Achieving Color Agreement: Evaluating the Options

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Abstract

Color repeatability addresses conformance to standards and process control to ensure color consistency in process color printing. While repeatable color is a virtue, poor color agreement often exists among color printing devices. In this research, a number of image adjustment methods, from applying transfer curves to applying device link profiles, were examined to see if one method would achieve significantly better color agreement than any other methods. We found out that there is no single method that produces significantly better visual agreement when the color differences between the two printing systems are small. On the other hand, the device link achieves the best color agreement when the colorants of the two color printing devices are different.

Keywords: printing, calibration, color matching, color management

1. Introduction

When sending the same CMYK file to different output devices, the hard copies often appear differently in color. This is because CMYK is device dependent. When print buyers demand color matching between different printing devices, they will not accept the above as an excuse. Thus, printers need a solution to reconcile the color difference between different color output devices. For repeatable printing devices, the reconciliation can be done by means of device calibration and color image adjustment.

Three Levels of Color Match

Before we delve into color matching solutions, let’s take a look at the three levels of color matching expectations: spectral match, colorimetric match, and appearance match. Spectral match, being the most stringent of the three, relies on ink formulation and colorant mixing. The match does not depend on light source and is regularly applied to ink mixing and spot color printing. Colorimetric match relies on the principle of tristimulus integration, i.e., by integrating spectral energy of the light source, the spectral reflectance of the colorant, and the color matching functions of the human eye. The match may exist between dissimilar colorants. Colorimetric match is applicable to proof and press sheet match. Appearance match, being the least stringent of the three, relies on visual judgment of human observers that can be influenced by the viewing conditions and the color vision of the observers themselves. Appearance match is applicable to pictorial color image agreement, e.g., between proof and print, and is frequently exercised by graphic designers and print buyers.

Objectives

Given that color differences exist between CMYK devices and that color differences can be reconciled using image adjustment methods, this research raises a basic questions, i.e., “Does a particular adjustment method yield better color agreement than the rest of the methods, and why?” In this research, color agreement of different image adjustments is determined by visual examination in the form of paired comparison.
2. Experimental

This section first describes a situation whereby two printing devices belong to two different color reproduction workflows. The output of the first workflow is the press sheet that serves as the reference. The output of the second workflow is the proof that serves as the sample. Sample proofs need to match the press sheet closely by means of different image adjustment methods. This section then describes input materials and equipment used in the experiment. This is followed by various color image adjustment procedures.

Two Color Reproduction Workflows

To explore various options in achieving color agreement between two dissimilar color printing devices, we consider the following two workflows: publishing and proofing. As shown in the top row of Figure 1, the publishing workflow involves the conversion of RGB images to the press CMYK space plus printing these images under calibrated press conditions. The press sheet (CMYK₁) represents the reference.

![Figure 1. Two workflows involving two color printing devices](image)

The color proofing workflow (bottom row of Figure 1) starts with the press CMYK as the input data. The adjustment of color image data from the press color space (CMYK₁) to the proofer color space (CMYK₂) is the objective of the study. Adjusted image data are then printed by the proofer under its calibrated conditions.

Materials and Equipment Used

The Heidelberg Speedmaster 74 sheetfed offset press is the output device in the publishing workflow. The Kodak NexPress 2100 digital press is the output device in the proofing workflow. Figure 2 depicts the test form used in the initial phase of the experiment. Here, color control bars are used for press calibration and printing process control; IT8.7/3 (basic) color patches are used to analyze color differences between the two color printing devices and are used to reconcile the differences; and pictorial images are used for visual assessment of color agreement between proof and press sheet.

![Figure 2. Test form for visual and quantitative analyses](image)
Four Image Adjustment Methods

The first adjustment method is gradation adjustment. A transfer curve is derived between the reference gradation and the sample gradation. As shown in Figure 3a, the procedure begins from (1) identifying an input value, e.g., 80% digital dot, and trace through the reference gradation to find out the magnitude of the output (1.0 density); and (2) finding the specific digital dot that produces the same magnitude in the sample device (85%). If we find enough data points, e.g., 80% vs. 85%, using the procedure and construct the transfer curve (Figure 3b), we can reconcile the gradation difference channel by channel.

Instead of using density as the gradation, transfer curves may be derived using metric chroma (C*) for chromatic inks and darkness (100 - L*) for black printer. Transfer curves are typically applied at the RIP stage prior to output. In this research, transfer curves are applied at the image editing stage (early device-binding) so that sample prints, prepared by different adjustments, can be printed in a single press run.

The second adjustment method is based on tone reproduction and gray balance (TrGb for short). This is accomplished by deriving three (CMY) transfer curves (Figure 4) that satisfy gray balance and, when added the adjusted black gradation by the first method, also satisfy the tone reproduction between the reference and the sample.

To implement the TrGb method, we need to know the combination of CMY that would render a series of neutrals (also known as equivalent neutral dot area) for both the reference and the sample device. One way to obtain equivalent neutral dot area is to construct ICC profiles without the black channel; then use a color...
management API, such as ColorThink 3.0 Pro, to find out the equivalent neutral dot areas for both the reference and the sample device.

As shown in Table 1, the same neutrals are rendered by different CMY amounts between the offset reference and the NexPress. Here, the neutral is represented by Darkness (DK), i.e., \((100 - L^*)\). So, Figure 4 is the result of plotting the equivalent dot area of the reference (x-axis) against the equivalent dot area of the sample (y-axis) for each of the cyan, magenta, and yellow channel. As in the gradation adjustment method, these transfer curves may be applied at the image editing stage (early device-binding) or at the RIP (late device-binding) stage prior to output.

Table 1. Equivalent neutral dot areas of two printing devices

| DK \((100 - L^*)\) | SM74 | | | | | | NexPress |
|---|---|---|---|---|---|---|
| | %DA C1 | %DA M1 | %DA Y1 | %DA C2 | %DA M2 | %DA Y2 |
| 75 | 89.6 | 80.6 | 87.4 | 96.6 | 97.7 | 81.7 |
| 65 | 78.2 | 65.2 | 69.6 | 78.3 | 76.1 | 70.4 |
| 55 | 63 | 50.4 | 52.7 | 63.1 | 60.2 | 56.7 |
| 45 | 48.3 | 39.1 | 41.7 | 48.7 | 45.7 | 44.8 |
| 35 | 35 | 26.5 | 30.3 | 35.4 | 31 | 32.1 |
| 25 | 21.6 | 15.5 | 19.7 | 22.2 | 19.9 | 20.9 |
| 15 | 8.7 | 5.5 | 9.4 | 10.1 | 8.9 | 10.1 |
| 5 | 1.1 | 0.2 | 3.5 | 1.2 | 0.6 | 2.8 |
| 0 | 1.2 | 0.2 | 3.7 | 1 | 0.4 | 2.7 |

The third adjustment (A-B-A for short) method converts color image data from the press CMYK (A) space, via the profile connection (B) space, to the proofer (A) color space. We use the Adobe Photoshop as the color management API to specify the two ICC profiles and the absolute colorimetric rendering intent. Depending on workflow considerations, other API, e.g., PDF and RIP, may also be used prior to output.

The fourth adjustment method converts color image data from the press CMYK space directly to the proofer space using a device link profile and the absolute colorimetric rendering intent. We use Alwan LinkProfiler to construct the device link profile by concatenating the source (offset press) profile and the destination (NexPress) profile together while preserving purity of all single ramps and two-color print solids. We use the Adobe Photoshop plug-in by Alwan to perform the device link conversion. Color conversion can also be applied to PDF files using Acrobat plug-in from Callas.

3. Results and Discussions

Results of the experiment are organized in the following three sections: (1) verification of adjustment methods, (2) color agreement testing by paired comparison, and (3) further color agreement testing using different colorants. Subsequent discussions are also included to reflect key findings in the research.

Verification of Adjustment Methods

Let’s begin with the before-and-after comparison of to gradation adjustment method. Figure 5 shows the adjusted NexPress print (dotted line) and the initial print (solid line). The left-hand side of Figure 5 is the overall gradation, expressed as % digital dot area vs. density; and the right-hand side of Figure 5 shows the density differences relative to the offset reference (x-axis). There are two observations: (1) the gradation difference is quite small to begin with (something that we did not envision beforehand), and (2) the experimental error is very small, i.e., we implemented the gradation adjustment well.
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The verification of the TrGb based adjustment is illustrated in Figure 6. Notice that the tone reproduction (solid line) between the initial print and the offset reference, as shown in Figure 6 (left), do not have a one-to-one relation. The adjusted tone reproduction becomes a straight-line at 45 degrees (dotted line).

Incidentally, the GRACoL Committee in the U.S. developed a Computer-to-Plate calibration technique, known as the G7 method (IDEAlliance, 2006). It requires the use of a specially designed gray balance target along with special-purpose software to derive the transfer curves relative to a few pre-defined reference conditions. The TrGb adjustment method, described in the paper, offers a generalized solution for any user-defined reference conditions.

The effect of the A-B-A method can be verified from color gamut of the initial state (solid line) and the adjusted state (dotted line) of the NexPress in comparison to the offset reference. As shown in Figure 7, (1) the color gamut of the NexPress is slightly larger than that of the offset reference; and (2) all corner points of the adjusted color gamut (dotted line), particularly the yellow solid and CMYRGB ramps, are closely aligned to that of the offset reference (gray line).
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A potential drawback of the A-B-A method is that primary colorants, e.g., cyan only pixels, are mapped to pixels with multi-colorants. Consequently, a small amount of magenta or yellow is also printed where the cyan is by the destination device. This effect becomes pronounced when single back type becomes rich (CMYK) black that challenges the registration ability of the press and causes quality issues in clarity and readability of small types.

The effect of the device link adjustment method is evidenced in Figure 8. Notice how corners of the adjusted color gamut stay unchanged due to the constraints imposed when constructing the device link profile. By preserving the purity of single solids and ramps, it overcomes the printability issues as discussed in the A-B-A method.

One may wonder what is the downside of using device link profile, particularly in the context of colorimetric accuracy. Our experiences have been none. This is because pixels in real life pictorial images do not have pixels with pure primary chromatic colors. Even though the device link profile trades colorimetric accuracy of the primary colorants for printability, colorimetric accuracy of pictorial images between the reference and the sample is preserved.

Color Agreement Testing by Paired Comparison
We conducted a paired comparison test using two pictorial subject matters, *Old Man* and *Gears* as shown in Figure 1. Each subject matter is prepared by five adjustment conditions: (A) initial or no adjustment, (B) gradation, (C) tone reproduction and gray balance, (D) color management, and (E) device link. Ten observers were asked to pick one from a pair of prints, under standard viewing conditions, which matches closer to the offset reference. The test was conducted one judge at a time (Figure 9).

By means of non-parametric statistical analysis (Rickmers, 1973), Table 2 shows that six out of ten judges are consistent in judging a given subject matter. Only four judges who are consistent in judging both subject matters. Due to similarity of the color gamut of the two devices, there is no real difference in the print samples. In fact, the initial print (A) was not ranked the last in both cases; and the longer one stares at the images, the less certain is about the visual difference between them. The only exception that a print has real difference is the *Old Man* print adjusted by the TrGb method. The TrGb method was ranked as the best match to the offset reference.

<table>
<thead>
<tr>
<th>Scene</th>
<th># of consistent judges</th>
<th>Ranking of adjustment methods from best to worst</th>
<th>Significant agreement among judges at 0.05 risk</th>
<th>Correlation coefficient (R)</th>
<th>Print that has real difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Old man</td>
<td>6</td>
<td>CBDAE</td>
<td>Yes</td>
<td>0.5</td>
<td>C</td>
</tr>
<tr>
<td>Gears</td>
<td>6</td>
<td>BAECDA</td>
<td>No</td>
<td>0.1</td>
<td>None</td>
</tr>
</tbody>
</table>

It became clear that color agreement between printing devices with similar colorants is lesser of an issue than color agreement between devices with different colorants. The reason is because there is not much color difference existed between the two devices to begin with. In addition, the magnitude of the process drift and run-to-run variability can easily reduce the effect of the adjustment.

**Further Color Agreement Testing using Different Colorant Conditions**

We conducted the experiment using different colorants between the reference and the sample device in order to further test the effect of image adjustment methods. In this case, we used the Heidelberg Speedmaster 74 sheetfed offset press as the reference device and the Epson 4000 inkjet printer as the sample device. Figure 10 illustrates the test from with the pictorial color images used to the color agreement assessment.
Figure 10. Test form for visual and quantitative analyses—Round Two

The ColorBurst 4.1 RIP controls the Epson 4000 inkjet printer by enabling all CMYK primary inks and disabling all light inks. Figure 11 illustrates the color gamut difference between the offset press and the Epson 4000 inkjet printer. Figure 11 suggests that the inkjet color gamut is significantly larger. In addition, the two magenta inks are very different with the printing ink being more reddish and the inkjet ink more bluish. In term, there are sufficient color differences in two-color overprints (red and green).

Figure 11. Color gamut comparison between offset press and the Epson 4000

Color Agreement Testing by Paired Comparison—Round Two

We conducted a paired comparison test using five pictorial subject matters prepared in five adjustment conditions: (A) density, (B) chroma and darkness, (C) tone reproduction and gray balance, (D) color management, and (E) device link. Ten observers were asked to pick one from a pair of prints, under standard viewing conditions, which matches closer to the offset reference. By means of non-parametric statistical analysis, the results are summarized in Table 3.
Table 3. Summary of color agreement by paired comparison

<table>
<thead>
<tr>
<th>Scene</th>
<th>Number of consistent judges</th>
<th>Ranking of adjustment methods from best to worst</th>
<th>Significant agreement among judges at 0.05 risk</th>
<th>Correlation coefficient (R)</th>
<th>Print that has real difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Camel</td>
<td>7</td>
<td>EDCAB</td>
<td>Yes</td>
<td>0.8</td>
<td>E and B</td>
</tr>
<tr>
<td>Pink Peony</td>
<td>8</td>
<td>EDCAB</td>
<td>Yes</td>
<td>0.7</td>
<td>E and B</td>
</tr>
<tr>
<td>Red Peony</td>
<td>6</td>
<td>EDCAB</td>
<td>Yes</td>
<td>0.9</td>
<td>E and B</td>
</tr>
<tr>
<td>Lotus</td>
<td>9</td>
<td>EDACB</td>
<td>Yes</td>
<td>0.8</td>
<td>E only</td>
</tr>
<tr>
<td>Pumpkin</td>
<td>7</td>
<td>DEACB</td>
<td>Yes</td>
<td>0.6</td>
<td>B only</td>
</tr>
</tbody>
</table>

To elaborate, six or more judges are consistent in judging a given subject matter. There is good agreement among these consistent judges. Due to large color differences between the two devices, there is real difference in the print samples prepared by the device link method (E) that produces the best match to the reference press sheet. The color-managed (D) print came as a close second. The print sample by tone reproduction and gray balance (C) falls in the middle of the color agreement ranking. The print sample prepared by the chroma adjustment method (B) produces the worst match to the reference press sheet.

4. Conclusions and Further Research

This research explored various image adjustment options in achieving color agreement between different color printing devices. When colorants are similar, the color difference between the reference and the initial sample print is small; no one color image adjustment method yields better color agreement than other methods. When the color difference between the reference and the initial print sample is large, the print sample adjusted by the device link method produces the best match to the reference. This is followed by the color management method.

To achieve color agreement between similar colorant conditions, e.g., from press run to press run, transfer curves derived from either the gradation adjustment or the tone reproduction and gray balance work well. To achieve color agreement between different colorant conditions, e.g., proof and print, device link method performs the best.

Several follow-up research projects are under way. We want to find out to what extent we can improve the color agreement further by means of profile editing. We want to predict visual assessment outcome by quantitative analysis with the use of a synthetic test image that is image content-based, as oppose to colorant-based, e.g., IT8.7/3 (basic) target. In addition, we want to explore the above research objectives by means of simulation, i.e., using soft proofing to replace hard copy, in order to eliminate process drifts and run-to-run color variations.

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Literature Cited