The Correlation of Line Quality Degradation With Color Changes in Inkjet Prints Exposed to High Relative Humidity

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Abstract

A test target containing both solid-fill colors and finely cross-hatched line patterns of colors was investigated as a method to correlate macro colorimetric measurements with changes in printed line quality on inkjet media exposed to high relative humidity. The objective was to achieve a single macro measurement technique that can simultaneously rank test samples for both humidity-induced color shift and loss of line quality or edge sharpness. The results show that the inclusion of the cross-hatched line patterns in the test target proved essential to achieve a high correlation with visually observed changes in line quality.

Introduction

Many inkjet substrates printed with aqueous dye-based inks are known to exhibit significant colorant migration in high humidity environments, and the rate of change in color has previously been shown to decrease as a logarithmic function over time at steady-state temperature and humidity levels.[1,2] A recent paper reported that humidity-induced line width changes can also vary dramatically as a function of colorant combinations.[3] Different printed colors contain diverse concentrations of colorants and residual solvents. These ingredients can act to selectively advance or retard the migration of the individual colorants in conjunction with increased moisture content supplied by elevated relative humidity in the surrounding environment. Lateral diffusion accounts for the visual changes in line quality whereas both vertical and lateral diffusion of the dyes can cause color shifts.

The humidity-induced degradation of line quality is often referred to as image "bleed" and can be manifested as changes in both line width and edge sharpness. Additionally, color fringes can emerge as a result of disproportionate migration of one or more of the individual colorants. In order to characterize the humidity fastness of a specific inkjet system (i.e., printer, ink, and substrate) and subsequently rank different systems' performance, both the tendency to shift in color as well as the changes to spatial image quality must be taken into account. Although quantitative image analysis techniques may be used to assess image quality, no single algorithm appears to be suitable as a means to quantify the

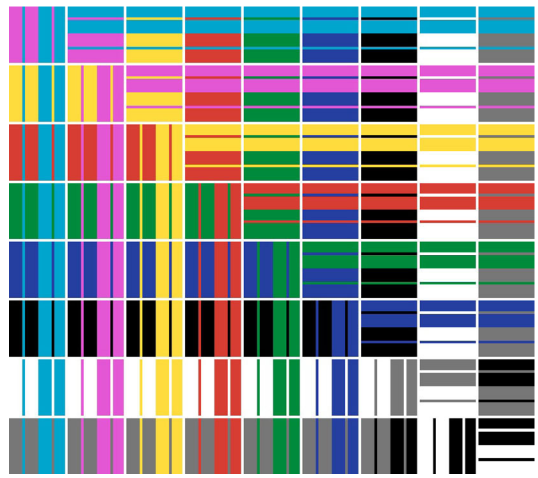

Figure 1. A line pattern test target of 36 color pairs (4 lines per color pair) for assessing image bleed in inkjet prints exposed to high humidity. 72 dpi line width.

line-width change, loss of edge sharpness, and color fringing that may take place in selective and highly image-dependent areas of a print. A psychophysical scaling method was thus implemented to quantify overall changes in line quality by visually rating a set of line patterns in a printed test target before and after humidity exposure (see Figure 1). The results were then compared to color difference measurements (ΔE) taken on patches of solid-fill colors as well as a special set of patches made with finely ruled and cross-hatched lines of different colors. The cross-hatched lines resembled a "checkerboard" pattern and had high enough frequency to be uniformly integrated by a conventional spectrophotometer with 4mm aperture or larger (see Figure 2). However, the checkerboard feature was coarse enough to be easily printed on typical desktop inkjet printers. The goal was to create cross-hatched lines with lateral space to bleed and consequently affect the color of the checkerboard patches.

Experimental

The subjective ranking approach was used to visually rate the magnitude of overall change in line quality using a test array

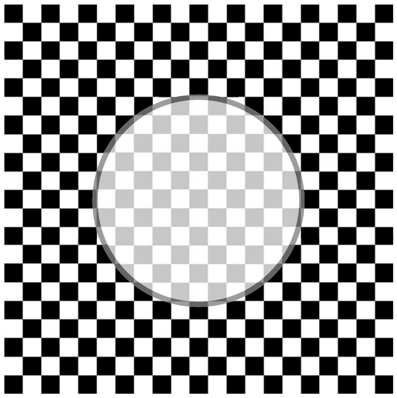

Figure 2. Checkerboard patterned patch with 72 squares-per-inch line frequency in each patch. Tne circle represents a 4 mm spectrophotometer aperture drawn to scale on a 7mm x 7mm patch.

containing 36 colored line-on-background patterns printed with vertical and horizontal line orientations and also with reversals of foreground and background color. The complete set of lines on backgrounds thus created a total of 144 lines to evaluate for each printed sample as can be seen in Figure 1. We refer to the psychophysical scaling results of these line patterns as the "Bleed rating" data in this paper. Next, the same foreground/background pairs of color were also used to create another 36 test patches with lines cross-hatched into a checkerboard pattern as shown in Figure 2. A design goal was to obtain good measurement repeatability using instrumentation having a 4mm aperture or larger. The data collected from the cross-hatched patches are referred to as the "Checkerboard" data. These data quantify the color differences (ΔE) between the initial measurement of each patch prior to high humidity exposure and the final measurement after exposure. Lastly, two additional sets of color patches were chosen to uniformly sample the colorspace of each printing system. These patches were printed as solid-fill colors at the highest "photo" quality each printer was capable of producing. One set sampled cyan, magenta, yellow, red, green, blue, neutral, and skin tones at uniformly spaced lightness (L*) values. We refer to this group of colors as the "Color scales". It contained 60 color patches (See Table I for LAB values). The other set of 36 color patches was created by averaging the digital values of the cross-hatched color pairs in the test target's digital image file. This set is referred to as "Blended colors". The blended colors closely resemble the 36 perceived checkerboard patch colors when viewing at a distance far enough away from the print such that the cross-hatching is no longer distinguishable. These data sets were also quantified as ΔE color differences.

The experimental design was intended to sort out several possibilities where a correlation might occur. Some possible correlations were:

1). Color scales ΔE data versus Blended colors ΔE data.
2). Color scales ΔE data versus Bleed rating data.
3). Blended colors" ΔE data versus Bleed rating data.
4). Checkerboard ΔE data versus Bleed rating data.
5). Blended colors ΔE data versus Checkerboard ΔE data.
6). Color scales ΔE data versus Checkerboard ΔE data.

The psychophysical scaling system devised for this study used a number rating scheme from zero to four. The bleed rating number was defined as follows: 0 = No noticeable bleed, 1 = Just noticeable bleed, 2 = Noticeable bleed, 3= Very noticeable bleed, 4 = Extreme bleeding. The ability to repeatably judge these levels and subjectively rate with a single number the separate and distinct appearance of line

Table I
"Color scales" Patch Values (LAB) Relative to Normalized Paper White (100, 0, 0)

White	Yellow	Magenta	Cyan	Red	Green	Blue	Skin	Neutral
100, 0, 0	95, 0, 46	95, 9, -5	95, -6, -5	95. 6, 5	95, -7, 6	95, 1, -5	95, 4, 6	95. 0. 0
	90, 6, 78	90, 17, -11	90, -15, -11	90, 12, 9	90, -13, 12	90, 2, -11	90, 9, 11	90, 0, 0
	80, 16, 98	80, 35, -21	80, -26, -20	80, 25, 17	80, -24, 23	80, 5, -21	80, 15, 18	80, 0, 0
		70, 51, -34	70, -24, -29	70, 38, 25	70, -33, 29	70, 9, -31	70, 16, 19	70, 0, 0
		60, 66, -37	60, -40, -35	60, 51, 35	60, -42, 31	60, 12, -39	60, 16, 18	60, 0, 0
		50, 76, -37	50, -41, -36	50, 60, 43	50, -48, 32	50, 16, -48	50, 16, 18	50, 0, 0
				40, 61, 44	40, -50, 33	40, 18, -55	40, 15, 16	40, 0, 0
						30, 19, -57	30, 15, 16	30, 0, 0
						20, 32, -66	20, 15, 16	20, 0, 0
							10, 7, 8	10, 0, 0
								0, 0, 0

All target patches were arranged in a digital image file using LAB colorspace. The LAB values were mapped to printer colorspace using respective ICC profiles with perceptual rendering intent. The shaded values were chosen to produce the 36 unique color pair combinations used in the line targets (see Figure 1) and the "checkerboard" patches (see Figure 2).

width expansion, edge sharpness, and color fringes was improved by scanning each target sample at 2400 dpi before and after humidity exposure, and then digitally moving the lines side-by-side using layers in Adobe Photoshop®. The display window was set to a consistent magnification level of 50%. The combined scan resolution and display magnification produced an actual sample magnification of 16.6X for critical comparison of the "before" and "after" results. Compared to the unaided eye, the psychophysical ratings are more sensitive by about one unit. In other words, a noticeable difference under this magnification method (i.e., Bleed rating = 2.0) would be just noticeable (i.e., Bleed rating = 1.0) to the human eye at close viewing distance. Figures 3-7 show examples of line target patches that have bleed ratings from zero to four. The bottom half of each figure's image contains a scanned layer with the "before" humidity exposure result while the top half contains the "after" humidity exposure result. When this document is printed on 8.5 by 11 inch letter-size paper the magnification of these figures is approximately 16X which is close to how they looked on the monitor as the rating was being judged. Figure 8 shows an example of black text on white background for a printer/ink/media combination that was given a "very noticeable" bleed rating = 3.0 for the Black/white color pairs in the line target.

Recall that the line patches shown in Figure 1 were derived from 36 different color pairs (i.e., foreground/background colors). Thus the same color pairs created four lines apiece in the line pattern array (i.e., one vertical, one horizontal, then repeated with foreground and background color reversed). A bleed rating number was to be assigned to each line. As the evaluation commenced it quickly became apparent that vertical and horizontal orientation was not leading to different ratings. The analysis could be simplified to an evaluation of the foreground/background line pairs. A single bleed rating number was then assigned to each pair by mentally averaging any split decisions that occurred. Thus the assigned bleed rating number was sometimes a value in between whole numbers (e.g., 1.5, 2.5, etc.)

Ten dye-based inkjet print systems were evaluated. These systems were comprised of three desktop printers using only OEM inks for each printer. Four papers were selected for the study. Two papers were swellable polymer type photo papers. The other two papers were microporous; one with matte finish and one with high gloss finish. The intial plan was to test all printer and paper cominations for a total of 12 print systems. However, one swellable polymer type paper identified as Paper #4 did not print well on two of the printers so the total test population was reduced to 10 systems. Initial print compatibility was judged to be excellent with no mottling or bronzing evident in any of the finished prints prior to humidity testing. Note, however, that initial print quality cannot predict image permanence attributes such as resistance to gas, heat, humidity, and light induced degradation.

ICC profiles were made for each system. The test target image was in LAB colorspace and converted to the printer colorspace by the corresponding printer/ink/media profile using perceptual rendering intent. This approach served to standardize the printed color patches within each system's normal colorspace and achieved very consistent color reproduction across the significantly different printer/ink/media combinations. All colorimetric measurements for both profiling and ΔE test data were made with a GretagMacbeth Spectrolino/Spectroscan spectrophotometer having a 4mm aperture and 0/45 degree geometry. GretagMacbeth Profilemaker 4.1.5 software was used to generate the ICC profiles. CIELAB data was computed from the spectral data using 2º/D50 illuminant specification. All samples were exposed to one continuous humidity event after being allowed to "dry" for 24 hours at 23ºC and 60% RH. The high humidity exposure was ten days at 22ºC and 85% RH. This single event produced significant color shift and line bleed. Finally, three population statistics were tracked in this study for all ten print systems; 1) the maximum value, 2) the average value of all patches in a group, and 3) the average of the worst 10% (i.e., averaging the data for the 10% of the population showing the largest changes in value).

Results

For reasons noted in the introduction not all patches change proportionately to ink load and even a print system exhibiting major changes in some patches can have little or no changes occur in numerous other patches. Tracking the worst 10% of the population was found in general to achieve the highest correlations. Averaging the whole population tended to diminish the ability to identify where the significant changes were actually occurring. In contrast, tracking only the maximum value restricted the measurement statistics to just one sample per print system for each correlation parameter and thus increased variability. Using the "worst 10%" criterion provided a better balance between smoothing of noise and sensitivity to significant changes in the sampled patches.

Figure 9 shows the correlation between the two groups of color patches, "Color scales" and "Blended colors" using the worst 10% criterion. Because both sets represent a sampling of each system's colorspace, a good correlation would be expected provided that the colorspace was well sampled by each set of colors. The correlation results were very high with an $R^2 = 0.96$. Using average ΔE data or maximum ΔE data was only slightly lower. These criteria both yielded an $R^2 = 0.94$.

Figure 10 shows a poor correlation between the "Blended colors" group and the "Checkerboard" group of patches with $R^2 = 0.30$ using the worst 10% of data to calculate the ΔE values for the ten print systems. Although both sets represent colorimetric differences caused by dye diffusion, this result indicates that the lateral bleed taking place in the checkerboard pattern produces a different effect than the bleed taking place in the solid-fill colors where the dyes are more homogeneously mixed at the beginning of the test.

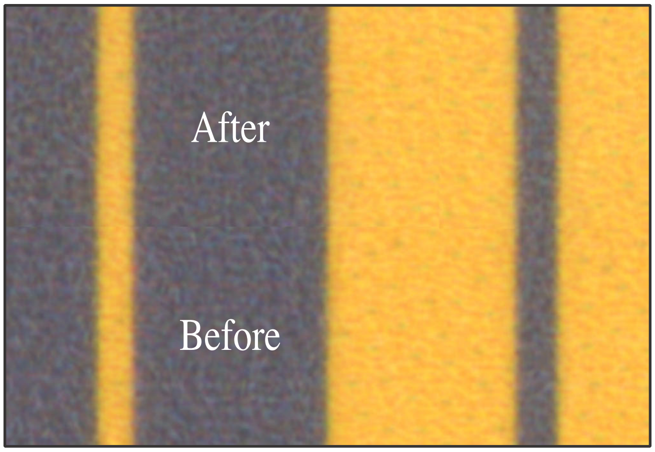

Figure 3. Yellow/gray color pair with line Bleed Rating = 0, "no noticeable bleed."

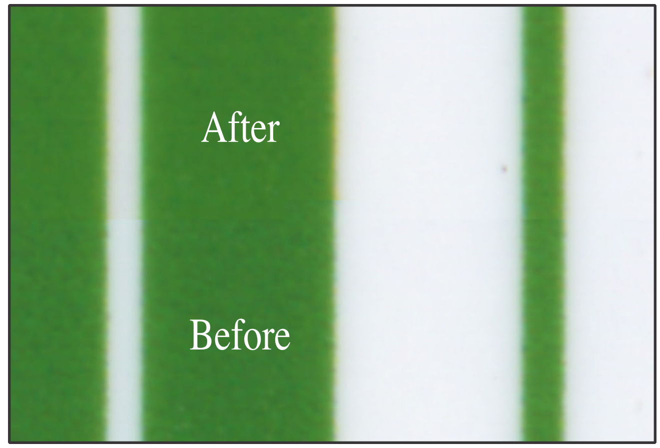

Figure 4. Green/white color pair with line Bleed Rating = 1.0, "just noticeable bleed" (slightly softer edge was observed).

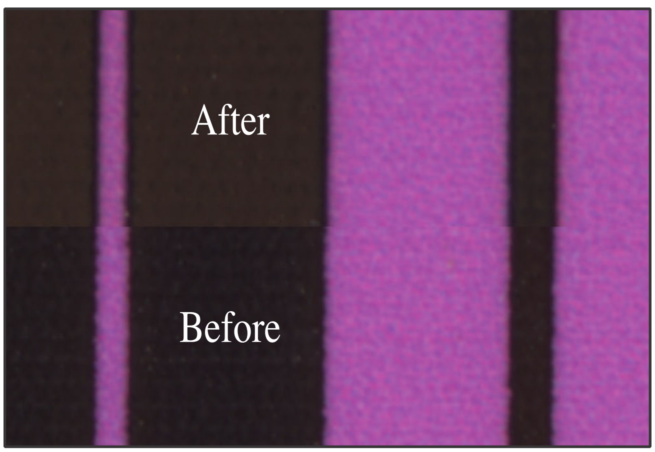

Figure 5. Magenta/black color pair with line Bleed Rating = 2.0, "noticeable bleed."

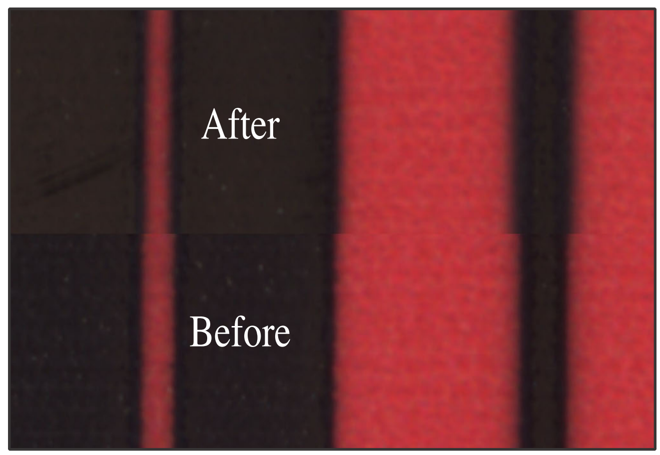

Figure 6. Red/Black color pair with line Bleed Rating = 3.0, "very noticeable bleed."

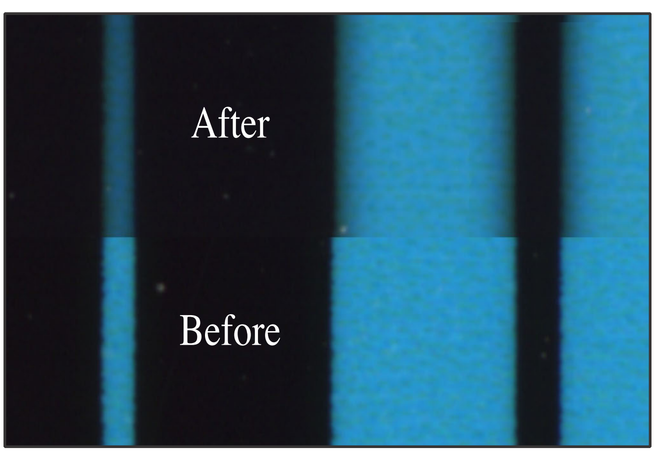

Figure 7. Cyan/black color pair with line Bleed Rating = 4.0, "extreme bleed."

Figure 8. Text printed on system having Black/white color pair line Bleed Rating = 3.0. Top row is "after" humidity exposure.

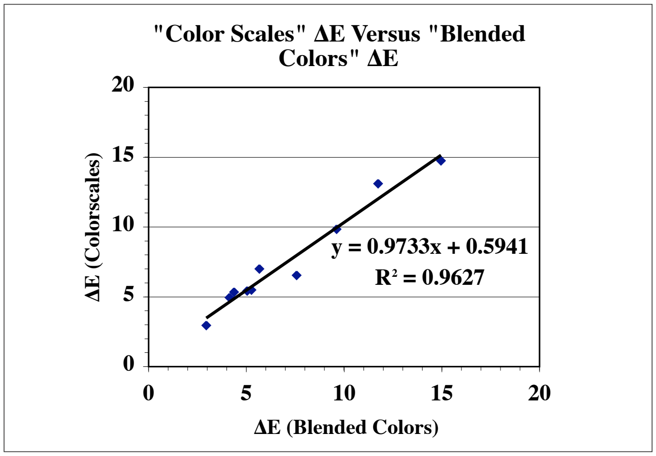

Figure 9. Ten print systems correlated using worst 10% ΔE averaged data criterion.

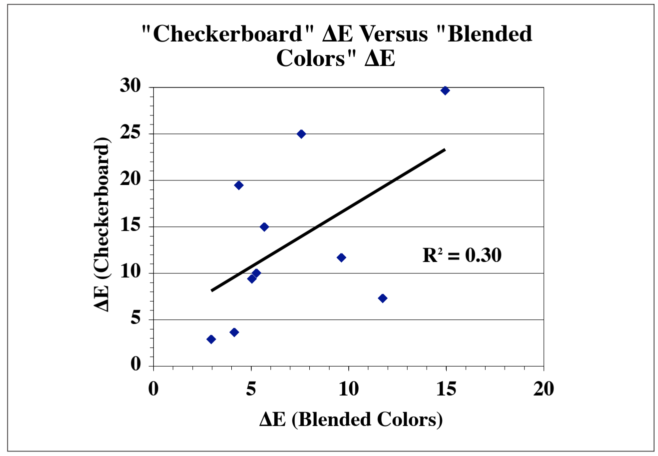

Figure 10. Ten print systems correlated using worst 10% ΔE averaged data criterion.

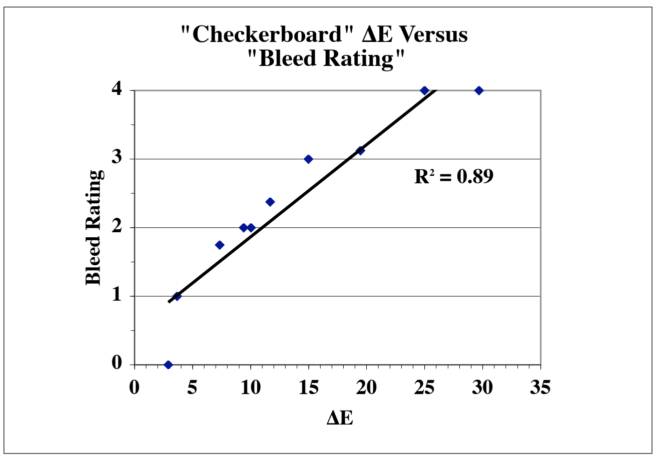

Figure 11. Ten print systems correlated using worst 10% ΔE averaged data criterion.

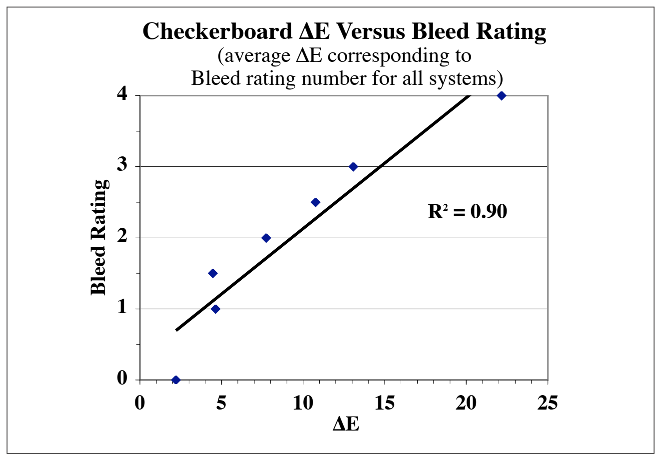

Figure 12. The correlation of ΔE versus bleed rating number by pooling all data confirms that the rating was not system dependent.

Table II
Rank Order Results for Humidity-Induced Line Quality Degradation

*Rank	Sample ID	ΔE (avg)	ΔE (Worst 10%)	ΔE (Max)	Bleed Rating (avg)	Bleed Rating (Worst 10%)	Bleed Rating (Max)
1	Printer #1_Paper #1	1.3	**2.9**	3.3	0.0	**0.0**	0.0
2	Printer #2_Paper #1	1.6	**3.7**	4.5	0.2	**1.0**	1.0
3	Printer #3_Paper #1	3.5	**7.3**	9.0	0.7	**1.8**	3.0
4	Printer #2_Paper #2	3.7	**9.4**	11.0	0.7	**2.0**	2.0
5	Printer #2_Paper #4	5.6	**10.0**	10.8	0.8	**2.0**	2.0
6	Printer #3_Paper #2	5.0	**11.7**	16.0	0.9	**2.4**	2.5
7	Printer #1_Paper #2	3.5	**15.0**	17.1	0.6	**3.0**	4.0
8	Printer #2_Paper #3	9.2	**19.5**	25.4	2.4	**3.1**	3.5
9	Printer #1_Paper #3	6.4	**25.0**	31.0	1.5	**4.0**	4.0
10	Printer #3_Paper #3	11.7	**29.7**	36.6	1.7	**4.0**	4.0

* Ranked from best to worst on Checkerboard ΔE (Worst 10%) criterion.

Figure 11 shows the correlation between the "Checkerboard" group and the "Bleed rating" data collected for each print system. Each data point on the graph therefore denotes the average response for the worst 10% of each system's data. Figure 12 shows the same high correlation between the "Checkerboard" data and the "Bleed rating" data only using a different evaluation method. In this method, the ΔE values of all samples receiving a specified bleed rating number were averaged. The average ΔE value corresponding to each bleed rating number is plotted. The results show that a linear fit to the data achieved an $R^2 = 0.90$. This second method of analysis is important because it confirms that the correlation between the visually rated line quality assessments (i.e., the bleed rating number) and the ΔE measurement of the checkerboard patches was independent of the tested systems. In other words, even though the initial print characteristics varied as a function of printer, ink, and media, the ability to rate a humidity-induced change in line quality was not influenced by the initial image quality for this population of desktop printing systems nor did it affect the measurement of the humidity-induced color differences in the checkerboard patches.

Table III
Rank Order Results for Humidity-Induced Color Shift Compared to Line Quality Degradation

Sample ID	Line Quality Rank	Color shift *Rank	Color scales ΔE (Worst 10%)
Printer #1_Paper #1	1	**1**	2.96
Printer #2_Paper #1	2	**2**	4.95
Printer #2_Paper #3	8	**3**	5.35
Printer #2_Paper #2	4	**4**	5.42
Printer #2_Paper #4	5	**5**	5.49
Printer #1_Paper #3	9	**6**	6.54
Printer #1_Paper #2	7	**7**	7.00
Printer #3_Paper #2	6	**8**	9.84
Printer #3_Paper #1	3	**9**	13.12
Printer #3_Paper #3	10	**10**	14.74

* Ranked from best to worst on Color scales ΔE (Worst 10%) criterion.

Conclusions

Table II shows the rank order result for the ten tested print systems with respect to humidity-induced line quality degradation. The systems are ranked from best to worst result based on the Checkerboard ΔE (worst 10%) data. Inspection of the columns of Bleed rating data (worst 10%) and the Checkerboard ΔE (worst 10%) data show that both ranking methods produced the identical rank order although precision is lower in the Bleed rating data because tie values occurred. The tie values stem from the fact that 10% sampling of each printed system is only four samples. Four values sometimes averaged to whole numbers, and some whole number results were thus the same. Nonetheless, the correlation results demonstrate that the inclusion of a checkerboard pattern design with sufficient color combinations allowed humidity-induced line quality degradation to be quantified as a ΔE measurement using a standard spectrophotometer. The magnitude of color change (ΔE) caused by diffusion of the colorants correlated very well with visual changes in line quality as determined by the psychophysical scaling method. A fairly large number of patches are required in order to properly sample the full colorspace of a print system and to smooth the noise. Narrowing the data to the worst 10% then worked well as a means to improve the correlation. Further work might refine this approach.

Although the solid-fill color patches also showed significant color change upon high humidity exposure, the correlation with loss of line quality was poor. Table III shows the ten systems ranked in terms of humidity-induced color shift. We conclude that solid-fill patches and patches containing the checkerboard pattern characterize the humidity-fastness of an inkjet system differently. The solid-fill patches characterize color shift issues while the checkerboard patches evaluate line bleed using just one device, namely a spectrophotometer, without the need to perform additional quantitative image analyses.

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Paper by Mark McCormick-Goodhart and Henry Wilhelm (Wilhelm Imaging Research, Inc.) entitled: “The Correlation of Line Quality Degradation With Color Changes in Inkjet Prints Exposed to High Relative Humidity” appeared on pages 420–425 in:

Final Program and Proceedings:

IS&T’s NIP19: International Conference on Digital Printing Technologies

ISBN: 0-89208-247-X

September 28–October 3, 2003
The Hyatt Regency New Orleans Hotel
New Orleans, Louisiana U.S.A.

Published by:

IS&T: The Society for Imaging Science and Technology
7003 Kilworth Lane
Springfield, Virginia 22151 U.S.A.
Phone: 703-642-9090; Fax: 703-642-9094
www.imaging.org