# Quantitative Analysis of Pictorial Color Image Difference

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Abstract: The magnitude of $\Delta E$ between two simple fields, e.g., flat colors or logo colors, correlates well with visual assessment. As such, the use of $\Delta E_{LAB}$ to specify color tolerances of ink has been common in the graphic arts. However, there is no easy way to assess color difference quantitatively between two complex images, e.g., a pictorial color proof and its corresponding press sheet. Consequently, the practice of qualifying a color proofing system which conforms to a known printing condition or verifying printed products that match a contract proof remains visual and subjective. This paper uses a standard press characterization target (IT8.7/3 basic block) to quantify pictorial color image difference by colorimetry. Colorimetric measurement conditions and $\Delta E_{(LAB)}$ calculations adhere to the ANSI CGATS.5-1993 standard. Comparison of color images with the same colorant conditions and images with different colorant conditions were investigated. The quantitative analysis mainly focuses on the use of cumulative relative frequency (CRF) of the $\Delta E$ distribution. We learned that a visual match between two color images can be specified by means of the CRF curve and its derived statistics. In addition, a visual match between two color images imposes a tighter colorimetric tolerance than process conformance as specified by solid ink density and dot gain.

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## Introduction

Visual assessment of two flat colors correlates well with colorimetric analysis when using ΔE. This is why ΔE is used to specify color tolerances of ink sets (ISO 2846-1, 1997). However, the agreement between two pictorial color images is typically determined by a visual assessment which is subject to variation from individual to individual. This raised a question: "Will colorimetric assessment of color difference between two pictorial color images correlate with visual assessment?" If the answer is 'yes,' then conformance to printing specification and qualification of a proof as a standard press sheet will be a verifiable event, and no longer just a desire. The objective of this study is to review recent work in this field and to devise a quantitative method whereby ΔE distribution between two color images can be analyzed for a variety of conditions.

## ΔE and Its Distribution

There are a few things about ΔE we should know. First, ΔE is the total color difference between a reference and a sample. It only reflects the magnitude of the color difference. It does not provide the direction as to how the two colors differ.

The measured color difference (ΔE) correlates relatively well with the perceived color difference if a pair of synthetic or spot colors is examined under a simple surround. But this is often not the case when colors are viewed under complex surrounds, such as reported by Felix Brunner, due to differences in color image contrast (TAGA, 1987).

There are a number of formulas for ΔE calculation, e.g., $\Delta E_{(Hunter)}$, $\Delta E_{(LAB)}$, $\Delta E_{(CMC)}$, $\Delta E_{(CIE94)}$, etc. In this study, colorimetric measurement conditions and $\Delta E_{(LAB)}$ calculations adhere to the ANSI CGATS.5-1993 standard.

Variation exists everywhere. If we want to know how consistent a printing process is, like 4-color printing using CMYK colorants, we can measure a color patch in terms of its CIELAB values over time. Once we measure a sufficient number of samples, the mean of these color measurements from the color patch can serve as the reference, and ΔEs between these color measurements and its mean becomes a measure of process precision.

ΔEs of multiple samples has a non-gaussian distribution. This is because ΔE is a positive quantity and zero ΔE represents a special (end) point. Using the average ΔE as an indicator of process precision can be deceiving because it only accounts for about half of the process variation. Chung used cumulative relative frequency (CRF) to express a range of values in monochrome pictorial images back in the 1970s (JAPE, 1977). CRF was applied to the ΔE distribution between two images in this study.

ΔE values derived from a multi-patch target produces a distribution between corresponding patches in two targets. In this study, measurements were made from the IT8.7/3 (ISO 12642) basic block. The data may be gathered either over time or between two imaging devices. Chan derived ΔE values whereby the ANSI CGATS TR 001 data set was the reference and an Epson ink jet proof was the sample (TAGA, 2000). Such a distribution may be graphically expressed as individual ΔEs in a 3-D plot (Figure 1). The same distribution can also be expressed as relative frequency (RF) and cumulative relative frequency (CRF) as shown in Figure 2. The conversion from a histogram to RF and to CRF is covered in textbooks, e.g., Statistics, An Introduction (Rickmers and Todd, 1967).

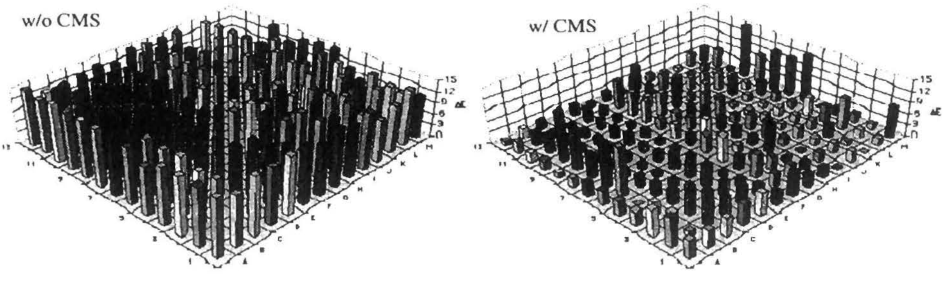


Figure 1. ΔE Distribution in 3-D plot.

Figure 1 illustrates two ΔE distributions plotted against the layout of the IT8.7/3 basic target. The left graph shows an overall large ΔE distribution between two images without color management applied. The right graph shows a reduced ΔE distribution due to the application of ICC-based color management. The 3-D plot is visually informative, but not analytic enough to answer the question of whether two color images match.

Figure 2 transforms the data in Figure 1 to relative frequency (RF) and cumulative relative frequency (CRF). We can see that the effect of color management has shifted the relative frequency (RF) of ΔE distribution towards smaller quantity. This is evidenced by the shift of the CRF of ΔE at the 50 percentile from 15 to 3.6. Due to the non-linearity of CRF curves, three points are useful to describe its shape: CRF at the 50 percentile, 90 percentile and at the unity. The unity corresponds to the largest ΔE value.

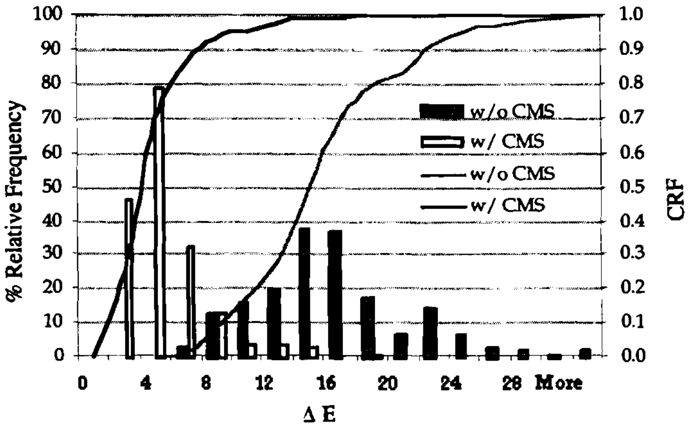


Figure 2. ΔE Distribution as relative frequency (RF) and cumulative relative frequency (CRF).

A CRF curve can be generated by measuring two IT8.7/3 basic targets. If a reference printing condition, such as TR 001, is used and not a physical sample, it is not possible to tell if a given CRF curve represents a visual match between two color images. Thus, a fundamental question still remains, "At what point does the CRF curve suggest a visual match between two color images?"

## Literature Review

When colorimetric differences are compared between an original and its photographic reproduction, Milton Pearson reported that large color differences exist between them due to tone reproduction and color gamut compression (Color Research and Application, 1986). An average color difference of 16 ΔE from sampling all 24 patches in the Macbeth ColorChecker was reported. This was not the case in our study because we matched the press sheet using a digital proofer with a larger color gamut than the press.

To present a solution for controlling color on press, Robert Mason showed how inking adjustments were derived from colorimetric measurements of image spots in printed samples as compared with those of the target values (TAGA, 1985). These inking adjustments reduced human errors as well as variations during press runs.

To show practical applications of IT8.7/3 test target and ANSI CGATS TR 001 data set, Sharon Bartels and Richard Fisch measured printed samples of the IT8.7/3 full data set (928 patches) and compared them with the TR 001 data set (TAGA, 1999). The data analysis technique (referred to as CumSum%), credited to Mike Rodriques of R. R. Donnelley, was similar to the CRF between a proof and a press sheet. More recently, CGATS/SC3 proposed a protocol for color image difference assessment (CGATS/SC3 N 406, 2000). It was based on the sum of ΔEs as a demerit from selected color patches from the IT8.7/3 basic target.

## Experimental Approaches

This section presents some basic ideas, assumptions and approaches we used to answer the research questions, "Will colorimetric assessment of color difference between two pictorial color images correlate with visual assessment?" and "At what point does the CRF curve suggest a visual match between two color images?"

A pictorial color image is a collection of pixels with varying tonality and color values. We assumed that the use of a multi-patch target, like the IT8.7/3 (ISO 12642) basic target for analytical work, and the use of an ISO SCID natural image for visual appraisal are sufficient to represent any pictorial color images.

We measured the IT8.7/3 basic target with a Spectrolino Spectro-Scan, a scanning spectrophotometer. It took eight minutes to measure the basic target (182 patches) and 40 minutes to measure the full target (928 patches). We used densitometry and an Excel template to validate printing conditions. We then use colorimetry and an Excel template to generate the CRF curve between the reference and the sample.

We collected samples from a number of experiments under known colorant-substrate-device conditions and performed CRF analyses. Specifically, we began by measuring a single sample more than once to learn the noise in the measurement device. This was followed by measuring the full IT8.7/3 target (whereby the basic target is a subset) from two consecutive press sheets to learn the sheet-to-sheet variation and the difference due to the number of patches measured (928 full data set vs. 182 basic data set). We then addressed the issue of validating a press sheet in relation to a reference printing condition. We analyzed press sheets with solid ink density variations and studied the CRF curves in relation to visual assessment of these images. Finally, we prepared digital proofs and compared them to a reference press sheet in terms of CRF and visual match.

## Experimental Findings

To investigate the use of CRF for color matching between two color images, a number of experiments were performed under two broad categories, i. e., images produced with the same colorant conditions and images produced with different colorant conditions.

First, we discuss the CRF analysis of two images with the same colorant conditions. Case One focused on the measurement noise. A CRF curve between two sets of measurements made from the same press sheet was generated. Curve A in Figure 3 has a ΔE of 0.19 at the 50 percentile, a ΔE of 0.40 at the 90 percentile and a ΔE of 0.64 for the entire range is an indication of instrument noise or repeatability.

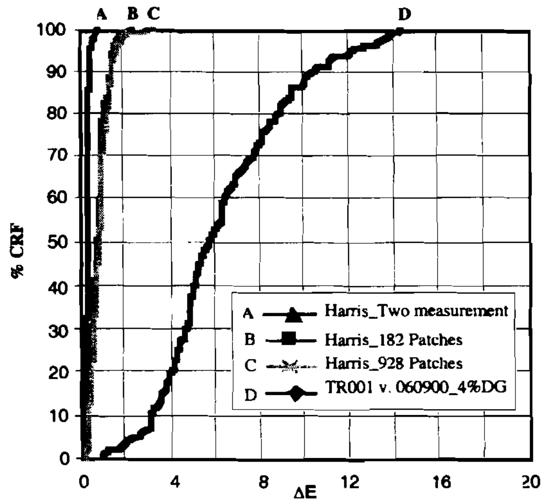


Figure 3. CRF curves from the same colorant condition.

Case Two showed variability between two consecutive press sheets using two measurement quantities. There was no visual difference between the two consecutive press sheets measured. Curve B in Figure 3 was derived from the basic target (182 patches) and Curve C was derived from the full target (928 patches). The shape of the two CRF curves is identical. The largest difference in ΔE statistics (Table 1) between two measurement quantities is one ΔE in range. We conclude that the region where CRF curves A, B and C locate is the 'no visual difference' zone.

| Reference-sample pairs | ΔE statistics | | | |
|---|---|---|---|---|
| | Avearge | 50 percentile | 90 percentile | Unity |
| Two measurements | 0.22 | 0.19 | 0.40 | 0.64 |
| Two samples (182) | 0.70 | 0.64 | 1.25 | 2.17 |
| Two samples (928) | 0.78 | 0.69 | 1.32 | 3.18 |
| Printing validation | 6.34 | 5.72 | 10.09 | 13.51 |

Table 1. ΔE statistics for two sets of measurement, two samples and printing validation.

Case Three investigated the use of TR 001 data to validate a printing condition (ANSI CGATS TR 001, 1995). Table 2 shows the qualification of the press sheet in terms of its densitometric conformance to SWOP printing requirements. The CRF (curve D in Figure 3) is a measure of colorimetric accuracy between the press sheet and TR 001 data.

| Colorant | | Solid ink density | % Dot gain |
|---|---|---|---|
| Cyan | Aim | 1.30 +/- 0.14 | 22 +/- 5 |
| | Sample | 1.24 | 20 |
| Magenta | Aim | 1.40 +/- 0.14 | 22 +/- 5 |
| | Sample | 1.39 | 24 |
| Yellow | Aim | 1.00 +/- 0.14 | 20 +/- 5 |
| | Sample | 0.94 | 25 |
| Black | Aim | 1.60 +/- 0.14 | 26 +/- 5 |
| | Sample | 1.51 | 17 |

Table 2. Validation of a press sheet to SWOP conformance.

The CRF curve D in Figure 3 is a quantitative assessment of the color image difference between a press sheet and its reference printing condition. We are not certain if Curve D is in the 'no visual difference' zone because the reference (TR 001) is a data set, not an image. In addition, printing tolerances are based on acceptability, and not perceptibility. Thus, the location of the CRF curve which ensures a visual match requires further investigation.

Case Four examined CRF curves from a number of press sheet samples with known solid ink density and dot gain deviations from a reference press sheet (Table 3).

| Press sheet description | SID (Status T, Abs.) | | | | % Dot gain | | | |
|---|---|---|---|---|---|---|---|---|
| | K | C | M | Y | K | C | M | Y |
| Normal CMYK inking_0 | 1.52 | 1.24 | 1.36 | 1.01 | 17 | 17 | 21 | 23 |
| High CMYK inking_1 | 1.76 | 1.33 | 1.59 | 1.10 | 20 | 19 | 24 | 28 |
| High M & Y inking_2 | 1.57 | 1.24 | 1.56 | 1.10 | 16 | 16 | 22 | 27 |
| High M inking_3 | 1.35 | 1.21 | 1.56 | 1.00 | 16 | 16 | 23 | 24 |
| Low M inking_4 | 1.53 | 1.28 | 1.26 | 0.99 | 19 | 19 | 18 | 25 |
| Low M & Y inking_5 | 1.51 | 1.23 | 1.16 | 0.89 | 16 | 17 | 17 | 20 |
| Low CMYK inking_6 | 1.38 | 1.11 | 1.22 | 0.89 | 15 | 15 | 18 | 20 |

Table 3. Density and dot gain data of press sheet samples.

The press sheet with normal inking, labelled as Normal CMYK inking_0 in Table 3, was the reference. The CRF curves, derived from the six inking conditions and the reference, represent some boundary conditions of SWOP solid ink density specifications.

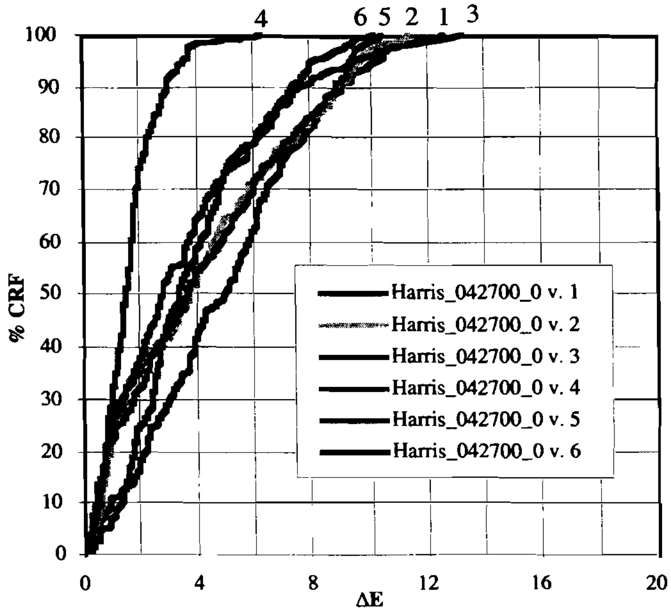


Figure 4. CRF curves with solid ink density variations.

Upon visual assessment, all six press sheets had noticeable color differences in relation to the reference. We conclude that these press sheets may conform to SWOP specifications, but a visual match between two color images imposes a tighter colorimetric tolerance than conformance to printing specifications.

| Inking variations | ΔE statistics | | | |
|---|---|---|---|---|
| | Average | 50 percentile | 90 percentile | Unity |
| High CMYK inking_1 | 5.05 | 5.01 | 9.01 | 12.42 |
| High M&Y inking_2 | 4.21 | 3.78 | 8.94 | 11.19 |
| High M inking_3 | 3.62 | 2.77 | 7.42 | 13.07 |
| Low M inking_4 | 1.66 | 1.50 | 2.97 | 6.19 |
| Low M&Y inking_5 | 4.18 | 3.66 | 8.89 | 10.29 |
| Low CMYK inking_6 | 3.93 | 3.39 | 7.36 | 9.92 |

Table 4. ΔE statistics for SID variations in a press run.

## Further Findings

The CRF analysis of two images with different colorant conditions are shown below. This reflects the digital proofing scenario where the reference is a press sheet and samples are digital proofs.

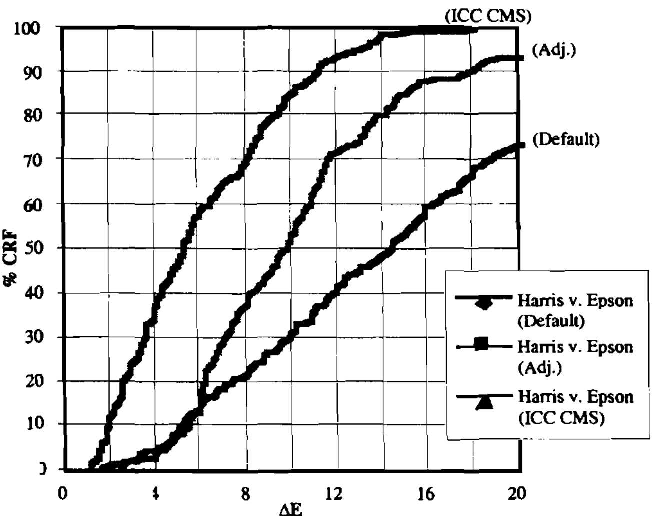


Figure 5. CRF curves of three digital proofs.

In this study an Epson SP5000 ink jet printout of the IT8.7/3 basic target was prepared at the printer default; a second Epson SP5000 ink jet printout was prepared with its CMYK amplitude (or density) adjusted to match that of the reference; and a third Epson SP5000 ink jet printout was prepared with the use of the ICC color management system.

The location of the CRF curves, shown in Figure 5, correlates well with visual assessment of the proof and press sheet. In fact, we demonstrated that amplitude adjustments between two color images with different colorant conditions did not achieve close color match. An ICC-based color management system showed closer color match, but not sufficiently close enough to be of no visual difference.

By examining the ΔE statistics in Table 5, we realize that the CRF curve for the ICC-based Epson proof has a ΔE of 5.33 at the 50 percentile, ΔE of 11.13 at the 90 percentile and ΔE of 17.03 for the entire range. While there is a noticeable color difference between the digital proof and the press sheet, it suggests that there is a fair color match zone which may be specified by means of the CRF curve.

| Sample | ΔE statistics (Reference: Harris) | | | |
|---|---|---|---|---|
| | Avearge | 50 percentile | 90 percentile | Unity |
| Epson 5K (Default) | 15.57 | 14.38 | 25.92 | 57.74 |
| Epson 5K (Adjusted) | 10.53 | 9.67 | 17.49 | 26.46 |
| Epson 5K (ICC CMS) | 6.09 | 5.33 | 11.13 | 17.03 |

Table 5. ΔE statistics for proof and press sheet agreement.

## Summary

Color image matching takes two forms, invariant match and metameric match. For images rendered with the same (CMYK) colorants, invariant match between a reference image and a sample image is achieved when the amplitude responses (% dot area vs. density) of these colorants are taken into account. For images reproduced with different colorants, metameric match is achieved for each of the pixels between a reference image and a sample image.

The goal of color control on press is to achieve invariant color matching. When the amplitude responses match between two identical colorant-substrate-device systems, color image match is assured. A number of color proofing devices were designed to match a targeted reference printing conditions. However, when the amplitude responses match between two different colorant systems, color match between the two color images is not assured. This is where color management system is needed to provide the pixel-level color matching with the use of two profiles and a CMM.

A CRF curve of the ΔE distribution, based on colorimetric measurements between two IT8.7/3 basic targets, correlates with visual assessment of two pictorial color images. A visual match between two color images imposes a tighter colorimetric tolerance than the conformance to printing specifications.

## Further Research

We propose that a CRF curve, located to the left of Curve A in Figure 6 (with a ΔE of 0.6 at the 50 percentile, a ΔE of 1.2 at the 90 percentile and a ΔE of 2.4 for the unity) has no visual difference between the two pictorial color images.

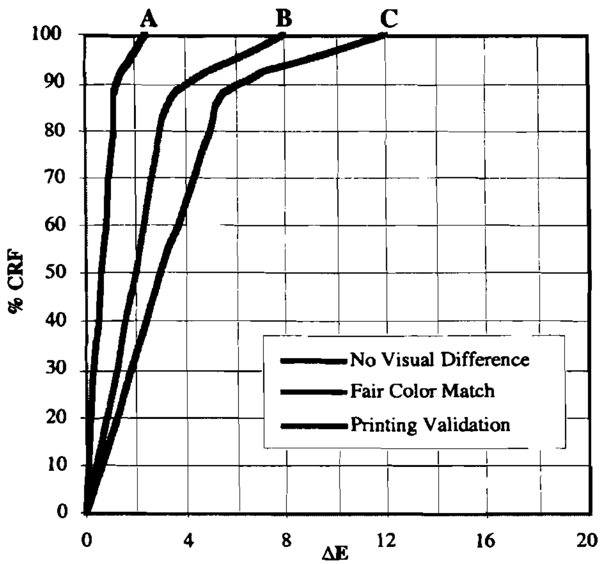


Figure 6. CRF curves for perceptibility and acceptability.

To answer the question of perceptibility, we propose that a CRF curve, located to the left of the Curve B (with a ΔE of 2 at the 50 percentile, a ΔE of 4 at the 90 percentile and a ΔE of 8 for the unity) has a fair color match between the two pictorial color images. To answer the question of acceptability, we propose that a CRF curve, located to the left of the Curve C (with a ΔE of 3 at the 50 percentile, a ΔE of 6 at the 90 percentile and a ΔE of 12 for the unity) conforms to its reference printing condition. Two color images with a CRF curve located to the right of Curve C in Figure 6 have poor color match.

Making the assumption that a multi-patch target is representative of any pictorial color image may prove to be false in some cases. Further studies are necessary to verify the above proposed conditions in relation to the effect of color image contrast, memory colors and dominant colors within a pictorial color image. These findings and observations should be deliberated and incorporated into the standardization efforts.

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