Metamerism, Color Inconstancy, and Chromatic Adaptation for Spot Color Printing

Awadhoot Shendye*, Paul D. Fleming III*, and Alexandra Pekarovicova*

Keywords: Spot colors, product gravure, metamerism, color inconstancy, chromatic adaptation

Abstract

The use of metamerism index and color inconstancy index is studied for approval of spot colors used in decorative gravure products, especially spot colors, which are viewed under different light sources at the customer's end. This work shows that metamerism index is not sufficient for approval of spot colors because it doesn't provide any idea about how colors will transform under different light sources. Color inconstancy index makes use of chromatic adaptation transforms to assess the effect of the change in light source, and thus, it helps in selection of a spot color and, at the same time, reduces color-engineering problems in color reproductions.

Introduction

In processes like product gravure, a lot of spot color inks are mixed in house. Manufacturers are often concerned about the best utilization of inks and, if possible, recycle press return inks to make the production more sustainable. Mixing spot colors from recycled inks may often lead to their metameric behavior. Moreover, these products, e.g., wood grain laminates and wallpapers, are tested in a standardized environment using light sources D_{50} or D_{65} (Wyszecki, 2000) for spot color approval, but they are exposed to fluorescent or incandescent light at the moment of purchase (Wu et al., 2008). Therefore, it is also necessary to assess their behavior under different light sources, which enables one to predict their performance.

Usually the decision about passing or failing of a spot color is decided on the basis of acceptable tolerances of color difference values. Many times, metamerism index and color inconstancy index are not considered, while making the decision of pass/fail of a color match (Noor, 2003). If other assessment methods are used, which include behavior of color under different light sources, along with color differences, then the criteria for deciding about acceptance or rejection of matches would be more reliable. Naturally, for deciding acceptance of matches for different recipes to match a specified standard, only regular (e.g., nonmetallic, nonpearlescent, etc.) color samples can be considered. Ideally, a color match should be selected on the basis of closeness of the reflectance spectra of ink pairs (Berns, 2000). Due to limitations in selection of colorants, it may not be always possible to generate unconditional matches (Berns, 2000). This leads to the necessity to include metamerism and color inconstancy indices in decision making about the acceptance or rejection of a particular shade.

According to Wyszecki, "metameric color stimuli have identical tristimulus values, but different spectral radiant power distributions" (Wyszecki, 2000). If this phenomenon is found in the case of objects (reflection or transmission), then they are known as metameric objects. If this occurs for illuminants, then they are referred to as metameric illuminants (Kang, 2006). One can determine the degree of metamerism, which is also known as magnitude of the effect for a given pair of samples. Two ways of doing this are suggested, leading to general and special metamerism indices. Metamerism index (MI) equation for change in illuminant (CIE 15.2 section 5.2 MI) suggested by Hunter (Hunterlab (A), 2008; Hunterlab (B), 2008), is defined as follows:

$$MI = [(\Delta L_{n1} - \Delta L_{n2})^2 + (\Delta a^*_{n1} - \Delta a_{n2})^2 + (\Delta b^*_{n1} - \Delta b^*_{n2})^2]^{1/2}$$

Where Δ indicates the difference between standard and sample, and subscripts n1 and n2 indicate first and second illuminant, respectively (Choudhury, 1998). The L* a* b* values can be of the Hunter or CIELAB color scale. This type of index does not distinguish between test and reference illuminants, but only the illuminant pairs. MI from 0 to 0.5 is considered as a "perfect" match, and 0.5 to 1 MI is considered as good match. MI > 1 corresponds to a questionable match, thus it needs to be a subject to additional analysis (Hunterlab (A), 2008; Hunterlab (B), 2008).

Wood grain laminates are designed electronically, and shades are selected many times without considering limitations in color reproduction. Shades on a computer can show their CIEL*a*b* values under some illuminant/observer condition, and reflectance data of those digitally selected shades are not available. When only CIEL*a*b* of a shade under one illuminant/observer condition is available, then there could be many shades of the same CIEL*a*b* values, which are metameric to each other, but with likely different behavior under different light sources. The least metamerism index is not sufficient, because a design is viewed under different light sources, without comparing to any other shade under that light source. Therefore, it is important to study color inconstancy along with metamerism.

A certain color may be perceived to change when it is viewed under different light sources, what is referred to as color inconstancy. In other words, color constancy is nothing but perceiving the same appearance after changing the light source (Berns, 2000). A memory-matching technique is involved, when a shade is viewed by switching light sources. To convert this memory-matching phenomenon into a numerical color difference, a corresponding color concept is used, which is predicted by calculation of a chromatic adaption transform. The difference between the corresponding color and color coordinates calculated from reflectance data, under the test light source, is defined as the color inconstancy index (Berns, 2000). An example of color constancy occurs when our eye accepts that a paper looks white after switching light sources. Our eyes accept lighting conditions and, theoretically, we should not perceive changes of color after acceptance.

Nevertheless, we do perceive changes in color after adjustment of our eyes to a given condition. So ideally, color constancy does not exist, because, if we look carefully, paper looks white under different light sources, but those whites are not the same. Therefore, we need to study how much color change is perceived after changing the light source and that phenomenon is known as color inconstancy. Color inconstancy is very important for printed gravure laminates, or other printed products, because they are viewed under several light sources, usually D_{50} or D_{65} at the print manufacturer site, but most likely they will be exposed to F_2 light source at the moment of purchase. When colors and recipes are selected, the criterion of color constancy is not usually considered. Metamerism has a close relation with color inconstancy. In metameric pairs, the two samples will likely have different color inconstancy indices (CII). So, the CII of a standard and recipe will help the matcher to select a recipe that has the least CII and MI. When a designer selects a shade, the behavior of the color under different light sources is not accounted for. The example of wallpaper printing shows that in color reproduction processes, as per matching practice, matching is carried out using one standard light source. When the light source is changed from the standard to any other one, then color appearance also changes. When the shade of wallpaper is approved under D_{65} and is viewed under illuminant “A,” then with memory matching (color perceived under D_{65} compared against its perception under incandescent light) one must not perceive drastic changes in shade of wallpaper with this light source changing.

While printing wood grain laminates, first a background ink is printed on special gravure paper. This is known as the pad layer. Then spot colors are printed on this pad-coated paper, as is the industrial practice. Most wood grain patterns are printed in yellow, beige, and brown colors. Therefore, yellows and reds are base colors used in the greatest quantities. Sometimes, these base colors are used directly as individual spot colors. The aim of this work is to evaluate and calculate how selected spot color inks will behave under changing lighting conditions. Two base color sets were selected for this experiment, in which the base colors are close to each other.

Experimental

Yellow 1 and Yellow 2 were standard yellow inks, and Yellow 1P and Yellow 2P were proposed replacement inks. Similarly, Red 1 and Red 2 were standard red inks, and Red 1P and Red 2P were their replacements inks. Drawdowns of two sets of base colors were made with the minimum lightness difference possible, using a K-proofer gravure laboratory proofing press. Metamerism indices (MI) and color inconstancy indices (CII) of both sets were calculated. CII for selected Pantone Matching System (PMS) colors were also calculated for comparison purposes.

Color Inconstancy Indices (CII) Calculation

The procedure for calculation of CII is given as follows:

Step 1) Measure/calculate tristimulus values of color under source illuminant.

Step 2) Use chromatic adaptation transforms to calculate tristimulus values under test illuminant.

Step 3) Calculate color difference (Wyszecki, 2000), between measured colors coordinates under test illuminant and calculated correlated color coordinates under test illuminant.

Chromatic Adaptation Transform Model CMCCON02 Calculation

The CMCCON02 formula is recommended with (l:c being 2:2), but any other color difference formula can be used (Luo, 2003). For the CMCCON02 formula, the procedure is the same as above, but the CAT02 model is used as the chromatic adaption transform and the CMC (2:2) formula is used for calculating color differences.

Step 1) Calculate tristimulus values under source illuminant, CIE XYZ and L*a*b*c*h*.

Step 2) Use CAT02 formula and calculate CIE XYZ & L*a*b*c*h* values under destination illuminant.

$$\begin{bmatrix} R \\ G \\ B \end{bmatrix} = M_{CAT02} \begin{bmatrix} X \\ Y \\ Z \end{bmatrix} \qquad M_{CAT02} = \begin{bmatrix} 0.7328 & 0.4296 & -0.1624 \\ -0.7036 & 1.6975 & 0.0061 \\ 0.0030 & 0.0136 & 0.9834 \end{bmatrix}$$

Rc = R[D(Rwr/Rw) + 1-D]

Gc = G[D(Gwr/Gw) + 1-D]

Bc = B[D(Bwr/Bw) + 1-D]

$$\begin{bmatrix} Xc \\ Yc \\ Zc \end{bmatrix} = M^{-1}_{CAT02} \begin{bmatrix} Rc \\ Gc \\ Bc \end{bmatrix}$$

$$M^{-1}_{CAT02} = \begin{bmatrix} 1.096124 & -0.278869 & 0.182745 \\ 0.454369 & 0.473533 & 0.072098 \\ -0.009628 & -0.005698 & 1.015326 \end{bmatrix}$$

(continues next page)

Where

X,Y,Z	Tristimulus values of color under reference illuminant
R,G,B	Cone responses of color under reference illuminant
Rc,Gc,Bc,	Cone responses under test illuminant
Rwr,Gwr, Bwr	Cone responses of reference illuminant
Rw,Gw, Bw	Cone responses of test illuminant
Xc,Yc,Zc,	Corresponding color tristimulus values
D	Degree of adaption

Step 3) Calculate color difference by any color difference formula, but the CMC (2:2) color difference formula is preferred by CMCCON02.

Results and Discussion

A comparative study was carried out between metamerism indices (MI) and inconstancy indices (CII) of metameric and non-metameric color pairs of solvent-based inks used in product gravure. Two base color ink sets were compared. Reflectance data readings were measured with a spectrophotometer and CIE L*a*b* coordinates were calculated for D_{65}, A, F_2, and D_{50} illuminants (Hunterlab (C), 2008). $D_{65/10}$ is chosen as the source illuminant, with illuminants A, F_2, and D_{50} being considered as additional light sources for calculating metamerism indices and color inconstancy indices. Some chromatic adaption transforms were used to calculate color coordinates and then inconstancy indices were calculated from the transformed values. Decisions of pass/fail based on ΔE, MI, and reflectance data were compared against decisions based on ΔE, MI, and reflectance data including CII.

Table 1 shows the color differences $\Delta E_{CMC(2:2)}$ under $D_{65/10}$, between drawdowns of the four ink color pairs. Ink pairs Red1/Red 1P, Red 2/Red 2P, and Yellow 1/Yellow 1P reached acceptable $\Delta E_{CMC(2:2)}$ bellow 3, but replacement yellow (Yellow 2P) has unacceptable $\Delta E_{CMC(2:2)}$ of 5.47. Figures 1–4 show the reflection spectra of the two sets of red and yellow ink pairs, from which the colorimetric (tristimulus) values were obtained. Spectra of Red 1 and Red 1P are almost identical in the range 380–610 nm, but for 620–720 Red1P shows a much larger reflectance, thus it is redder. Red 2 and Red 2P reflectance spectra differ in the region of 380–360 nm, thus in the blue region. Yellow 1 and Yellow 1P differ in the blue region in the range of 380–480 nm and also in red region from 600–720 nm. Yellow 2 and yellow 2P differ in blue and green region of spectrum (380–560 nm). However, it is difficult to judge suitablility of color replacement based soleley on difference in reflection spectra. Therefore, metamerism indices (MI) were calculated. Table 2 shows the MI of the different ink pairs for A, D_{50}, and F_2 illuminants. The lowest MI were found for Red 2 and Red 2P, being in the range of 0.11–0.44, followed by the Yellow 1 and Yellow 1P pair with 0.3–1.38 range of metameric indices. The largest MI were found for Yellow 2 and Yellow 2P, being I the range 0.7–3.03. As expected, the lowest MI occurred with illuminant change from D_{50} to D_{65} (0.11–0.70), with lowest MI for Red 2 to Red 2P at D_{50} to D_{65} being 0.11. The largest MI was found for illuminant change from D_{65} to F_2.

Table 1. *Color difference $\Delta E_{CMC(2:2)}$ of ink shades used in decorative laminates printing.*

Standard	**Proposed**	**$\Delta E_{CMC(2:2)}$**
Red 1	Red 1P	1.37
Red 2	Red 2P	2.21
Yellow 1	Yellow 1P	0.97
Yellow 2	Yellow 2P	5.47

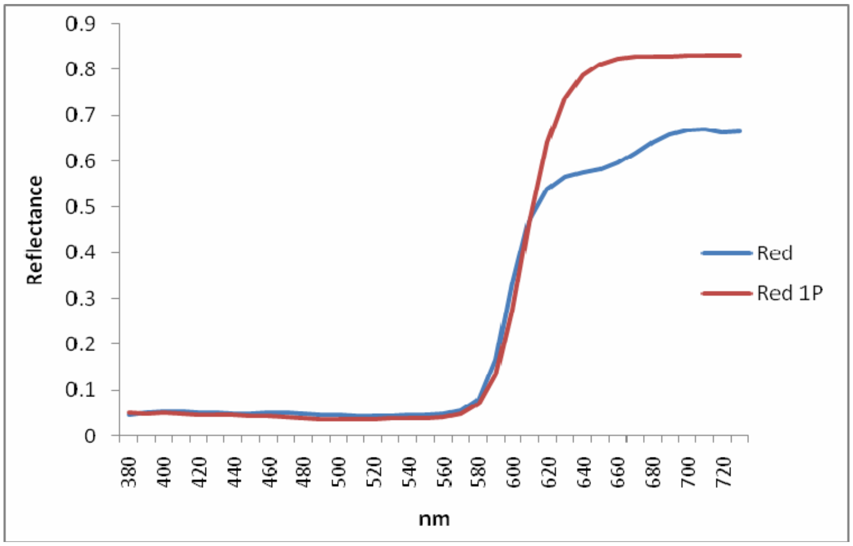

Figure 1. *Reflectance spectra of red inks Red 1 and Red 1P.*

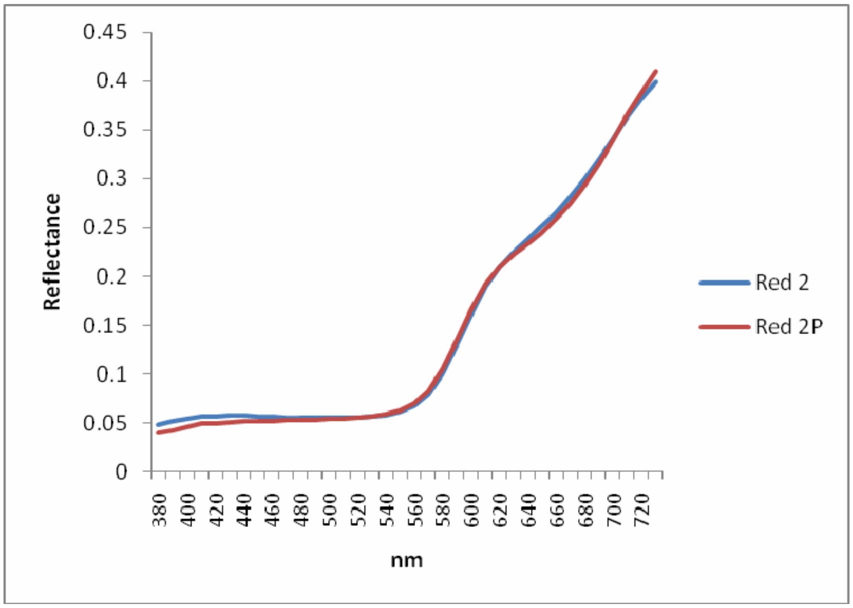

Figure 2. *Reflectance spectra of red inks Red 2 and Red 2P.*

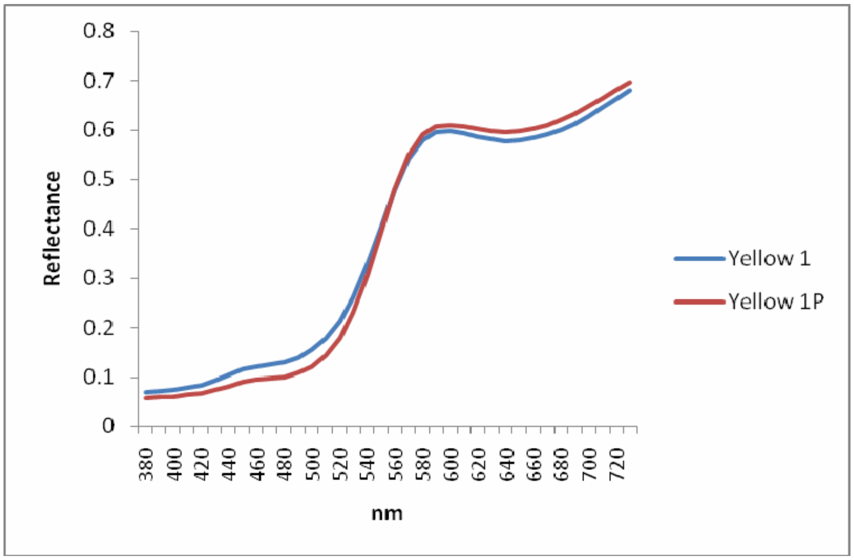

Figure 3. *Reflectance spectra of yellow inks Yellow 1 and Yellow 1P.*

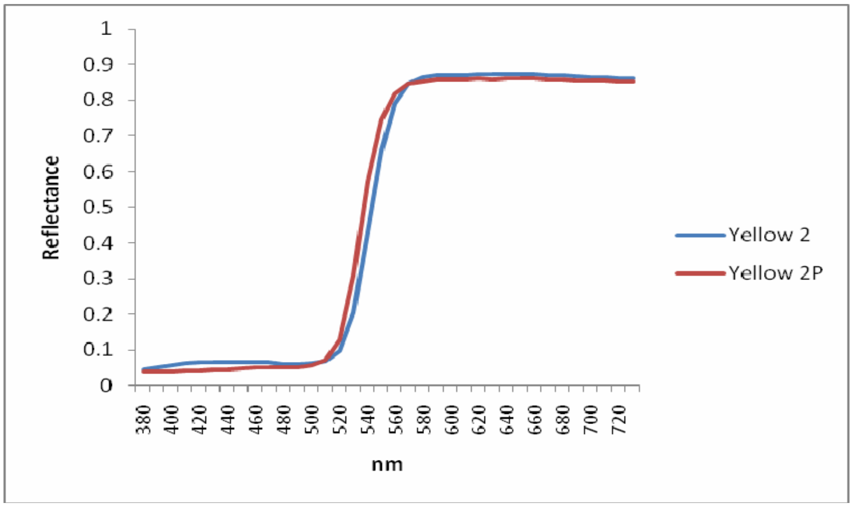

Figure 4. *Reflectance spectra of yellow inks Yellow 2 and Yellow 2P.*

Table 2 *Metamerism indices (MI) of standard and replacement ink pairs for decorative laminates*

Ink 1	**Ink 2**	**D_{65}→A**	**D_{65}→D_{50}**	**D_{65}→F_2**
Red 1	Red 1P	2.36	0.61	2.88
Red 2	Red 2P	0.20	0.11	0.44
Yellow 1	Yellow 1P	1.38	0.30	1.89
Yellow 2	Yellow 2P	3.03	0.70	2.59

Color inconstancy indices (CII) for all inks are illustrated in the Figure 5. CII for illuminant change D_{65} to A was found in the range of 1.74–3.51, smallest was found for Red 2P being 1.74, and largest for Red 1P being 3.51. CII for illuminant change from D_{65} to D_{50} were in the range of 0.26–1.50, the smallest was found for Yellow 1 (0.25) and largest for Red 1P being 1.50. As expected, the largest CII was found in illuminant change D_{65} to F_2, which was in the range of 3.14–9.85, the largest being for Yellow 2 ink.

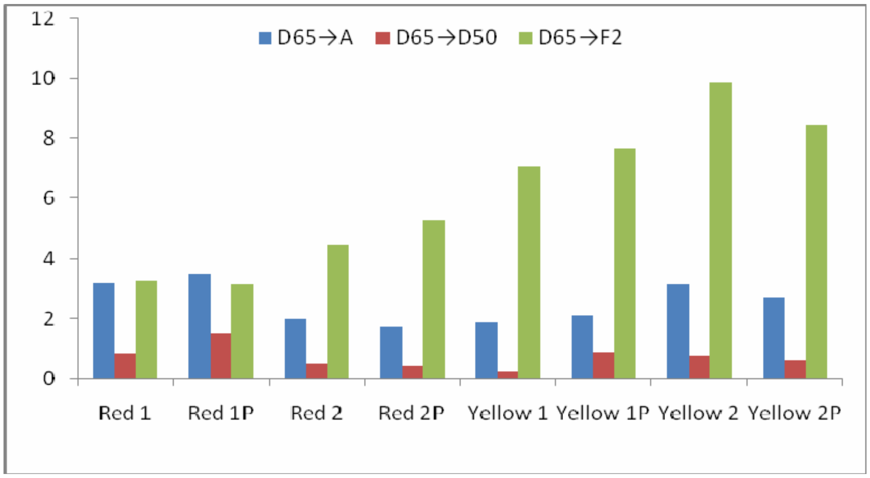

Figure 5. *Color Inconstancy Indices (CII) of standard and proposed substitute inks.*

To summarize, considerable spectral color difference was found between Red 1 and Red 1P, along with considerable MI up to 2.88, but the least CII values, and even if they have the least CII values, Red 1P becomes a doubtful match. In the case of Red 2 and Red 2P, they show low metamerism and moderate color difference, but acceptable CII along with similar spectra, and therefore the Red

2P shade can be accepted. Yellow 1 and Yellow 1P pair show the least color difference, but doubtful MI and large CII values, and therefore the proposed replacement shade may not be acceptable for changes in light source conditions. Yellow 2 and Yellow 2P shades show similar reflection spectra, but the two colors have unacceptable ΔE values, along with large MI in illuminant A, as well as unacceptable CII under illuminant F_2. Thus, the substitute shade becomes unacceptable for the required situation.

Color inconstancy is an inherent property of the behavior of color, when viewed under different light sources. For comparison, calculations of CII for several PMS basic colors (Figure 6) were done. It was found that PMS yellow, yellow 12, Red 032, violet, blue 72 have less inconstancy, while PMS process blue and orange 21 show unacceptable color inconstancy for the required criteria. Acceptable limits of color inconstancy index can be decided by psychophysical experiments or by the contract proof method. This limits selection of these basic colors, or shades, in various product-printing conditions. The important point to notice from Figure 6 is that large CII for some illuminant changes shown in Figure 5 are not that unusual, since similar behavior is shown for inks used to print PMS books. Thus, the two ink sets discussed here are not necessarily "bad," but some light sources create more artifacts under light source changes than others.

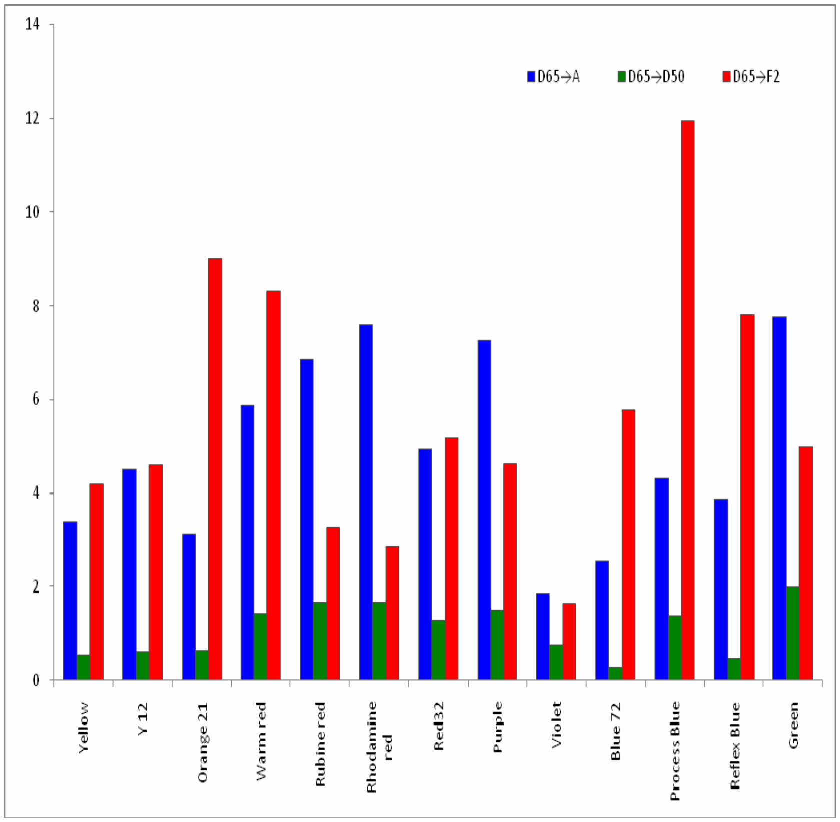

Figure 6. *Color Inconstancy Indices (CII) of Pantone Basic Colors.*

Conclusion

This study confirmed that the spectral reflectance curves of ink pairs, along with metamerism indices are not sufficient measures for finalizing a shade match, especially when the printed jobs are exposed to different light sources. Combination of spectral reflectance graph matches, MI and CII help to select the best ink shades for the job, and thus help to reduce color-engineering problems.

Acknowledgment

Authors are grateful for generous support from Omnova Solutions, Inc.

References

Berns, R. S. 2000. *Billmeyer and Saltzman's Principles of Color Technology*, 3rd Edition, Wiley, 29–215.

Choudhury, A.K.R. and S.M. Chatterjee. 1998. *Color Research & Application*, Volume 21, No. 1, 26–34.

Hunterlab (A). 2008. “Metamerism Index,” *Insight on Color*, Vol. 9, http://www.hunterlab.com/appnotes/an03_97.pdf, accessed 3/3/2010.

Hunterlab (B). 2008. “Metamerism,” *Insight on Color*, Vol. 6, No. 13, http://www.hunterlab.com/appnotes/an11_95.pdf, accessed 3/3/2010.

Hunterlab (C). 2008. “Equivalent white light sources and CIE lluminants,” *Insight on Color*, Vol. 17, No.5, http://www.hunterlab.com/appnotes/an05_05.pdf, accessed 3/3/2010.

Kang, H. 2006. *Computational Color Technology*, SPIE press, 27–28.

Luo, M.R., B. Rigg, and K.J. Smith. 2003. “CMC 2002 Colour inconstancy index: CMCCON02,” *J. Coloration Technology*, Volume 119, No. 5, pp. 280–285(6).

Noor, K**.** 2003. “Effect of Lighting Variability on the Color Difference Assessment,” M.S. Thesis, North Carolina State University, http://www.lib.ncsu.edu/theses/available/etd-05182004-031941/unrestricted/etd.pdf, accessed 3/3/2010.

Wu, Yu Ju, A. Pekarovicova, and P.D. Fleming. 2008. “The Effect of Paper Properties on the Color Reproduction for Digital Proofing of Gravure Publication Printing,” *TAGA Journal,* 4(2), 72–83.

Wyszecki, G. and W.S. Stiles. 2000. *Color Science: concepts and methods, quantitative data, and formulae*, Wiley-Interscience; 2nd Edition pp. 451–830.