mL) and there was only slight effect on the contact angle. The paper gloss mainly affects the print color intensity because it influences the degree to which light is reflected. The gloss of the treated paper was measured at 60° and 75°, and the results were shown in Fig. 2(b). The gloss of samples 4# was slightly higher than the other treated paper. The paper gloss was affected by the paper surface roughness, refractive index, the incident angle of light, and incident light wavelength (Ataeefard 2015). During the experiments, the incident angle of light and the incident light wavelength of the analysis equipment were constant. As shown in Fig. 2(a), there was almost no effect on the surface roughness. The gloss of the treated paper was mainly affected by the refractive index. The concentrations of the dye solutions were very low, and the gloss of the treated paper was slightly affected by the dye treatment.

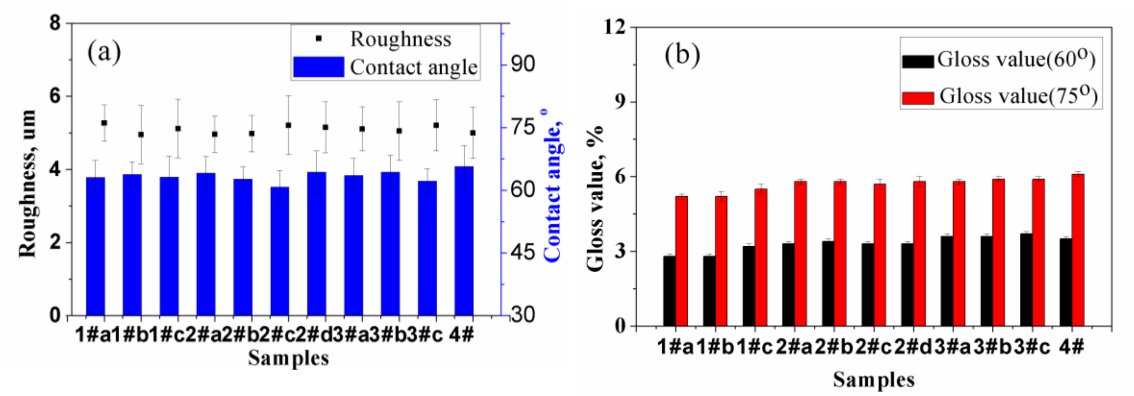

Fig. 2. The gloss value, roughness, and contact angle of the treated paper

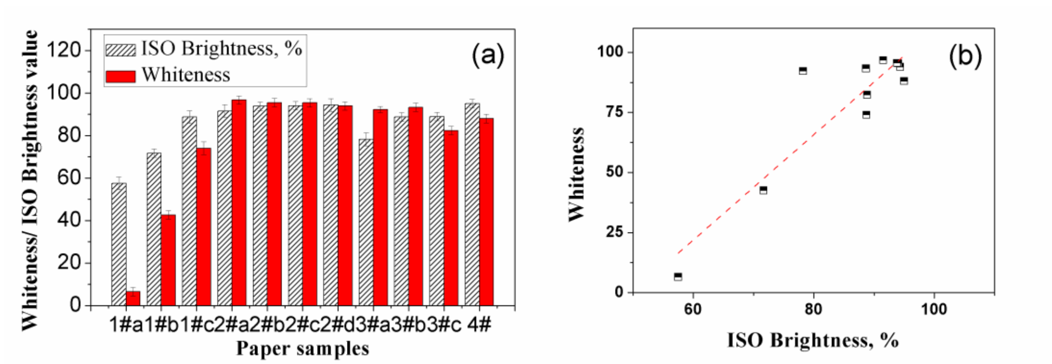

Fig. 3. The whiteness and ISO Brightness of the treated paper (a) and their relationship (b)

Paper whiteness (W_{CIE}) measures the amount of light diffusely reflected from the paper sheet at all visible wavelengths. The ISO brightness is based on the sensitivity of the human eye to blue and yellow tints. The whiteness and ISO brightness of the treated paper are shown in Fig. 3. The paper whiteness and ISO brightness changed within a wide range. The paper whiteness of samples 2#a,2#b, 2#c, 2#c, 3#a, 3#c was higher than 93. Samples 2#a, 2#b, and 2#c had very similar whiteness and showed the highest degree of whiteness. Sample 1#a showed the smallest degree of whiteness. Samples 2#a, 2#b, 2#c, 2#d and 4# showed the similar ISO brightness. ISO brightness of sample 1#a was smallest among the treated paper samples. The paper whiteness and ISO brightness are important paper optical properties to characterize the paper's colorimetric qualities. The linear correlations between paper whiteness and ISO brightness were studied (as shown in Fig. 3(b)), and the linear regression analysis was carried out using the least square method. The paper whiteness had a positive correlation with ISO brightness, and the linear correlation coefficient was 0.82. The paper with high whiteness had high ISO brightness. The paper whiteness variation was not the same as the ISO brightness. The ISO brightness is defined as the diffuse reflectance of a thick stack of paper at the mean wavelength of about 457 nm. The paper whiteness correlates with the lightness (*L* value) and color (*b** value).

The *L a* b** color space is designed to approximate human vision and has three channels (*L*, *a**, and *b**) to characterize color. The *L* channel is for the lightness ranging from 0 up to 100, corresponding to shades from black to white. The *a** channel is the values ranging from -128 up to +127, corresponding to colors from green to red, and the *b** channel is the values ranging from -128 up to +127 corresponding to colors from blue to yellow (Murali and Govindan 2013). The treated paper colors were also changed, as the variation of the *L*, *a**, and *b** values implies (Table 1). The *a** and *b** values of sample 1# were all greater than zero. That is, sample 1# contained red and yellow. For samples 2# and 3#, the *a** values were positive and the *b** values were negative, which represented that samples 2# and 3# contained blue and red.

Effect of Paper Whiteness on the Print Density

Print density, which is an important factor to be considered for printed products, affects the perceived saturation of a color and is a practical way of evaluating the depth of the tone in the print. To see if paper whiteness and brightness had an influence on the print color reproduction, the relationships between the print density of all primary printing colors and paper optical properties (whiteness and ISO brightness) are shown in Fig. 4. The print density decreased linearly when the whiteness value was below 82, and after this value the print density was hardly changed (Fig. 3(a)). The effect of the paper whiteness on print density was similar to the effect of brightness. The print density was essentially unchanged when the brightness value was greater than 90, and before which the print density linearly decreased.

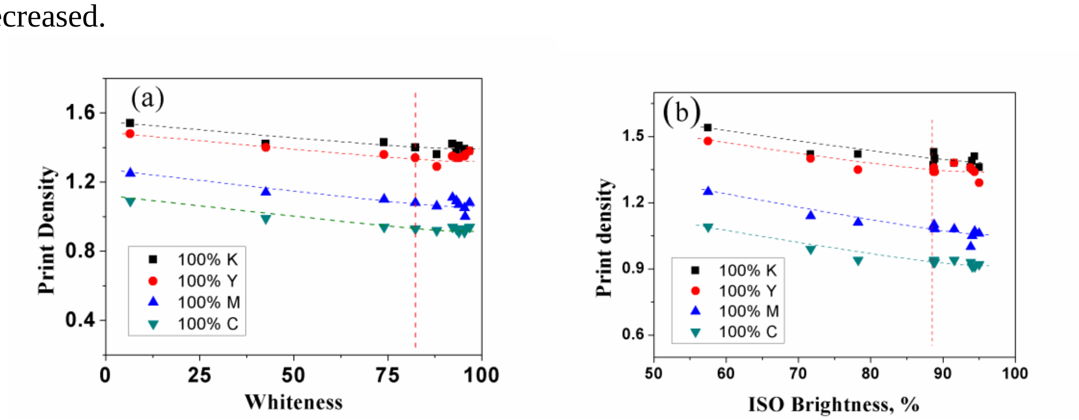

Fig. 4. The relationship between print density and whiteness (a) and ISO brightness (b); C: the cyan print; Y: the yellow print; M: the magenta print; and K: the black print

The paper samples with whiteness values below 82 and/or ISO brightness values below 90 were selected to investigate the linear correlation between paper optical properties (whiteness and brightness) and print density. The linear regression analysis was studied using the least-square method. The print densities of 10%, 60%, and 100% dot area coverage percentages were chosen, which respectively represented the bright tone, halftone, and solid tone. Linear plots of print density against paper whiteness and brightness were plotted (Fig. 5). The linear correlation coefficient values are shown in Table 2. The linearity of the plots (R^2)(Table 2) and the linear fit (Fig. 5) indicate that a negative correlation was found when the print density of all primary printing colors was compared with the whiteness and ISO brightness of paper. A strong negative correlation was found when the paper whiteness was compared with print density of all primary printing colors. A slightly weaker correlation was shown between the ISO brightness and print density. The paper whiteness is more qualified than the ISO brightness for the effect of paper color on the color reproduction. The paper was treated with dye solution and formed the dyed and undyed fiber layers, which changed the paper whiteness (Fig. 6). When a beam of light exposed on the print, a part of light was absorbed and scattered by the ink and the residual light could reach the paper surface and be absorbed and scattered by the dyed and undyed fiber layers. The paper with high whiteness could adsorb less light and reflected more light from the paper. The print density represents the percentage of adsorption of the ink film of the light exposed on it.

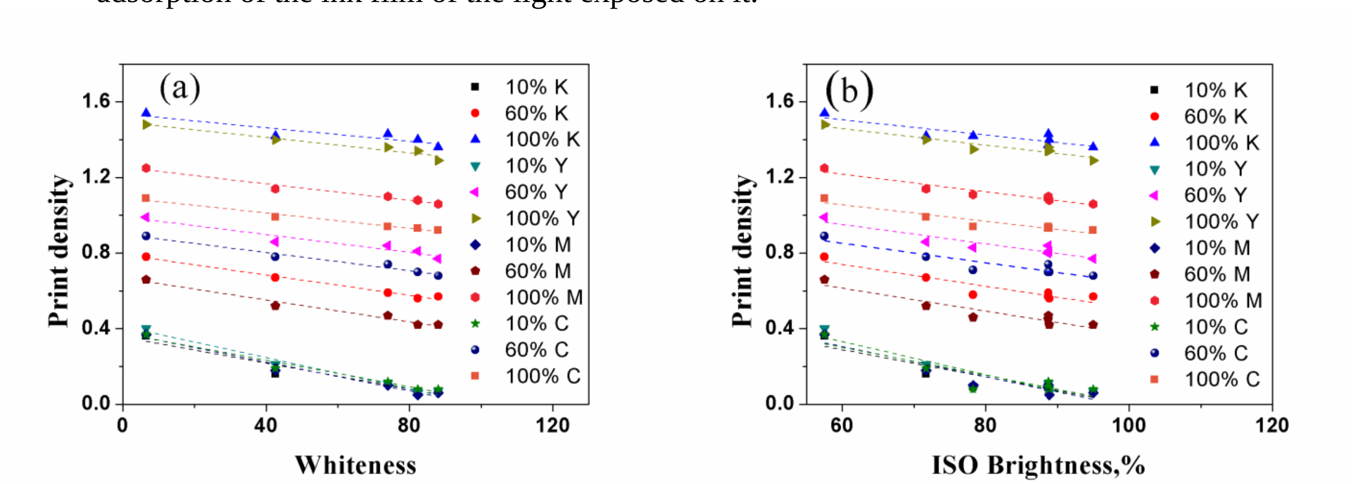

Fig. 5. Relations between print density and whiteness (a) and ISO Brightness (b); 10%: 10% dot area coverage percentage; 60%: 60% dot area coverage percentage; 100%: 100% dot area coverage percentage

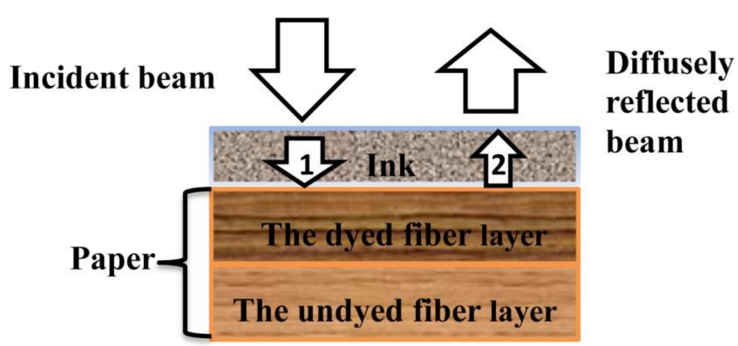

Fig. 6 The model of light path in print. 1 refers to the light that passed through the ink and entered into the paper. 2 refers to the light that diffusely reflected from the paper .

Table 2. Linear Correlation Coefficient between Print Density and Optical Properties (Whiteness and ISO Brightness)

Sample	Whiteness	ISO Brightness
10% Cyan	0.968	0.810
60% Cyan	0.973	0.858
100% Cyan	0.977	0.888
10% Magenta	0.970	0.877
60% Magenta	0.971	0.880
100% Magenta	0.971	0.923
10% Yellow	0.980	0.923
60% Yellow	0.926	0.875
100% Yellow	0.944	0.903
10% Black	0.939	0.822
60% Black	0.987	0.868
100% Black	0.833	0.791

*10%: 10% dot area coverage percentage;
60%: 60% dot area coverage percentage;
Note: 100%: 100% dot area coverage percentage

Effect of Paper Whiteness on CIE Color Difference

CIE color difference is a criterion to assess how closely the product matches to the selected standard color. The CIE color differences of all primary printing colors were calculated, and the relationships between the CIE color difference and the paper optical properties (the whiteness and ISO brightness) are shown in Fig. 6. The CIE color difference decreased linearly when the whiteness value was below 82, after which the CIE color difference was hardly changed (Fig. 6(a)). The brightness had slight or almost no effect on the CIE color difference when it was greater than 90, and before which the CIE color difference linearly decreased (Fig. 6(b)).

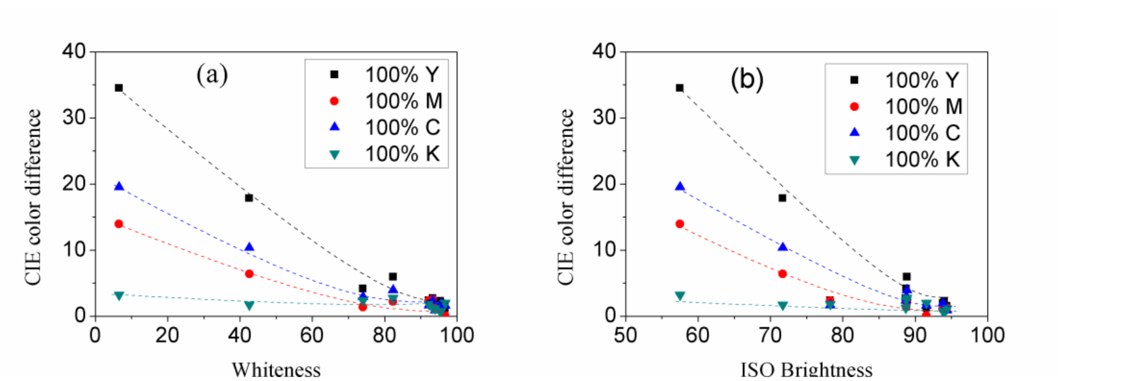

Fig. 6. The relationship between CIE color difference and whiteness (a) and ISO brightness (b); C: the cyan print; Y: the yellow print; M: the magenta print; and K: the black print

The paper samples with whiteness values below 82 and/or ISO brightness values below 90 were selected to investigate the linear correlation between paper optical properties (whiteness and brightness) and CIE color difference (Fig. 7). The least square method was used to study the linear regression analysis and the linear correlation coefficients were calculated and shown in Table 3. According to Fig. 7 and Table 3, it can be seen that a negative correlation was found when the paper optical properties (the whiteness and ISO brightness) was compared with the CIE color difference. The linear correlation coefficient between CIE color difference and whiteness was higher than that between CIE color difference and ISO brightness. The paper whiteness could be better express the effect of paper color on the color reproduction.

Table 3. Linear Correlation Coefficient between CIE Color Difference and Optical Properties (Whiteness and ISO Brightness)

Sample	Whiteness	ISO Brightness
100% Cyan	0.96	0.84
100% Magenta	0.97	0.89
100% Yellow	0.97	0.85
100% Black	0.09	0.18

*Note: 100%: 100% dot area coverage percentage

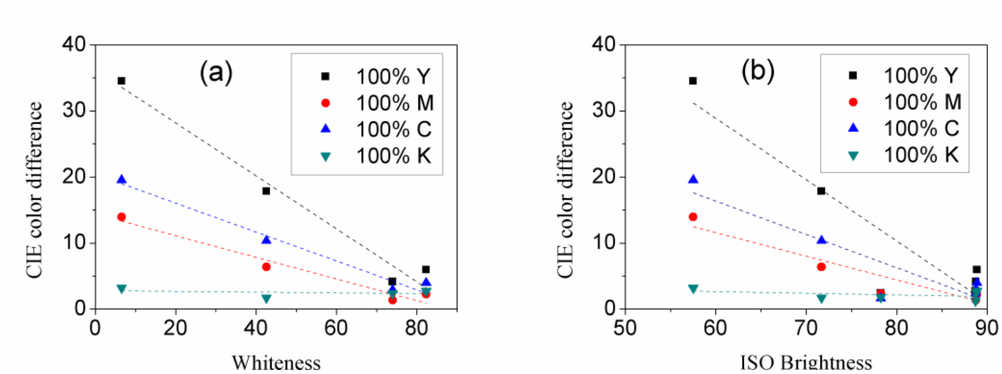

Fig. 7. Relations between CIE color difference and whiteness (a) and ISO Brightness (b)

Effect of Paper Whiteness on the *L*, *a**, and *b** Color Space

To see the effect of paper whiteness on the measured colorimetric values (*L* (lightness) and *C**(chroma)), the printed samples were estimated under a D50 illuminant and the relationships between the whiteness and colorimetric values are shown in Fig. 8. Among all of the primary printing inks, the lightness value of yellow ink was the highest followed by magenta ink, and the least was cyan ink (Fig. 8(a)). The lightness value increased linearly as the paper whiteness was improved, and when the paper whiteness was above 82, the lightness value was basically unchanged. The increase rate of yellow ink lightness was higher than the cyan and magenta inks. In other words, paper whiteness had more influence on the lightness of yellow ink than on that of cyan and magenta inks. When the paper whiteness value increased from 6 to 95, the lightness value of yellow ink increased from 58 to 88.

As shown in Fig. 8(b), the whiteness could increase the chroma value when the paper whiteness was below 82, after which the paper whiteness did not have a noticeable impact on the chroma value. This result was consistent with the study of Norberg and Andersson (2009). When a beam of white light is exposed on the printed area, the light is reflected and absorbed by the image and a part of light passed through the ink layer and reached the paper surface. The paper with high whiteness could increase the light reflected from the paper surface. The reflected light could increase the chroma of the image. In contrast, the paper with low whiteness could absorb more light which reached on the paper surface and decrease the quantity of reflected light leading to a decrease of the chroma value. The chroma value of yellow ink was highest in all of the primary printing inks, magenta ink took the second place, and cyan ink was slightly lower than the magenta ink.

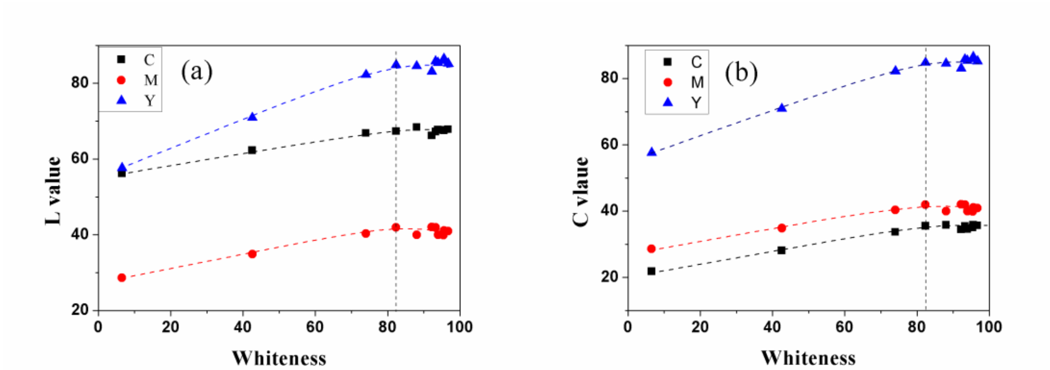

Fig. 8. The lightness value (L value (a)) and chroma value (C value (b)) changes with different paper whiteness

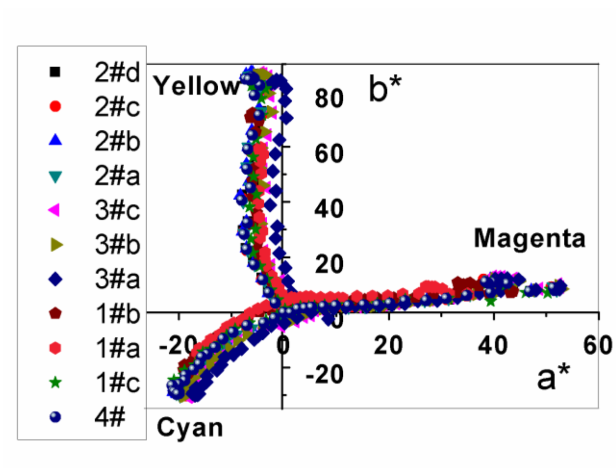

Fig. 9. The *a** and *b** value of different prints with different dot area coverage

The *a** and *b** values of all primary printing colors were measured to determine the influence of paper whiteness on the print color. The treated samples were printed with cyan, yellow, and magenta inks at various dot area percentages (from 0% to 100%). The *a** and *b** values of these prints are shown in Fig. 9. For the yellow print, the *a** value changed from -10 to 0, and the *b** value changed from 0 to 90. As shown in Table 1, the *a** value of sample 3#a was largest among these paper samples and sample 1#a showed the largest *b** value. For the yellow prints, the *a** value of print 3#a was larger than the other prints, and the *b** values of all the prints showed no noticeable difference. The yellow print was mainly affected by the *a** value of the paper.

For the cyan print, the *a** value of print 3#a was largest among these prints at the same *b** value. At the same *a** value, the *b** value of print 1#a was largest amongst these prints. The *a** and *b** values of paper both had a great influence on the cyan print.

For the magenta print, the *a** value changed from 0 to 50 and the *b** value changed from 0 to 12.5. The *b** value was slightly larger than the other prints when the *a** value of print 1#a was less than 32, after which the *b** values of these prints showed no obvious difference.

CONCLUSIONS

1. Paper whiteness had a positive correlation with ISO brightness, whereas the whiteness variation was not the same as the ISO brightness.
2. Print density was affected by the paper whiteness and brightness. Print density linearly decreased with the paper whiteness and ISO brightness increased. When the whiteness and ISO brightness values were respectively above 82 and 90, the print density showed no noticeable difference. The paper whiteness had a strong linear correlation with the print density of all primary printing colors.
3. The lightness and chroma values increased linearly as the paper whiteness was improved. When the paper whiteness was above 82, the lightness and chroma values were essentially unchanged. The increase rate of yellow print lightness was higher than that of the cyan and magenta prints.
4. The print color was affected by its corresponding paper color. The yellow print was more affected by the *a** value of paper than the *b** value of paper, whereas the magenta print was just opposite. Both the *a** and *b** values of paper all had great influence on the cyan print.

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