The typical purpose of the linearization curves in conventional four-ink printing is to compensate for dot overlapping and dot size variations and therefore accommodate the non-linearity of the printing process. (Noyes, Hardeberg, and Moskalev, 2000)

Color matching accuracy and a profile may be assessed by B2A1 (device to LAB, colorimetric tag) and A2B1 (LAB to device, colorimetric tag) are used to assess ICC output profiles. The accuracy of the B2A1 part of the output profile can be measured by calculating the color difference between the source LAB values sent to a printer and the measured LAB values printed by the printers. (Sharma, 2005)

CIEDE2000 is the most accurate tool at present to predict visually perceived color difference among the last three CIE-recommended formulas. (Melgosa, Huertas, and Berns, 2004) CIEDE2000 color difference formula predicts visual color differences of high chroma colors better than the CIELAB color difference formula. (Chung, 2005) Thus, CIEDE2000 was chosen to assess color matching ability in this study.

**Equipment & materials**

Variation during the processes can impact the color management performance. The result can vary if different printer, different paper, or different color management profiling software is used. The experiment was tested under the following conditions:

- Operation System: Mac OS X
- CMS: Profiling Software: GretagMacbeth ProfileMaker 4.1.5
- API: Adobe Photoshop CS
- RIP: Harlequin RIP Eclipse Release SP4
- Printer: Epson Stylus Pro 4000 Print Engine with UltraChrome Ink. The same ink cartridges were used through the entire study. Only cyan, magenta, yellow, and photo black were used in this study.
- Paper: Epson proofing paper commercial semimatte (S041744)
- Measurement and analysis Instrument: GretagMacbeth Spectroline; Spectroscan system
- Test targets: ECI 2002R CMYK profiling target; IT8.7/3 basic target (page 60): CIELAB test target; ISO color chart 57A; spatial uniformity target (ISO 12640, 1997); printer calibration target
- Excel spreadsheet: Calibration.xle; Transfer.xle. Process. xle

Only colorimetric matching ability based on CIELAB
(D50, 2 degree) was evaluated and color differences are displayed as CIEDE2000 (\(\Delta E_{00}\)) in this study. All measurements were collected under standard white backing. (ANSI CGATS.5., 2004)

**Methodology**

Calibration adjusts a device’s output to correlate with a requested value. In the case of a color printer, calibration ensures that the correct amount of cyan, magenta, yellow, and black colorants are printed. “Linearization is the process of adjust values on output so that the result is proportional to the values request.” (Global Graphic, 2004) There are many approaches in achieving printer calibration, and dot curve linearization is one of them. In this study, the methodology focuses on calibrating the printer linear to dot area.

Fig. 1 is a flowchart explaining the testing process. Part A is the device qualification stage. Part B is the experimental stage that includes printer calibration, building ICC profiles, and the color matching analysis.

**Part A. Device qualification**

Stable and repeatable devices are the key requirements within an experiment. Before the color matching performance test, substrate spatial uniformity, printer spatial uniformity, temporal consistency, and printer gamut were verified.

**Substrate spatial uniformity**

A random sheet of Epson ink jet proofing paper commercial semi-matte was measured using the same template for IT8.7/3 basic target (5.5” x 6”) on a GretagMacbeth SpectroScan with GretagMacbeth MeasureTool software. Following Chung and Shimamura (2001), total of 182 measurement samples were collected for substrate spatial uniformity. Substrate uniformity was estimated by (a) the average \(\Delta E_{00}\) between the average \(L^*, a^*,\) and \(b^*\) values of all samples and the individual CIELAB values, and (b) the cumulative relative distribution of all \(\Delta E_{00}\)s (CRF). (Eqs. 1-5)

\[
\sum \frac{L^*}{n}, \quad \sum \frac{a^*}{n}, \quad \sum \frac{b^*}{n}, \quad \sum \Delta E_{00}^*.
\]

The average \(\Delta E_{00}\) of substrate spatial variation is 0.07. The CRF curve shows (1) 50 percent of the \(\Delta E_{00}\)s are 0.06 or less, and (2) 90 percent of the \(\Delta E_{00}\)s are 0.12 or less (Fig. 2). The substrate spatial variance is very small, and therefore this substrate is qualified for the testing.

![CRF curve of substrate spatial uniformity](image)

**Part B**

<table>
<thead>
<tr>
<th>Method One</th>
<th>Method Two</th>
</tr>
</thead>
<tbody>
<tr>
<td>Default printer setting</td>
<td>Custom printer setting - 0% dot gain</td>
</tr>
<tr>
<td>Print ECI 2002 profiling target</td>
<td>Print ECI 2002 profiling target</td>
</tr>
<tr>
<td>Create ICC profile (Profile One)</td>
<td>Create ICC profile (Profile Two)</td>
</tr>
<tr>
<td>CIELAB test target</td>
<td>CIELAB test target</td>
</tr>
</tbody>
</table>

![Testing workflow](image)

Fig. 1: Testing workflow

Fig. 2: CRF curve of substrate spatial uniformity
Printer spatial uniformity

Printer spatial uniformity is defined as the degree of ink uniformity within a single print and it is assessed colorimetrically. Four solid color strips, cyan, magenta, yellow, and black across a single sheet were printed by Epson Stylus Pro 4000 (Epson SP4000). Each trip is 8 x 0.25 inch and this target is printed twice in two orientations, horizontal and vertical.

30 CIELAB measurement samples were collected width wise from each strip. Spatial uniformity is estimated by (a) the average \( \Delta E_{00} \), i.e., the average of each L*, a*, and b* value between the individual CIELAB values. The sum of CIELAB was then divided by the number of measurements. (b) The cumulative relative distribution of all \( \Delta E_{00} \) s (CRF).

Fig. 3 shows the CRF curves of horizontal (top) and vertical (bottom) printer spatial uniformity. The horizontal print presents a result that 90% of all CMYK \( \Delta E_{00} \) s are equal or less than 0.16. The vertical print shows 90% of all CMYK \( \Delta E_{00} \) s equal or less than 0.39, but the largest \( \Delta E_{00} \) 0.74, is much higher than the largest \( \Delta E_{00} \) 0.17, of the horizontal print. The average \( \Delta E_{00} \) of spatial uniformity is 0.11 \( \Delta E_{00} \) (horizontal 0.07 \( \Delta E_{00} \) and vertical 0.14 \( \Delta E_{00} \)).

Sources of variability in spatial uniformity can be assignable or random. Assignable variation can be differentiated from random variation by observing patterns from individual \( \Delta E_{00} \) s as a function of width wise. In brief, any assignable caused variation can be identified by the non-randomness in a distance dependent plot. The horizontal print shows random variation and good uniformity. However, it is obviously that the vertical print shows assignable variations in the head and the tail of the test strips with the largest \( \Delta E_{00} \) 0.74 (cyan).

Printer color consistency

A 78-patch ISO color chart, S7A.tif (ISO, 1997), is printed by Epson SP4000 each day for one week and followed by once a week for a month. The first print was treated as a reference. \( \Delta E_{00} \) s of each patch between reference and samples were calculated and recorded in an Excel spreadsheet for color consistency analysis.

Fig. 4 shows the time plot of printer color consistency. It shows no assignable caused variation in the plot. The average of all prints is 0.25 \( \Delta E_{00} \) and the maximum \( \Delta E_{00} \) is 0.33.

CIELAB test target & printer color gamut confirmation

A CIELAB test target is needed in this study to test the printer profiles in color matching ability from LAB color space to CMYK color space. Using Adobe Photoshop CS, an IT8.7/3 basic target was converted from CMYK to LAB color space via the standard ECI offset profile, ISOWebcoated.icc. It was converted under absolute colorimetric intent and Adobe CMM engine. The LAB IT8.7/3 basic target was saved as a TIFF file. Furthermore, the CIELAB values of 182 patches were recorded from Photoshop CS after the conversion and saved in an Excel spreadsheet for color gamut analysis.

To reproduce all of color patches in the LAB IT8.7/3 basic target, we need to confirm that: the Epson Stylus Pro 4000 with Epson UltraChrome Ink on Epson proofing paper commercial semi-matte can reproduce all the color patches on the LAB IT8.7/3 basic target. A CMYK IT8.7/3 basic target was printed via printer default setting, and its CIELAB colorimetric data was measured and compared to the gamut of the LAB IT8.7/3 basic target. To assess whether the printable gamut of Epson SP4000 covers all the patches in the LAB IT8.7/3 basic target, a CMYK IT8 basic chart was printed and the colorimetric data was analyzed in the Excel template, Process.xls.

In the Excel template, the CIELAB data of the LAB IT8.7/3 basic target was treated as a reference in comparison to the sample, CIELAB values from the printed CMYK
Part B. Printer calibration & color matching analysis

After the device qualification, the printer is calibrated per 0% dot gain. Two printer settings, default and 0% dot gain, were used for ICC printer profiling and color matching analysis.

Printer per default and 0% dot gain calibration
When printing per default, no ink tonal adjustment was applied to the printer. To calibrate the printer to 0% dot gain, Harlequin RIP Eclipse Release SP4 was used to control the printer. A printer tonal calibration target was printed via Harlequin RIP. Density data of the printed target was measured by Spectrolino and recorded in Excel templates, Calibration.xls and Transfer.xls. Transfer curves were calculated to calibrate the printer to 0% dot gain. The transfer curves were then loaded into the Harlequin RIP for color profiling. Fig. 7 shows the CMYK dot gain curves of default and 0% dot gain printer setting.

Printer profiling and color matching analysis
An EC12002R CMYK profiling target was printed under default (Method One) and 0% dot gain (Method Two) printer conditions. The profiling targets were measured and profiles were generated using GretagMacbeth ProfileMaker 4.1.5 under the GretagMacbeth predefined separation setting, Inkjet 400. (400TAC, black start: 40, GCR3) Both ICC profiles, Profile One (default) and Profile Two (0% dot gain) were used to convert the CIELAB test target to CMYK mode in Adobe Photoshop CS. The Adobe CMM was used, the intent was Absolute Colorimetric, and Dither was not selected. These two converted test targets were then printed by the printer under default and 0% dot gain settings separately.

The printed test targets were measured by GretagMacbeth Specrosan for CIELAB values under the condition of CIE illuminant D50 and 2-degree standard observer (ANSI CGATS .5-1993) on a white standard backing. These values were then compared to the reference values of the CIELAB test target.
Experimental results

Table 1 provides a descriptive statistical summary of the color matching experiment (SAS, 1990). A number of conclusions can be stated: (1) the average color matching performance under the default setting is 3.1 $\Delta E_{00}$ as opposed to 2.8 $\Delta E_{00}$ under the 0% dot gain setting; (2) the variance in $\Delta E_{00}$ distribution under the default setting is smaller (1.6) than that under the 0% dot gain setting (5.5); and (3) there is less skewness in the $\Delta E_{00}$ distribution (0.7) under the default setting than that under the 0% dot gain setting (1.5).

Table 1: Summary of color matching performance comparisons

<table>
<thead>
<tr>
<th></th>
<th>Method One</th>
<th>Method Two</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Default</td>
<td>0% dot gain</td>
</tr>
<tr>
<td>Total Patches</td>
<td>182</td>
<td>182</td>
</tr>
<tr>
<td>Average ME00</td>
<td>3.1</td>
<td>2.8</td>
</tr>
<tr>
<td>Standard Deviation</td>
<td>1.3</td>
<td>2.4</td>
</tr>
<tr>
<td>Variance</td>
<td>1.6</td>
<td>5.5</td>
</tr>
<tr>
<td>Skewness</td>
<td>0.7</td>
<td>1.5</td>
</tr>
</tbody>
</table>

A T-test (unequal variances) was performed to test the hypothesis whether the two population means are the same or not. The result shows that the P-value, is 0.18. P-value is the probability of stating that the two means are significantly different. Thus, it is concluded that there is no significant difference between the two population means at the alpha risk of 0.05. In other words, there is no significant color matching improvement using 0% dot gain as the criterion for device calibration.

Discussion

The $\Delta E_{00}$ distribution, expressed as a cumulative relative frequency (CRF), for each of the two calibration methods is shown in Fig. 8. The key point of interest to find out is whether these color differences are randomly distributed throughout the lightness range or not.

Fig. 8. CRF curves of color matching ability, default setting and 0% dot gain

Fig. 9 plots color difference as a function of $L^*$ for all color patches. The distribution of color differences (left-hand side) appears to be random in the default setting, but not random in the 0% dot gain setting. Specifically, larger $\Delta E_{00}$s tend to fall between 20 $L^*$ and 30 $L^*$ in the 0% dot gain setting. The finding suggests that the ICC profile built under the default setting performed color matching equally throughout the tonal region and the ICC profile built under the 0% dot gain did not.

The other point of interest is whether the patches having large color differences in the 0% dot gain setting are distributed in a specific region of the color space or not. Tables 2a and 2b list the worst 10% color patches with their colorimetric properties ($L^*$, a*, b*, C*, and h). By observation, many of the color patches are in the shadow area of the color space and hue angle is between 135 to 300 degree.

The idea behind the 0% dot gain calibration is to see if the increased slope in the shadow region of the tonal scale can improve the color matching performance of the ICC profile (Fig. 10). What we have learned in this study is the opposite of what we envisioned.
Acknowledgements

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References


Suggestions for further study

In this study, only calibrating a printer linear per dot area was researched. The result showed that there is no improvement in color matching performance. There are other approaches that may be examined for printer calibration, such as linear to L* or C* (Fig. 12).

Using $\Delta E$ formulas to express color difference of synthetic targets does not provide concrete evidence whether two pictorial images match or not. A full-scale color management study involving proofer calibration, profiling, color managed press run, and digital proofing is recommended to provide an opportunity to test color matching performance in both quantitative and visual assessment between press sheets and digital proofs.

Fig. 11 plots the hue progression of primary (CMY) and overprint (RGB) colors between default and 0% dot gain settings on an a*b* diagram. Most of the data points were shifted to low chroma area, and not enough data points were used to model the color behaviors in high chroma area. It explains why highlight patches show much better result in color matching ability than shadow patches via the 0% dot gain setting.

Fig. 11: Hue progression comparison

Fig. 12: Calibration per lightness (left) and chroma (right)