Color and Lightfastness Performance of Different Epson Ink Sets

Veronika Chovancova▲, Paul D. Fleming III▲, Paul Howell, and Adam Rasmusson
Center for Ink and Printability, Department of Paper Engineering, Chemical Engineering and Imaging, Western Michigan University, Kalamazoo, Michigan, USA

The development of high performance ink jet printers and inks is advancing rapidly. Presently, manufacturers seem to introduce their new technology inks to the market on an almost daily basis. Chemists in the ink laboratories are still fighting with the issue of combining the wide gamut of dye based inks and the lightfast and weather resistance qualities of pigment based inks into their new age ink formulations. Simply, the evolution cannot be stopped! Three different ink jet printers and inks were investigated in this work: the Epson Stylus® Pro 5000, using a dye based ink set, the Epson Stylus® Pro 5500, employing Archival ink technology, and the Epson Stylus® Photo 2200, with 7-color UltraChrome™ inks. A number of different commercial and experimental substrates were sampled. Printability tests were carried out to test and evaluate ink/printer/substrate interactions. Particle size analyses of the three ink types were investigated. Color gamuts and ICC profiles for each of the different printer/ink/substrate sets were compared. In addition, the accuracy of each printer's color profile was investigated. The results of the profile accuracy measurements were expressed in terms of CIE $L^*a^*b^*$ coordinates and Root Mean Square (RMS) ΔE. Results of accelerated lightfastness tests for the different ink sets were interpreted in terms of change of profile and color gamut. Neutralization of the optical brightening agents added to the papers themselves during accelerated aging, was shown to contribute significantly to perceived color change.

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Introduction

Undoubtedly, we are now seeing wide development of novel technologies in manufacturing inks and substrates, and due to that, an expansion of ink jet printing technology into desktop, outdoor and industrial applications.[1,2]

The Epson Corp. has recently introduced two types of pigment based inks. They combine the advantages of both dye and pigment based inks in their formulations. Both their Archival and UltraChrome™ ink systems represent new ink solutions, where each pigment particle is encapsulated in a resin. This technology offers many advantages over conventional pigment and dye based inks. The primary advantages being those of uniform particle shape and particle size, greater color gamut, advanced optical density, exceptional gloss for photo prints, enhanced lightfastness and support for a wider range of media.

Pigment based inks tend to satisfy the requirements of most ink jet printing demands, but the suitable combination of ink and substrate is still crucial. Ink jet inks require a fine particle size, due to possible clogging of the printing head. For low viscosity inks there is a tendency of particle migration with time.[3] Pigment based inks behave differently than dye based inks. The spreading behavior of these inks is determined by the hydrodynamic properties such as the Weber or Reynolds's number. On the other hand, in pigment based inks, after initial spreading, the pigment particles coagulate on the surface of the microporous layer, creating a filter cake that limits the penetration of the carrier liquid. This results in longer absorption times and recessed dots that stay on the top of the substrate layer, and affect all the other printability properties.[4]

In addition, the precision of color reproduction depends on the image processing, e.g., color separation, rendering intent, and on the stability of the printing process, which usually is carried out with the help of an ICC profile and Color Management Modules.[5–9] In order to understand the whole process, the influence of paper properties on color reproduction has to be taken into consideration. The grade or type of the substrate used will definitely affect the results of the profile calculations and therefore the printing gamut.[10,11]

The ability of pigment and dye based inks to maintain accurate color strength over time due to light exposure and subsequent fading is as important as the printed color itself.[12] Resistance to fading is significant in several situations. The archiving of sensitive documents is affected by fading and light fastness. Another application is digital photography, where consumers are now producing ink jet prints of digital photographs.[13] In both of these cases, inks and papers used for archival purposes should be reliable in their light fastness because of the need for long-term storage. Photographic prints from digital files are also expected to maintain accurate color over a moderately lengthy period.[12,13]

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▲ IS&T Member

Corresponding Author: P. D. Fleming III, dan.fleming@wmich.edu

TABLE I. Particle Size of All Ink Sets in Terms of Mean Intensity-Weighted Diameter

Particle Size	C (nm)	M (nm)	Y (nm)	K (nm)
PRO 2200	119	172	74	99
PRO 5500	141	190	123	113
PRO 5000	Dye	Dye	Dye	Dye

TABLE II. RMS Δ*E* Results

EPSON Paper	Target vs. Profile	Profile vs. Test	Target vs. Test	IT8.7 Test
Photo 2200				
Archival Matte	2.42	2.11	2.54	7.55
Luster Photo	1.48	2.8	2.87	4.39
Glossy Photo	1.33	1.65	2.02	3.79
PRO 5000				
Archival Matte	1.1	1.8	2.02	7.38
Luster Photo	0.91	2.09	2.3	3.27
Glossy Photo	2.04	2.55	3.59	4.86
PRO 5500				
Archival Matte	4.5	1.37	4.55	12.86
Luster Photo	1.01	1.85	1.92	8.33
Glossy Photo	1.38	1.89	2.17	9.66
Kodak Paper	**Target vs. Profile**	**Profile vs. Test**	**Target vs. Test**	**IT8.7 Test**
Photo 2200				
Satin	1.52	1.56	1.99	6.8
Glossy Photo	1.26	1.93	2.16	6.67
PRO 5000				
Satin	1.24	5	5.17	5.43
Glossy Photo	1.18	5.76	5.87	6.18
PRO 5500				
Satin	4.78	2.3	5.77	13.06
Glossy Photo	3.33	2.05	4.28	11.31

Procedures and Results

Preliminary results of these studies were presented elsewhere.[14] All the printers (Epson Stylus Photo 2200, Epson Stylus PRO 5000, Epson Stylus PRO 5500) were profiled as CMYK devices, using the Best Designer RIP on the six selected substrates (Epson Archival Matte, Epson Premium Luster Photo, Epson Premium Glossy Photo, Kodak Glossy, Kodak Satin Paper and experimental substrates with a special ink jet coating applied[10,11,15,16]), using a GretagMacbeth SpectroScanT spectrophotometer (in reflection mode), Gretag–Macbeth ProfileMaker 4.1.5 and the ECI2002 Random Layout CMYK Target.[17] Sample test prints were produced from Adobe InDesign. In "Color Settings" the CMYK working space was set to the appropriate ICC profile. The prints were made using the Best designer RIP, with color management set to source space as proof and the applicable CMYK profile for the print, with the intent set to Absolute Colorimetric for the sample output. (The "proof space" is the only management that allows the intent to be manually set.) Therefore, all output was set for an absolute colorimetric intent.

Particle Size Measurements

A NICOMP 370 Submicron Particle Sizer was used to measure the particle size of all the ink sets. As expected, no particles were detected in the dye based ink set for the Stylus PRO 5000. The measured particle sizes of all pigmented inks are found in Table I.

ICC Profile Test

Profile accuracy tests were carried out using the following steps. The values of the ColorChecker® target in Photoshop with the profile applied for each paper sample were checked first. This was accomplished by selecting a large portion of each patch and then recording each of the $L^*a^*b^*$[18] values from the "Histogram" palette. The Mean values obtained from the histogram were converted to actual $L^*a^*b^*$ values. Using the GretagMacbeth SpectroScanT, $L^*a^*b^*$ values were obtained under specific conditions; D_{50}, 2°, no UV filter. The measurements were made for each of the sample patches of the ColorChecker® target for all of the substrates and for each of the sample printers. Employing the formula for color difference (ΔE)[18] Eq. (1), the actual ΔE values were calculated.

$$\Delta E = \sqrt{\left(L_1^* - L_2^*\right)^2 + \left(a_1^* - a_2^*\right)^2 + \left(b_1^* - b_2^*\right)^2} \qquad (1)$$

The original $L^*a^*b^*$ values of the ColorChecker〉 target (Target values) were compared with the values from Photoshop with the profile applied (Profile values). These values were also compared with the actual values measured from the printed ColorChecker® portion of the verification samples produced from InDesign, and finally the original values were compared with the values measured from the printed ColorChecker® Target (Test values). The resultant values for ΔE are listed in Table II.

IT8.7/2 Subset Test

A subset of the IT8.7/2 scanner chart[7,8] was also included in the verification page layout. The $L^*a^*b^*$ values of the patches were measured with the GretagMacbeth SpectroScanT and compared with the original data of IT8.7/2 chart in order to investigate the quality of the profiles made for each scanner/printer/paper set. The resulting RMS ΔE's are shown in Table II. The large values of ΔE for some of the papers represent out of gamut colors, in addition to inaccuracy of the printer and scanner (embedded in the IT8 subset image, which is present for all papers) profiles.

Color Gamut Comparison

Using CHROMiX ColorThink 2.1.2, the profile gamuts for each of the printers were graphically compared in this order: Epson Photo 2200, Epson Stylus PRO 5000, Epson Stylus PRO 5500 (Figs. 1 and 2). The axis represents the CIELab color space: from "–*a*" (green) to "+*a*" (red) and from "–*b*" (blue) to "+*b*" (yellow) colors.

Then we compared the similar substrates, glossy and matte/Satin, from each printer to each other. The results were combined and are shown on the 3D gamut plots (Figs. 3 and 4).

The gamuts are also compared with Monaco GamutWorks 1.1.1 in terms of "Gamut Volumes" (Table III).

We also compare gamuts for experimental papers.[10,11,15,16] These were formulated with a 50:50 ratio of alumina to boehmite nanopigments,[11] at a pigment-to-binder ratio of 7:1 and final solids of 30 ± 1%. The coatings were applied to a 75 g/m² commercial base paper using a Cylindrical Laboratory blade coater at a speed of 2000 fpm. Coating weights between 6 and 12 g/m² were

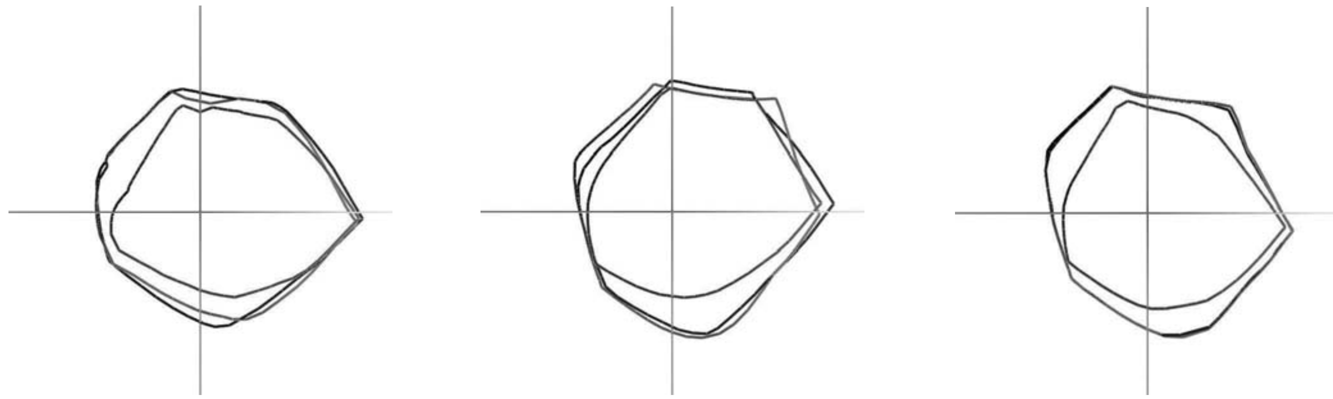

Figure 1. Gamut projection plots for Epson papers, Matte (red), Luster (green) and Glossy (blue) from different printers 2200 (left), PRO 5000 (middle), PRO 5500 (right).

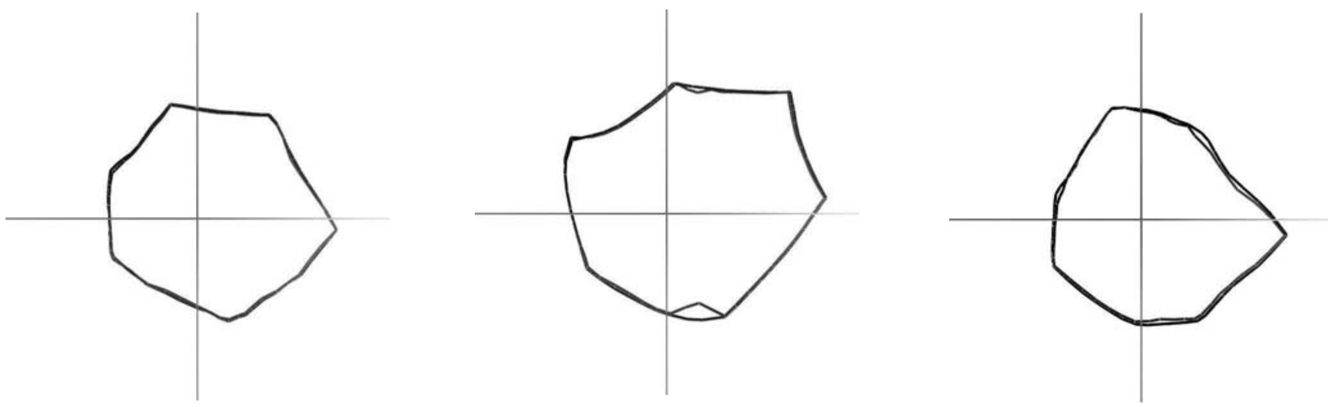

Figure 2. Gamut plots for Kodak papers Satin (red) and Glossy (blue) from different printers 2200 (left), PRO 5000 (middle), PRO 5500 (right).

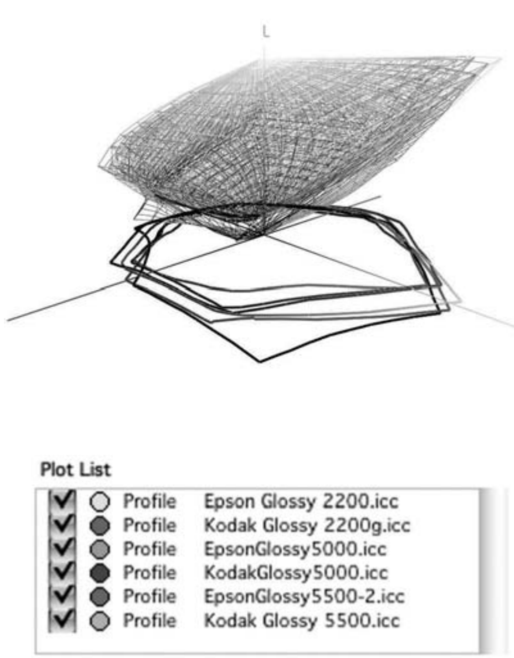

Figure 3. Gamut plots of glossy substrates from all printers.

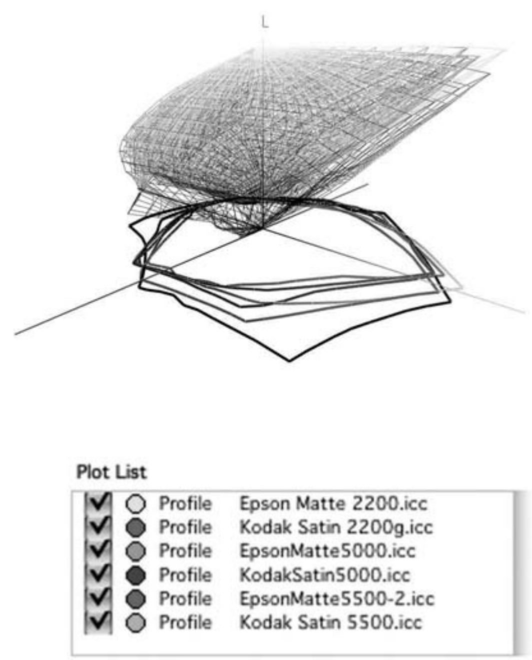

Figure 4. Gamut plots of matte substrates from all printers.

TABLE III. Gamut Volume Results for All Substrates

EPSON Paper	Gamut Volume
Photo 2200	
Archival Matte	890,439
Luster Photo	1,196,587
Glossy Photo	1,225,282
PRO 5000	
Archival Matte	933,011
Luster Photo	1,273,885
Glossy Photo	1,275,029
PRO 5500	
Archival Matte	765,089
Luster Photo	1,079,069
Glossy Photo	1,045,882
KODAK Paper	**Gamut Volume**
Photo 2200	
Satin	831,257
Glossy Photo	855,898
PRO 5000	
Satin	1,347,120
Glossy Photo	1,384,975
PRO 5500	
Satin	807,574
Glossy Photo	859,992

TABLE IV. Gamut Volume Results for Experimental Papers Before and After Calendering

EPSON Printer	Gamut Volume		Gamut Volume Difference
	Before	After	
Photo 2200	738,962	827,987	89,025
PRO 5000	701,520	740,994	39,474
PRO 5500	509,913	502,182	–7,731

TABLE V. Average and RMS ΔE Values Before and After Fading Test for Different Printers and Papers

Printer	Paper	Average ΔE	RMS ΔE
Photo 2200	Archival Matte	2.20	2.74
PRO 5000	Archival Matte	10.62	11.34
PRO 5500	Archival Matte	2.19	2.76

obtained. Some of the 12 g/m^2 samples were printed on the three printers with the i1 CMYK Target 1.1,[19] before calendering. The remaining coated samples were calendered on one side, through 3 nips at 123 kN/m and 60°C. Three 10 g/m^2 calendered samples were printed with the i1 chart on the three printers. ICC profiles for the printers with the noncalendered and calendered papers were calculated using the printed i1 chart, with ProfileMaker.

The profile gamut plots for the experimental papers are given in Figs. 5 through 7. Figure 5 and Table IV show the effect of calendering on color gamuts. While Figs. 6 and 7 compare the calendered and noncalendered papers with the Epson glossy and matte, respectively on the three printers; Epson Photo 2200, Epson Stylus PRO 5000, Epson Stylus PRO 5500.

Fading Tests

The patches of the ECI 2002 Random Layout CMYK Target were measured with the GretagMacbeth SpectroScanT before they were put into the Atlas fade meter. The Suntest CPS+ tabletop xenon exposure system was equipped with an 1100 watt air cooled xenon arc lamp light source. They were submitted to 129,600 kJ/m^2 of energy over 48 hours (@ 765 W/m^2) with the uncoated quartz glass filter configuration and measured again. This represents about 4.5 months (June) of daylight exposure in Florida.[20]

The $L^*a^*b^*$ values of the printed patches for all the printers on Archival Matte substrate before and after the tests were taken from the data file and the ΔE calculation was performed to obtain the range of color difference between them. These are shown in Table V.

Table V shows that the pigmented inks change colors much less than the dye inks as expected. However, values ~ 3 for the pigmented inks are larger than expected for inks rated at more than 75 years, albeit for indoor conditions.[18,19] Examination of the data shows that there is a systematic shift toward yellow and green. The Epson 2200 shows an average Δb^* of 1.57, while the Epson 5500 shows an average Δb^* of 1.89. Thus, for the pigmented inks, most of the average ΔE results from the systematic Δb^* shift, reflecting the drop in the Optical Brightening Agent (OBA)[20,21] contribution (see below). The dye

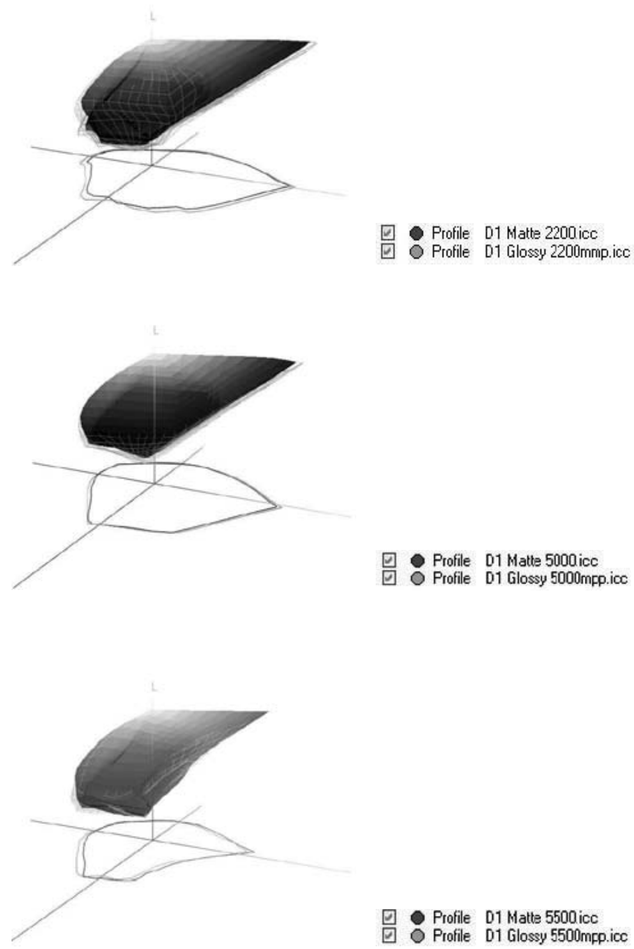

Figure 5. 3D Gamut plots for experimental papers using Epson Photo 2200, Epson Stylus PRO 5000, Epson Stylus PRO 5500.

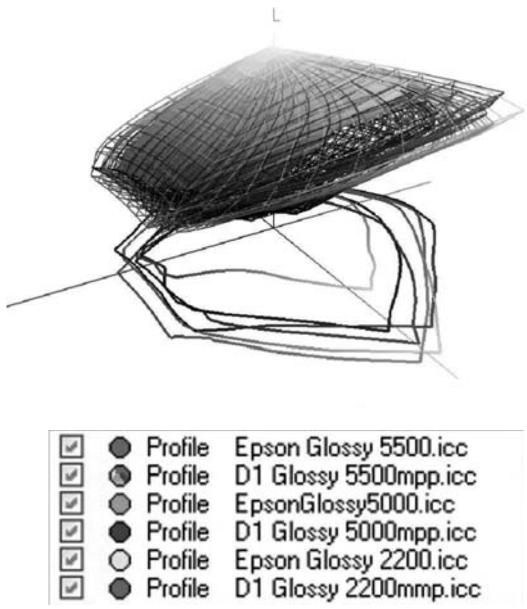

Figure 6. Gamut comparison for experimental calendered paper and Epson Glossy paper for all printers.

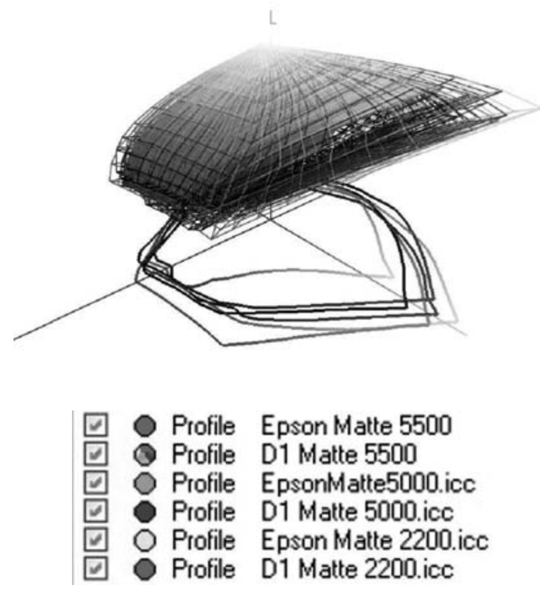

Figure 7. Gamut comparison for experimental non calendered paper and Epson Matte paper for all printers.

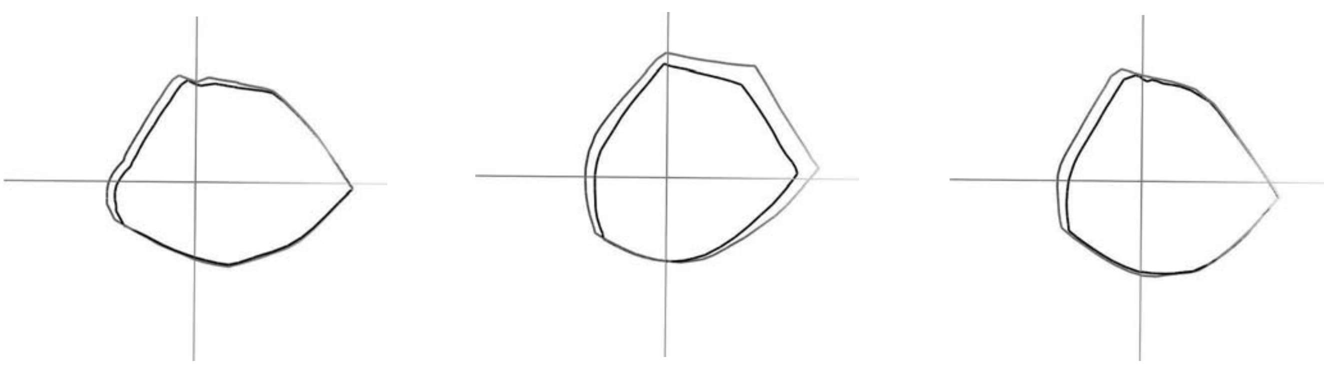

Figure 8. Comparisons of projections of the color gamuts before (full color) and after (black) fading test for pigment based Epson 2200 (left), dye based Epson 5000 (middle) and pigment based Epson 5500 (right).

ink, Epson 5000, shows an average Δb^* of only 0.77, but the average ΔL^* is 6.96. Therefore, that ΔE is mostly due to actual ink fading.

Again, the profile gamut plots for the papers are given in Fig. 8. Figure 8 shows the gamut plots before and after the fading test.

Gamut volume change representation is shown in Table VI. Note that the Epson 5000 shows a significant decrease in color gamut. The printers with the pigmented inks, the Epson 2200 and 5000, show the aforementioned shift towards yellow, but little decrease in gamut.

The Epson Stylus Photo 2200 printer together with the Epson Archival Matte substrate was chosen for further investigation of the fading properties. This substrate with the printed chart from the 2200 was submitted to longer time light exposure equivalent to 13 months (June) of daylight exposure in Florida (104 hrs @ 765 W/m^2). The gamut plot and gamut volumes of this test are shown in Fig. 9 and Table VI, respectively.

TABLE VI. Gamut Volume Results Before and After Fading Tests

EPSON Printer	Gamut Volume		Gamut Volume Difference
	Before	After	
Photo 2200	890,439	832,483	57,956
PRO 5000	933,011	723,520	209,491
PRO 5500	765,089	719,311	45,778
Photo 2200 (long term test)	890,439	814,679	75,760

In this case, the color shift is even more significant in the yellow region of the spectrum.

From this information we decided to look at the changes in properties of the plain substrates. $L^*a^*b^*$ values of the substrates before and after the tests were obtained. Parameters for ΔE calculations for the range of color difference are shown in Table VII.

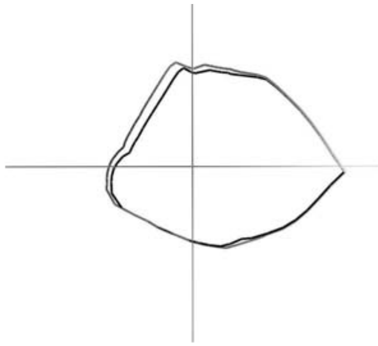

Figure 9. Comparisons of color gamuts before and after fading test for Epson 2200 and Archival Matte substrate.

TABLE VII. Average and RMS ΔE Values for Papers Before and After Fading Test for Different Papers

Substrate		L*	a*	b*	ΔE
Epson Archival Matte	Before	96.1	0.8	–4.3	4.34
	After	95.8	–0.4	–0.1	
Kodak Satin	Before	93.3	0.7	–6.3	2.49
	After	93.4	–0.1	–3.9	
Epson Premium Glossy	Before	94.6	–0.4	–3.9	0.50
	After	94.4	–0.6	–3.5	
Kodak Glossy	Before	92.8	0.3	–6.7	2.66
	After	93.7	0.1	–4.2	
Epson Archival Matte (long term test)	Before	95.9	0.8	–4.0	4.91
	After	95.8	–0.6	0.7	

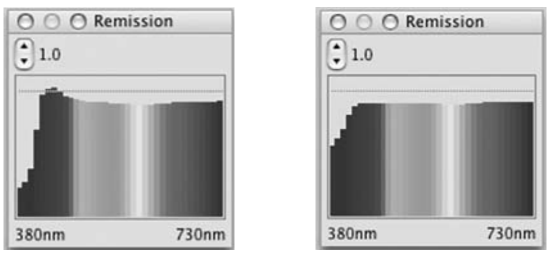

Figure 10. Reflection spectra of Epson Archival Matte substrate before (left) and after fading (right).

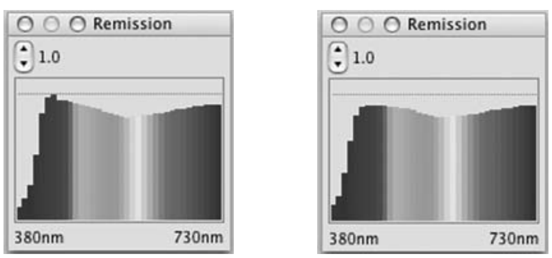

Figure 11. Reflection spectra of Kodak Satin substrate before (left) and after fading (right).

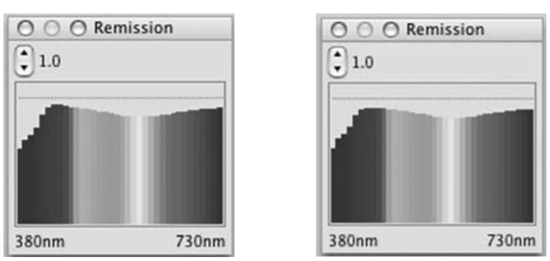

Figure 12. Reflection spectra of Epson Premium Glossy substrate before (left) and after fading (right).

The GretagMacbeth MeasureTool 5.0.0 software was used to compare the spectra of the substrates before and after the fading test. The spectra for the Epson Archival Matte substrate, claiming the best archival properties, Epson Glossy substrate, Kodak Glossy substrate and for Kodak Satin substrate are shown in Figs. 10 to 13.

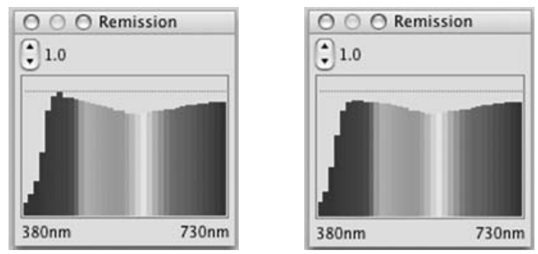

Figure 13. Reflection spectra of Kodak Glossy substrate before (left) and after fading (right).

The spectra and the $L^*a^*b^*$ values suggest that the contribution of optical brighteners, added to improve the perceived whiteness of the paper, has been neutralized for the Archival Matte paper and greatly diminished for the Kodak Satin papers. OBAs are fluorescent materials that absorb in the ultraviolet and emit in the blue.[23,24] This is the source for the blue peak in the spectra and the negative values of b^* before the fading test. These peaks and negative b^* values are seen with the Illuminant A light source, which has little UV component, present in the Gretag–Macbeth Spectralino/SpectroScanT. A true daylight source or idealizations such as D_{50} or D_{65} will show more pronounced effects of OBAs.[23,24] This means that, regardless of the permanence of the printed dye or pigmented ink, there will always be some shift in the perceived color of printed images in virtually any light source, including indoors under glass.[12,13] Note from Tables VI and VII that the majority of the OBA neutralization has occurred in the first simulated 4.5 month period, with little (barely significant) additional change in the remaining simulated 8.5 months. Additional image permanence data are presented elsewhere.[25]

Other Properties of Printer/Substrate Combinations

Other properties of the Printer and substrate combinations are given in a companion paper.[26] In particular, the paper roughness by Parker Print Surf,[27] profilometer[28] and Atomic Force Microscopy[29] have been examined. In addition, ink and paper gloss were measured for both 60 and 75°.

Discussion

The comparison of the difference in ΔE values for the original $L^*a^*b^*$ ColorChecker® target to those of the values calculated in Photoshop indicate small dissimilarities in almost all cases. The ΔE values for most of the patches on all substrates and from all printers were found to be generally less than two. Exceptions include the dark patches when printed on the matte papers and when printed from the Photo 2200 and PRO 5500 using pigment based inks. In the case of the pigment based ink printers (Epson 2200 and Epson 5500) the average and RMS ΔE were always higher for the matte substrates than for the luster, satin and glossy substrates. This is most likely due to out of gamut colors for the matte substrates.

The ΔE values for the comparison of the patches calculated in Photoshop to those measured with the SpectroScanT show similar values to the differences between the original values and the values from Photoshop in the case of the Epson papers. The only exception is the Epson Stylus PRO 5000 in combination with Kodak substrates.

Comparisons of the measured samples in most cases very closely approximate the values of the original ColorChecker〉 reference values, with the largest variances indicated on the glossy papers printed from the PRO 5000 and the matte from the PRO 5500. Matte paper printed from the PRO 5500 produced the largest variances of all the samples.

In comparing the profile gamuts it was noted in all cases that the matte paper profile represented the smallest gamut whereas the luster and glossy papers were generally similar and contained the complete matte gamut. Comparing the printers to each other on the same substrate, we found that the Photo 2200 generally included a similar size gamut to that of the PRO 5000 printer and dye based inks but the PRO 5500 represented the smallest color gamut. It could be seen from the gamut comparisons (Fig. 3 and Table III) that the Photo 2200 with its pigment based inks is able to provide a color range that very closely matches that of the dye based prints from the PRO 5000.

The smaller gamuts produced by the PRO 5500 printer, compared to the Photo 2200 (Table III), result from the different technology, larger particle size of pigment, used in the ink manufacturing process. The archival properties of the ink set used by that printer are still better then dye based ones. It can be stated that bigger particles offer better stability but are less chromatic.[30] The fact that the pigment based inks used in the Photo 2200 printer closely match those of the dye based inks of the PRO 5000 is noteworthy, but it can be expected that the archival properties as advertised for this ink set may not be as good as those of the PRO 5500. It should also be noted that the increased archival properties of the matte paper in combination with archival pigment based inks produce the smallest color gamut of the samples analyzed.

For the Kodak papers, there is no significant difference in gamut size between glossy and satin substrate (Table III). In addition, Epson vs. Kodak paper gamuts did not show any significant discrepancies in the terms of color gamut size. It is seen from Figs. 3 and 4 that the widest gamut was obtained when printed from the Epson Stylus PRO 5000 dye based ink jet printer followed by Epson Photo 2200 and Epson Stylus PRO 5500, both pigment based ink jet printers.

After the printed samples were submitted to the fading test it could be seen that the gamuts decreased. The Epson 5000 showed a significant decrease (209,491 in terms of gamut volume difference), while the 2200 (57,967) and 5500(45,778) showed smaller changes. In the case of the Epson Archival Matte and the Kodak substrates, it was found that, even without any change in ink composition, the color performance will change because of the loss of brightener effect (Figs. 10 through 13). This led to a systematic shift toward the yellow, especially when exposed to longer time tests, as shown in Fig. 9. This deviation was not seen when inspecting the Epson glossy substrate.

Thus, it is important to be aware of the presence of OBAs in the paper or its coating, and to know if their effect is diminished by extended light exposure, when assessing the effect of ink on image permanence. The presence of OBAs is signaled by a negative b^* value or by the peak in the blue portion of the spectrum[23,24] of the unprinted or "white" patch of profiling targets. All of the papers studied here had OBAs present, but only the Archival Matte and the Kodak papers showed significant reduction in brightener activity.

The particle sizes of the pigment based inks were found to be <190 nm, most of them below 150 nm, showing smaller particle sizes for the PRO 2200 ink set than for the Photo 5500 ink set. The Particle Sizer's light detector was not able to distinguish any intensity in the case of the PRO 5000 ink set, which is consistent with the dye based ink system of the printer. The color gamut decreases with increasing particle size, with the smallest particle size, the Epson 5000 dye, having the largest gamut, while the largest particle size, the Epson 5500, gives the smallest gamut. However, the dye based ink in the 5000 showed significant fading from only a simulated 4.5 month exposure.

Conclusion

Different ink jet printers and their corresponding ink sets were studied in terms of printability tests, including ink/printer/substrate interactions, particle size analyses, color gamut comparisons, the accuracy of printer's color profile, and fading tests. It can be definitely said that the new technology of the manufacturing the inks with pigment particles encapsulated in specific resins is able to approach the properties of the dye based inks, especially in the term of gamut width. In addition, the increased archival properties of the matte paper in combination with archival pigment based inks are reflected in the smaller color gamut compared to the gamut of glossy paper. The pigment based inks show much better lightfastness than the dye based inks, but for some substrates there is a drift towards the yellow as optical brighteners lose their effect.

For future work we suggest investigating the substrates which do not include optical brighteners in their composition, e.g., art paper. In addition, there are newer dye based ink sets becoming available, with enhanced archival properties. Hewlett-Packard[31] and Epson[32] have claimed to have created new generations of inks to achieve over 100 year predicted indoor lightfastness performance, while simultaneously improving the color gamut over previous products.

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