Exploring the Color Inconstancy of Prints

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ABSTRACT
The color inconstancy of prints is related to the ink spectral properties and the lookup table for multi-ink printing systems. In this paper, color inconstancy was investigated for several ink-jet printers based on their ink set and the default lookup tables. A virtual model for each printer was created to determine the range of color inconstancy that a specific ink set could achieve. The color inconstancy performance of each default lookup table was evaluated by evaluating the color inconstancy of a printed test target. The optimum combinations of three- and four-chromatic inks were investigated to minimize the color inconstancy and keep a relative large color gamut simultaneously. The results showed that the color inconstancy can be decreased significantly without compromising the reproduction colorimetric accuracy. Moreover the color inconstancy can be improved by appropriate ink design.

1. INTRODUCTION
Color constancy is the general tendency of the color of an object to remain constant when the level and color of the illumination are changed.[1] It is a result of both physiological and psychological compensations. Conversely color inconstancy is the undesirable change in color caused by changes in illumination. There does not yet exist a computational theory sufficient to explain the mechanism of color constancy of human vision. For many applications, it is very important that colored materials exhibit color constancy. However they often deviate significantly in hue when viewed under different light sources. In fact, color inconstancy is unavoidable. That means the perceived color always changes under different illuminants. In some cases, it could be become very serious. Figure 1 shows some printing samples with large color inconstancy between D50 and F11.

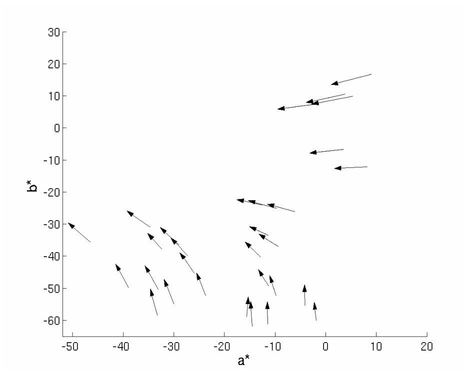

Figure 1. Some printing samples exhibiting a high degree of color inconstancy. The tail of arrows represents the tristimulus values of prints under illuminant F11 and the head of arrows represents the tristimulus values under illuminant D50.

Color inconstancy is a very important factor to evaluate for the image quality of prints since prints are viewed under many different lighting conditions. For example, color inconstancy occurs frequently when profiles are created for standardized daylight (D50) but viewed under narrow-band fluorescent illumination (F11), or vice verse. This can be an acute problem depending on the ink spectral properties and method of building the color look-up-table (CLUT). In this paper, the relationships between color inconstancy, ink spectral properties, and the color separation algorithm used to create the CLUT were explored.

2. METHOD
Generally a color inconstancy index (CII) is used as a metric to evaluate the extent of color inconstancy. The color inconstancy index is the total color difference between a sample's colorimetric coordinates under reference and test illuminants using a perceptually uniform color-difference equation. The calculation of the color inconstancy index is described in references 1-3: Tristimulus values are calculated for illuminants of interest from their spectral reflectance. Using a chromatic-adaptation transform such as CIECAT02,[4] corresponding colors are calculated from each illuminant to D65. The corresponding-color tristimulus values are converted to CIELAB using D65 as the reference white. A weighted CIE94 color difference is calculated with $k_L = k_C = 2$ between pairs of corresponding colors. In this manner, hue inconstancy is penalized twice as much as lightness or

chroma inconstancy. As a rule-of-thumb, samples with excellent color constancy have CII values below unity. The color inconstancy is related to the color lookup table. For multi-ink printing systems, there are usually more inks than colorimetric coordinates. As a consequence, many colors can be matched using more than one combination of inks and those different ink combinations have varied properties of color inconstancy. The lookup table combined with color constant ink combinations can provide not only high colorimetric reproduction accuracy but also high image quality. Therefore the creation of the color lookup table is very important for multi-ink printing systems.

For a specific printer, its color inconstancy range is determined by its ink set and the substrate used. In order to explore the color inconstancy property for each printer, a virtual printer model was developed based on the spectral reflectances of the inks and the substrate used by the printer. The virtual model was based on the Yule-Nielson modified Spectral Neugebauer model (YNSN) and Kubelka-Munk turbid media theory.[5] The linear relationship between actual ink amount and digital counts was assumed. Though the virtual printer model cannot provide a highly accurate prediction for a specific color, it can be used to evaluate some basic properties of printers, such as the gamut volume, color inconstancy, etc.

In this research, the virtual printer model was combined with an optimization algorithm to perform the colorimetric reproduction of a test target. With the similar colorimetric reproduction accuracy, the maximum and minimum color inconstancy index, which each printer can achieve with its specific ink set and substrate, are estimated. The objective function is described as Equation 1. The MATLAB built-in optimization algorithm, sequential quadratic programming (SQP), was utilized.

$$\begin{aligned} &R_{pred} = YNSN\ (ink\_a, ink\_R) \\ &\underset{ink\_a}{Minimize}\ \left[w1 * CII\ (R_{pred}) + w2 * \Delta E_{00} \right] \end{aligned} \tag{1}$$

Where *ink_a* represents the ink amounts for different inks. The predicted reflectance, R_{pred}, is calculated from ink amount and the reflectance of inks based on the virtual model. In this step, the reflectances of inks are measured from real prints. Function *CII* was used to calculate the mean CIIs of predicted reflectance between illuminants D50 and F11. ΔE_{00} is the mean color difference between predicted reflectance and original reflectance under illuminant D50. The objective function is minimized by searching ink amounts, *ink_a*. The weights, w1 and w2, can be adjusted to minimize or maximize color inconstancy index of the reproduction and to guarantee colorimetric accuracy simultaneously.

As mentioned above, color inconstancy also depends on the ink spectral properties. Color inconstancy can be minimized by optimizing the ink spectral properties while maintaining a relative large color gamut. We developed a computer simulation to investigate the optimum ink combinations in order to maximize the color gamut.[5] At that time, the color gamut was the only optimization objective. In this research, the color inconstancy index will be used as the optimization objective and color gamut will be used as a constrained condition. The objective function can be expressed as Equation 2.

$$\begin{aligned} &\underset{ink\_R}{Minimize}\quad \left[CII\,(R_{pred}) \right] \\ &R_{pred} = YNSN\ (ink\_a, ink\_R) \\ &Subject\ to \quad Gamut\ (ink\_R) \geq 95\,\% * Max\_Gamut \end{aligned} \tag{2}$$

At this phase, the optimization objective is changed to minimize color inconstancy by investigating the optimum ink reflectance. The ink amounts, *ink_a*, are set to regular grid points in the colorant space. The constrained condition is a compromise in color gamut created by the optimal ink primaries for CII and should be less than five percent of the maximum color gamut created by the same ink primaries. The function, Gamut, was used to calculate the color gamut based on new ink primaries. The maximum color gamut, *Max_gamut*, was taken from our previous research.[5]

3. RESULTS

In order to check color inconstancy, several test targets including a grey scale, Color Checker, and Color Checker DC, were printed by different printers. Then the spectral reflectances of these prints were measured and their CIIs computed. The tested color printers included five inkjet printers and one photographic printer. The semi-gloss or glossy photo papers corresponding to each printer were used as test papers. The description of these printers, ink type, and paper are listed in Table 1. The CIIs based on measured reflectance were calculated between illuminant D50 and F11. Table 2 shows the CII of the reproductions printed by different printers. For a specific printer, different profiles may cause different color inconstancy, but the data in Table 2 still reflects the general level of color inconstancy for each printer. The results show that the color inconstancy of prints varied among the different printers. The fact that newer model printers (printer 4 and printer 5) had relatively low color inconstancy shows that printer companies may be trying to solve this problem.

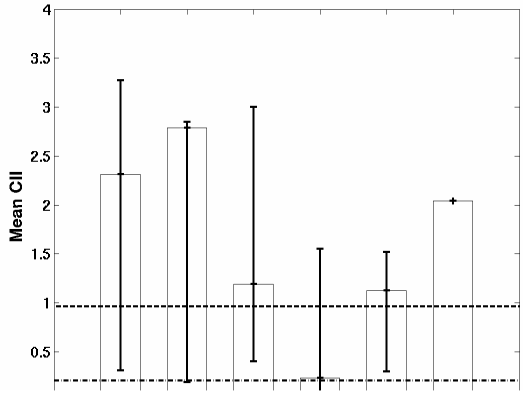

Figure 2. The mean CII of the default lookup table and its CII range of each printer for the grey target

Table 1. The basic properties of the test printers

	Printer 1	Printer 2	Printer3	Printer 4	Printer 5	Printer 6
Num of inks	4	6	4	6	6	3
Type of inks	Dye	Pigment	Pigment	Pigment	Dye	Photo-Dye
Type of paper	Matte	Semi-glossy	Semi-glossy	Semi-glossy	Glossy	Glossy

Table 2. The color inconstancy indices (D50→F11) of three targets for different printers.

	Printer 1	Printer 2	Printer 3	Printer 4	Printer 5	Printer 6
Mean	2.72	2.6	1.70	0.88	1.18	1.84
Min	0.24	0.03	0.08	0.03	0.19	0.17
Max	7.78	8.44	8.11	10.12	4.23	5.07

In order to evaluate each printer's default lookup tables, the range of the mean CII corresponding to each target for each printer was calculated according to Eq. 1. In Figures 2 - 4, the CIIs of the default lookup table are shown as bars for each printer. The minimum and maximum CII are shown as error bars in which the top limit represents the largest possible mean CIIs the printer can reach, or the worst ink combinations for color inconstancy; the bottom limitation shows the minimum possible mean CIIs the printer can reach, or the best case for color inconstancy. Notice that the real lookup tables cannot achieve the optimal minimum CII in the figures, when many other factors, such as color gamut, spatial image quality, and lookup table smoothness, are considered. Nonetheless, these estimations still can indicate the performance of a specific lookup table and the extent that it can be improved. From the minimum CII that each printer can provide, we find that 6-ink printing systems provide lower color inconstancy possibilities than 4-ink systems. However a poor profile may waste this advantage: such was the case for printer 2. From Fig 2 to 4, we can find that the ink combination selection is reasonable for printer 4 corresponding to its color inconstancy range. However, the CII could be decreased a lot for printer 2 by improving the lookup table.

Color inconstancy can be decreased by introducing the color inconstancy metric to the creation of the CLUT.[6] That means the color inconstancy can be minimized by selecting the combinations of inks with minimum CII. A multi-ink color-separation algorithm[6] was applied to one of these printers to create an optimized CLUT to minimize CII. Fig. 5 shows the CII comparison between the original Color Checker and reproductions by the default profile and the new CLUT. Figure 6 shows a spectral curve comparison of the same sample reproduced by the default profile and the new CLUT. We can find that the CLUT created by this algorithm can decrease color inconstancy significantly.

According to Eq 2, the optimal three-ink set and four-ink set were optimized for minimizing color inconstancy. A real black ink was added into the optimal inks to create two ink sets: the optimal three inks plus black and the optimal four inks plus black. The optimal three inks were also used as an ink-set to evaluate the contribution of black ink. The reproduction of the targets was predicted with the minimum mean CII by the virtual model based on these three ink-sets. In Fig 2 to 4, the dashed line, the dash-dot line and the solid line represent the minimum CIIs achieved by these ink-sets: the three optimal inks without black, the three optimal inks with black ink and the four optimal inks with black ink, respectively. The figures show that the black ink decreases the color inconstancy significantly, especially for the grey target and more ink primaries can provide a lower color inconstancy possibility.

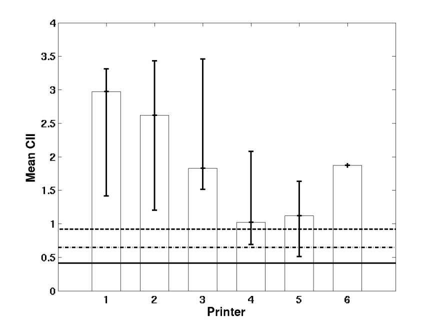

Figure 3. The mean CII of the default lookup table and its CII range of each printer for the color checker target

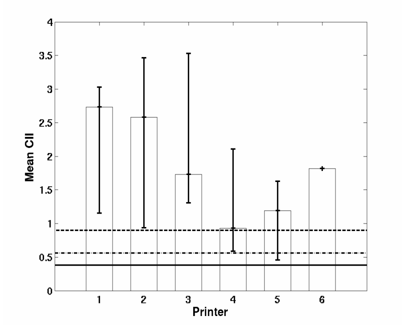

Figure 4. The mean CII of the default lookup table and its CII range of each printer for the CCDC target

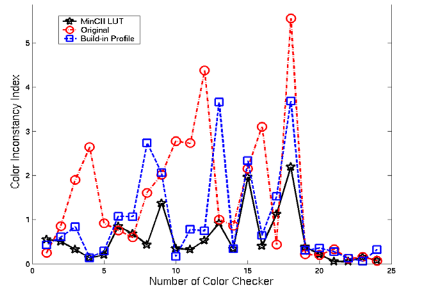

Figure 5. The CII comparison of Color Checker produced by different profiles.

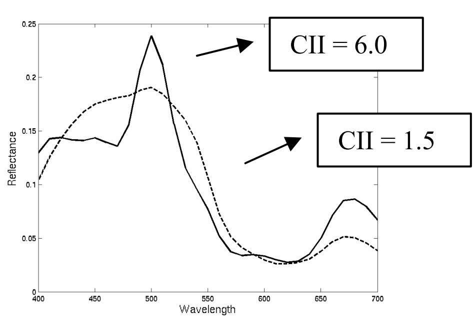

Figure 6. Spectral curves comparison of one color reproduced by different profiles.

4. CONCLUSIONS

In this research, the problem of color inconstancy was explored for different printers. The result shows that color constancy can be improved by optimizing the color lookup table or by ink design. However color constancy is only one criterion for image quality. The final color lookup table depends on compromises between color constancy, color gamut, spatial image quality, ink amount, etc.

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