Print Performance Evaluation of Ink Jet Media: Gamut and Dye Diffusion

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A method to quantify gamut based on equiluminance planes is applied to characterize ink jet media and ink sets. Due to a mixture of spectral interpolation and interpolation in L*,a*,b* the base set of experimental data can be much smaller if only L*,a*,b* interpolation is used. The robustness of the interpolation to the reduction of data points in hue direction is demonstrated. The method is applied to the characterization of different ink jet ink sets on photo glossy media. The effect of media gloss, paper color, printing pattern and colorants is shown. The influence of the spectral measurement geometry on gamut has to be taken into account when colors are compared on samples with different surface finish. Printed colors may change over time due to the diffusion of dyes inside the layer. A test pattern was developed to quantify dye diffusion of ink jet prints under varying environmental conditions.

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Introduction

The basic principles for digital color reproduction have been developed for many years[1,2] in the photographic[3] and printing industry,[4,5] mainly for 3- and 4-color systems. Ink jet printing freed creative printing from the many restrictions proper to closed systems as photography or thermal dye transfer. It offers great flexibility in the number and types of colors, for example process colors, hexachrome color, spot colors, and special effect colors. It allows even more choices for the media from plain to RC glossy papers, clear to metallic films, and canvas to leather.

The selection of the right dye sets, ink concentration, media properties and halftone pattern for best color gamut and color rendition has become of prime importance in the imaging field. Color characterization, color profiling, and digital proofing are an area of great activity.[6,7] A profound understanding of digital color reproduction is necessary for color management, which in return is a requirement of open color document exchange.[8] With ink jet printing supplanting traditional photography in certain areas, the expectations for color reproduction have risen. The choice of 6-color versus 4-color systems and continuous tone versus halftone printing for an imaging system needs to be made. As the diluted colors do not contribute to the maximum saturation points of the gamut, the 2-dimensional polygon method as described in Ref. 9 is expected to fail for color prints made up of concentrated and diluted colors.

Whereas color matching and color management frequently deal with color appearance and visual phenomena under varying illumination,[10] color comparisons of media and inks are mostly fixed to one viewing condition that characterizes the components best.[11] We addresses two areas of print evaluation. Color gamut comparisons are used to characterize ink jet ink/media components. A method to quantify the humidity sensitivity of prints is also described.

Part I: Gamut Investigation of Ink Jet Prints

Experimental Set-Up and Numerical Calculation

To look into details of color gamut and color reproduction, a fine scan of the color space is necessary. The gamut evaluation is based on 252 original data points measured on 12 printed color wedges with 21 density steps. Pure colors (100% Y, M, C, R, G, B) are printed to white and to black in steps of 5% ink load, whereby black was mixed in as composite black. The wedges were printed on the same printer, with the same fixed color profile (45° curve) and a defined halftone algorithm.

The prints are left to dry for at least 24 h at ambient conditions (45–55% r.h.). The wedges were measured in a proprietary spectrometer with automatic sample feed. The spectrometer is based on the commercial Bruins Omega 20, with Czerny–Turner monochromator, holographic grating and photo multiplier. The equipment works as a pseudo two-beam instrument. It measures in 45°/0° geometry against a white backing (according ISO 5/4) and with a tungsten halogen light source (about 0.6 Mlux). The aperture size is 4 mm. Each sample is referenced to ideal white and measured in the range of 380–750 nm in steps of 1.0 nm, which are averaged to steps of 5 nm for further data processing. The spectra are converted into L*a*b* coordinates based on the 2° observer and D65 illuminant.

The interpolation from the 252 measured data points to the finer wire mesh needed for precise gamut investigations is done in two steps, graphically represented in Figs. 1 and 2. The graph shows a segment of the color space between two experimental wedges (ribs). In a first

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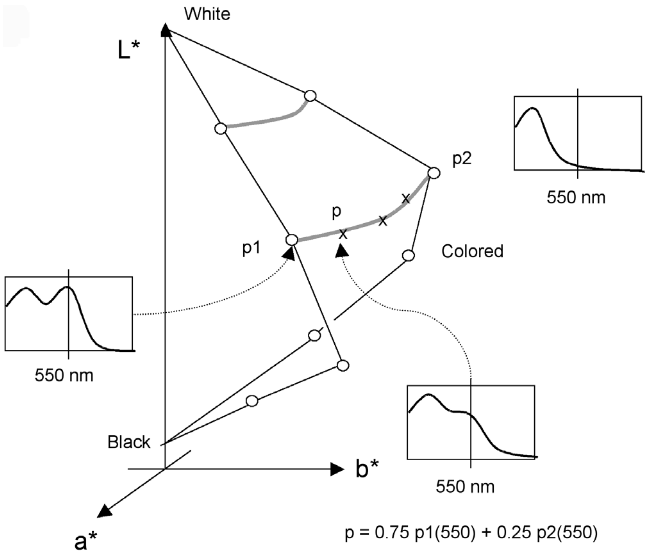

Figure 1. Interpolation step 1

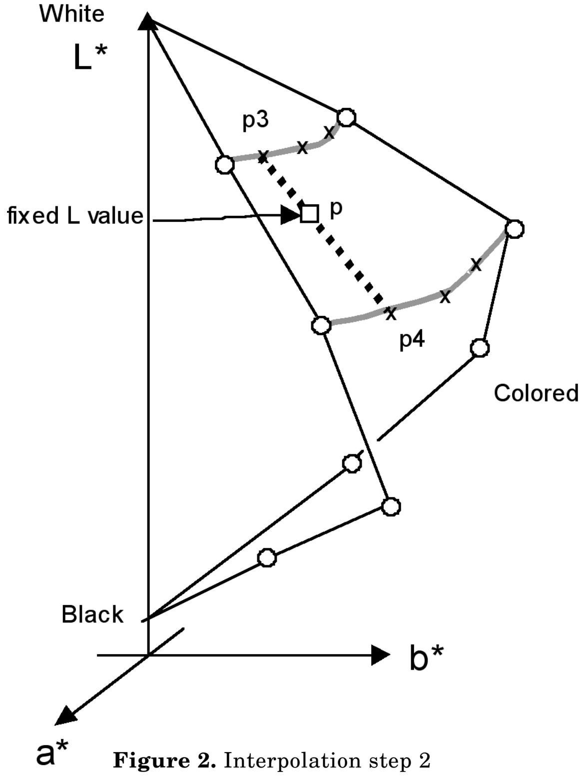

Figure 2. Interpolation step 2

step, 9 intermediate spectra are interpolated between point p1 and p2; both original color patches on two adjacent ribs. Only three of the nine intermediate states are shown in the graph for simplicity. Although only sketched for one wavelength (550 nm), the interpolation is actually done in 75 wavelengths between 380 to 750 nm for the spectral absorbency of each of the nine intermediate states according to

$$S_p = (1-m)S_{p1} + mS_{p2} \qquad 0 < m < 1. \tag{1}$$

TABLE I.

Gamut volume	Ink set 1 (fig. 3) media 1	Ink set 2 (fig. 4) media 1	Ink set 3 (fig. 5) media 1	Ink set 2 media 2	Ink set 2 media 3
Y	8105	10307	8114	9141	8573
R	6156	6604	6879	6008	5947
M	3496	5216	7796	4831	5471
B	2696	3463	4248	3164	3547
C	3045	3695	3591	3789	3521
G	4955	7737	5877	7658	7035
Total	28453	37024	36506	34591	34094
Metam. Index	6	6	9		

The corresponding L*a*b* values are calculated. The hue mesh is constructed out of 170100 interpolations. The second step of the interpolation relates to the *L* values along a rib between point p3 and p4. To find the correct L*a*b* values for the equiluminance planes of the gamut, a linear interpolation in L*a*b* is done as shown in Fig. 2. As an example, the calculation for *L* = 70 would be:

$$\begin{aligned} m &= \frac{L^*_{p3} - 70}{L^*_{p3} - L^*_{p4}} \\ a^*_p &= (1-m)a^*_{p3} + ma^*_{p4} \\ b^*_p &= (1-m)b^*_{p3} + mb^*_{p4} \end{aligned} \tag{2}$$

In a final step, equal distant hue angles are calculated and the gamut volume is obtained by adding the squares of the saturation for every point. This is strictly proportional to the areas of the equiluminance planes. The last step provides arbitrary units (divided by 70 for matching a previous database) not L*a*b* volume units. The conversion is possible by using a factor of 70 π/6.

To test the quality of the interpolation, some experimental color wedges were suppressed and the program was forced to spectrally interpolate over a much wider range. When omitting the red rib, the total gamut would only change by –2%, the Y and R sector by –3% and by –6% respectively. Omitting the blue rib reduced the B sector gamut by 5% and grew the M gamut by 9%. The suppression of the green rib had the largest effect. Total gamut was reduced by 7% and Y, C and G sector gamut by 5%, 5% and 25% respectively.

The calculation replaces the missing experimental ribs red and blue very well and proves that the interpolation does predict the actual shape of the color space satisfactorily in most sectors. The suppression of the green rib is not recommended. A further reduction in the number of interpolation steps could also be envisaged but needs further investigation.

The representation and visualization of device gamut has become of great interest for the area of printing as documents are openly exchanged. Herzog and Hill[12] as well as Braun and Fairchild[13] describe an alternate method of gamut representations. Instead of L* as function of a* and b* both methods deal with C* as function of L* and hue to obtain uniqueness. In this C* versus L* hue representation, Herzog and coworkers map the edges and corners of a kernel gamut to the edges and corners of an experimental gamut. The kernel gamut is obtained from a cube in the L*,a*,b* space whose diagonal is parallel to the L* axis.

TABLE II.

Paper color	Media 1	Media 2	Media 3
L*	96	95.5	92.4
a*	0.2	–0.4	3.8
b*	–1.6	1.0	–8
Gloss			
20°	60	40	40
60°	91	76	78
85°	84	77	79

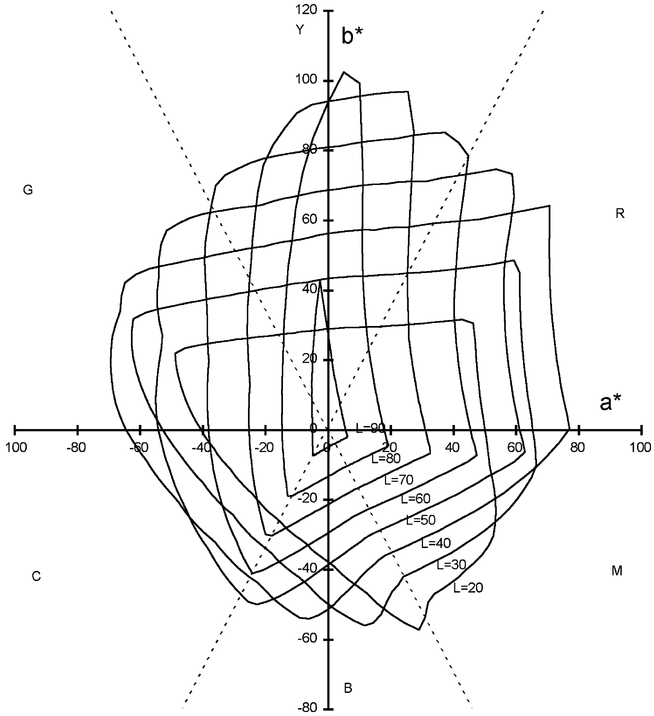

Figure 3. Full gamut plot of ink set 1 on media 1

The method of Fairchild and coworkers is based on cube surfaces intersected by 20 vertical and horizontal lines that results in 2400 experimental points. Intermediate L*,a*,b* values are obtained by triangular interpolation.[13] Such a fine mesh size is required for L*,a*,b* interpolation. Total gamut and sector gamuts are not calculated in Refs. 12 and 13 because the main application of the visualization method is gamut mapping and matching of different device gamuts. The method presented in this article requires only about a tenth of the experimental data as input, because between the ribs of the gamut not L*,a*,b* data are interpolated but original color spectra. This allows a wider interpolation step size. If only L*,a*,b* data are available as is frequently the case in gamut mapping and visualization, the presented method cannot be used. However, it is well suited for the comparison of colorants on printer devices due the lower experimental overhead and the easy access to gamut volumes.

Application: The Influence of Ink and Media on Gamut

The gamut plots, total and sector gamut volumes have been used to characterize gamut in media and ink design. The size of the mesh is fine enough to resolve differences in raster algorithm, print gloss and media tint.

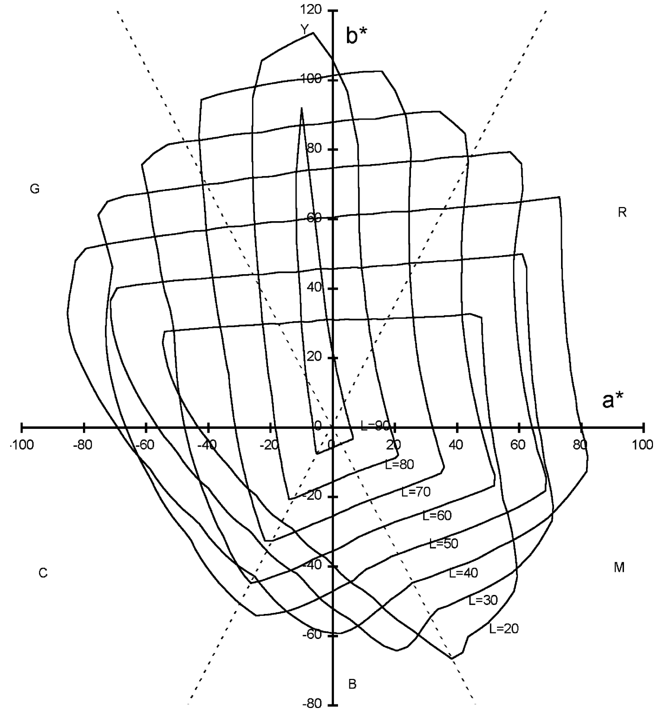

Figure 4. Full gamut plot of ink set 2 on media 1

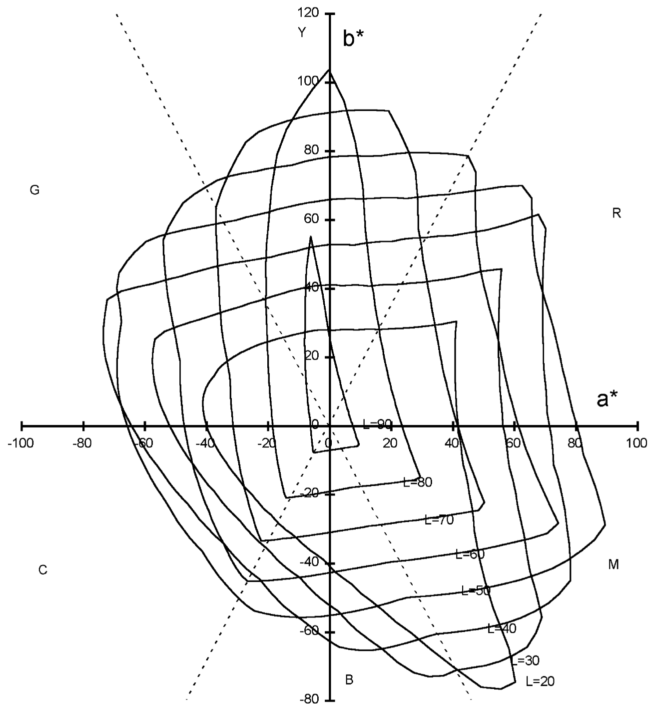

Figure 5. Full gamut plot of ink set 3 on media 1

The very important contribution of the inks and colorants on gamut is well known. The gamuts of three typical ink jet ink sets are shown as equiluminance plane diagrams in Figs. 3, 4, and 5. The inks are all printed on the same photo glossy paper.

The color gamut volumes of the three ink sets on photo glossy media 1 per sector and in total are listed in Table I, first three columns. The largest ink gamut has 13% more volume than the smallest gamut.

The larger gamut is mainly due to the higher color brilliance of the magenta colorants in ink set 3 compared to ink 1 and ink 2. Brilliant colors are often obtained from dyes with very narrow absorption curves. Such narrow dye absorption curves can lead to stronger metamerism. Illuminant metamerism[1] is created by the interaction of color spectra with different light sources. A metameric index was calculated for the three ink sets of Table I and is listed in the last row of Table I. For the metameric index, a neutral gray wedge of the three ink sets is calculated from the dye spectra under illuminant A. The illuminant is changed to C while leaving the spectra unchanged. The resulting colors under illuminant C are compared to the original neutral gray. The step with the highest deviation from gray is chosen and its ΔE from neutral is given as the metameric index.

The ink set with the highest index is set 3 which has a magenta dye with a very narrow absorption peak. A high metameric number points to difficulties in balancing prints for different display conditions or changing illumination, as good neutrality will not be possible for tungsten as well as for daylight at the same time.

The media used is another very important factor even if only comparing the class of photo glossy products. Dot size, paper color, and paper gloss have an influence on the gamut. Ink set 2 was printed on two other commercially available photo glossy papers (media 2, media 3) that vary in color and gloss from the first photo glossy media 1 as shown in Table II.

The gamut volumes of ink set 2 in the last two columns of Table I show a reduction of 5% for the same imaging layer but with semi-gloss finish instead of glossy (media 2). A reduction of 7% is caused having semi-gloss as well as darker tint (media 3).

The authors in Ref. 9 use a 2-dimensional polygon method to describe the gamut of digital color printers and the media influence. For 4-color systems, such a simplified approach to estimate gamut gives very satisfactory results. The polygon methods applied to the comparison of ink set 1 and 3 in Table I yields a difference of 19% compared to 22% in the refined method of this study. It is less suitable to use this polygon method for ink sets including diluted colors. If in ink set 1 magenta and cyan are composed of full strength ink and one dilution at 25%, the polygon method shows only a gamut gain of 3% compared to the full strength ink alone, whereas the refined gamut investigation shows 12%—three times more.

Pearson[4,5] applies the Neugebauer equations to the study of printing ink gamuts, but describes this theoretical approach as tedious. Vertical slices in Hunter Lab are selected as most appropriate to visually represent gamuts in printing. Such a theoretical method would need to be adapted to combinations of halftone and continuous-tone printing as are available with ink jet printers. The semi-empirical method of this study was preferred to a more theoretical approach because it does not assume a specific print method or restriction to a certain number of colorants. Contrary to printing, many ink jet printers use dye-based inks not pigments in which the covering power and scattering behavior are considerably different. In glossy RC ink jet papers, dots are not semi-opaque ink films, but transparent areas of dye based inks.

Influence of Measurement Geometry and Surface Finish

The method attempts to describe the color gamut of prints viewed under the same illumination conditions to characterize media, dyes and ink. It does not claim to provide an appearance based rating or color matching.[10] The great variety of surfaces available for ink jet makes color matching very challenging.

The influence of the spectral measurement geometry (0°/45° versus 0°/diffuse) on L*a*b* values has been reported in the literature.[11,15] The human observer has yet another, possibly an intermediate geometry of observation for a typical color. This relationship is schematically shown in Fig. 6. Color appearance will critically depend on the observation geometry and the size of the color variation with the observation angle was of interest to us. Yellow and magenta colors on two media with very different gloss and surface finish, namely an RC glossy paper and a fine arts paper as well NCS color patches[14] were spectrally measured both with 0°/45° geometry and with an integrating sphere. The L*a*b* yellow and magenta sector are shown for the two measurements in Figs. 7, 8, and 9. The effect of surface finish on color saturation is clearly visible for the case of a RC glossy paper (Fig. 7), the fine arts prints (Fig. 8), and NCS color patches (Fig. 9). Whereas the measurement geometry has only a minor influence on the fine arts paper print (–1.5% for 45° to diffuse), it has a remarkable influence on glossy paper (–14% for 45° to diffuse). Ink jet media, with their wide range of gloss, are more susceptible to large gamut differences due to surface finish than other printing methods that are often on different types of matte-coated paper.[5] Introducing an asymptote of 1.2 in the 0°/45° data approximates the 0°/diffuse data and may represent the visual appearance better.

Continuous versus Halftone Printing

It is often assumed that by reducing the dot size, the ink jet print will finally resemble continuous tone prints. Although this may be true for extreme reductions, this is not true on the current scale below 1000 dpi. While graininess and other image quality attributes benefit from the dot size reduction, the colorimetric appearance does not. Continuous tone images generally have an advantage in the reproduction of saturated pastel colors. Colormetrically, the additive mixing of full color dots and white background leads to desaturation especially in light colors. This has been known from comparisons of offset printing to photography before the digital age.

Some printers now offer variable concentrations (typical 10%, and/or 30% ink concentration) next to the 100% ink. This allows better color rendition and extends gamut in light areas. The superiority in color saturation of this continuous tone/halftone approach in printing is shown in Fig. 10. The saturation for ink diluted to 80%, 60%, 40%, 20% and 10% of its original concentration is compared to the saturation of a wedge printed with the ink at 100% concentration. The hue curves in Fig. 10 were measured on wedges printed with the specified ink concentration. The steps of equal lightness are compared. For the same lightness of $L = 74$ shown in the graph, the saturation difference between the 30% ink and the 100% ink is 10 L*a*b* units in favor of the diluted ink.

The combining curve 'theory' is the true continuous tone curve for a cyan wedge made up of the same colorant. With very diluted inks as in the 10% ink curve, ink jet prints will approach continuous tone image

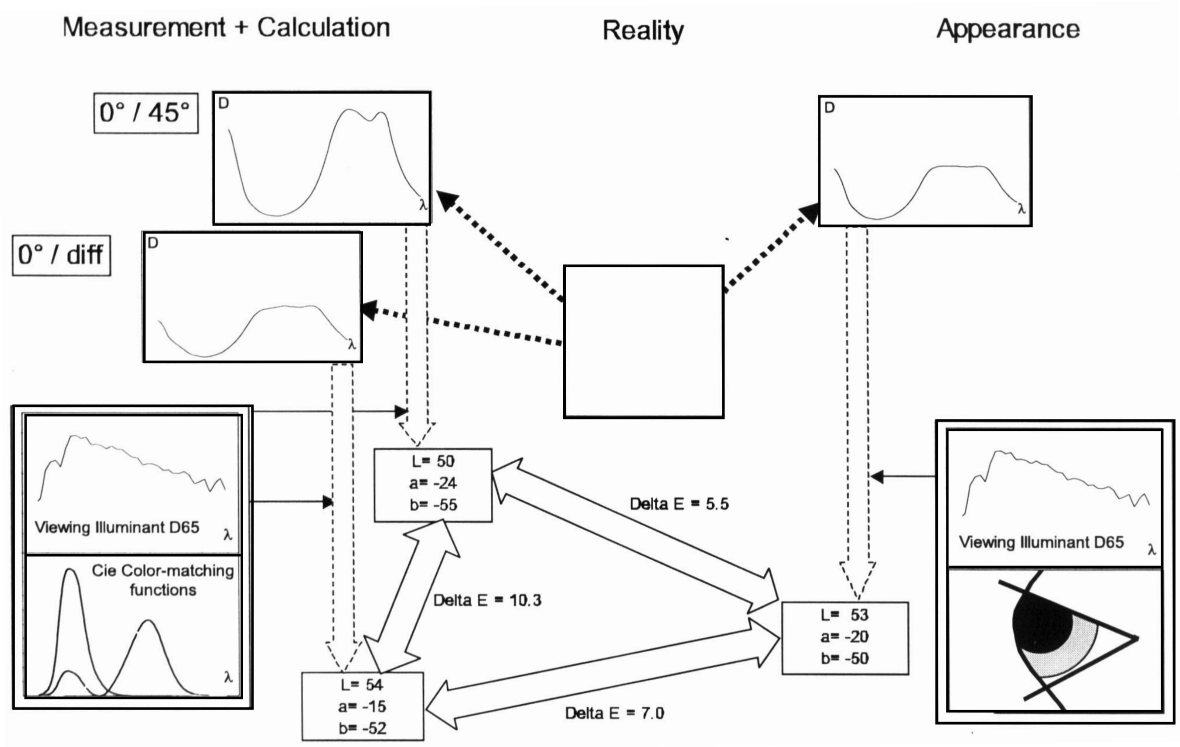

Figure 6. Schematics of color perception

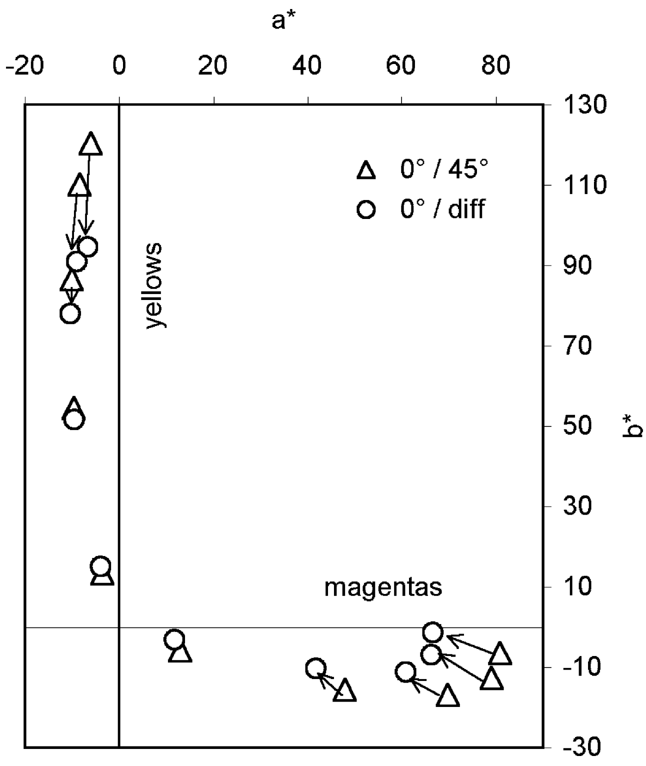

Figure 7. Geometry effect on glossy print

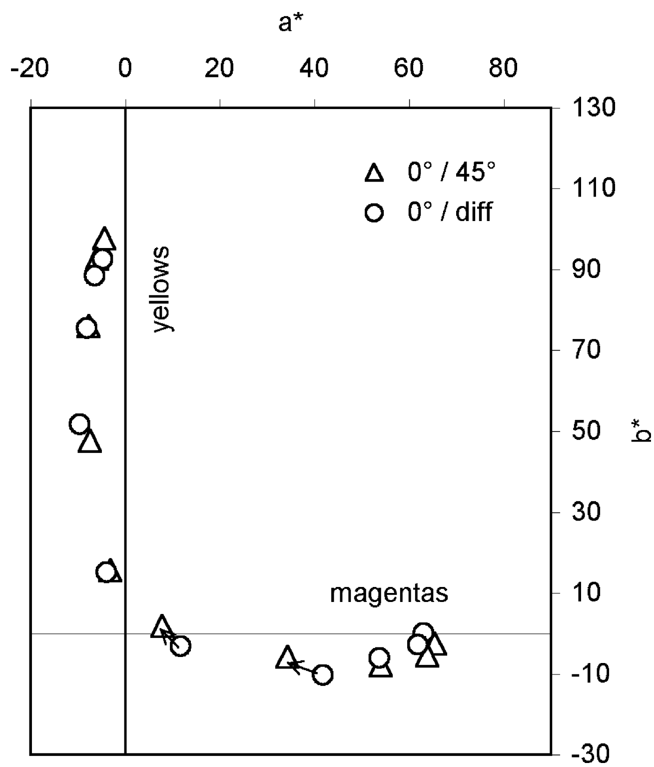

Figure 8. Geometry effect on fine arts print

gamut and quality. Clapper, Gender and Brownstein[3] have compared the saturation of photographic dyes in continuous tone imaging to TV phosphors. The investigation in CIE U*V*W* using idealized photographic dyes concludes that a subtractive continuous tone image gamut may reach or surpass the gamut of practical additive system such as TV. However, in ink jet printing, drying and permanence put a practical limit on printing with diluted inks.[15]

Part II: Dye Diffusion in Ink Jet Prints

In a humid environment, an often observed change in ink jet prints is the diffusion of colorants into neigh-

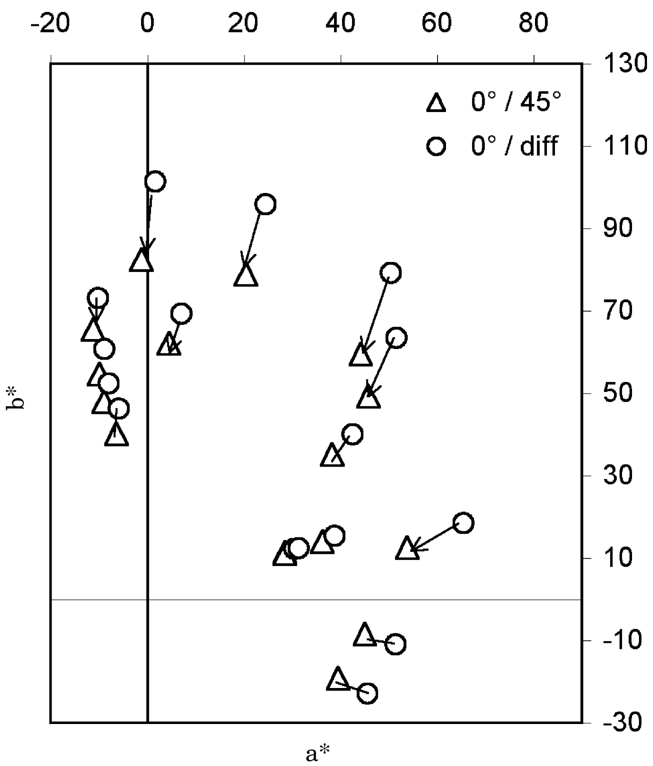

Figure 9. Geometry effect on NCS samples

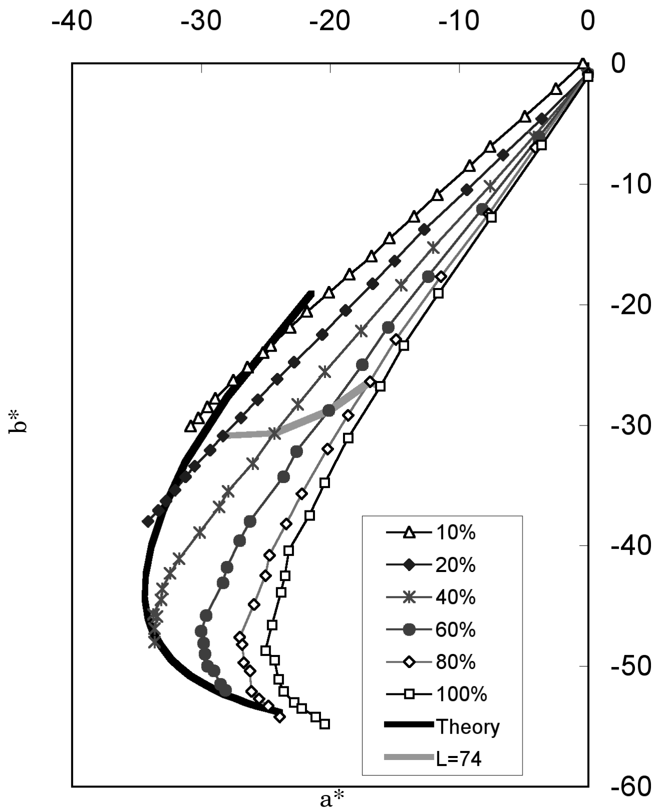

Figure 10. b* versus a* plot for different ink concentrations cyan

boring areas visible as color bleeding into white or color, unsharp text, color shifts, density and contrast changes. Dye diffusion changes the colors and makes print comparison over longer periods difficult.

The aim of this study was to find a test target and quantitative evaluation procedure that allows the investigation of dye diffusion. It should give reproducible results for different ink/media combinations, be most critical and quantitative and be able to discriminate between different ink and media properties. In low dot percent areas, the individual dot gain can be observed after exposure to humidity. Such dot gain turns out to be much less discriminating between different combinations, does not represent actual dark keeping in files and does not well predict the bleeding of small text inside full color areas. A much larger amount of humectants and water is available in a full color square fueling diffusion.

Experimental Method

A set of samples consisting of different ratios of white lines to color lines, and of different color densities and color composition (monochromes and bichromes), was printed with two ink sets on several media to find the most sensitive and reproducible color test pattern. The samples were submitted to climatic tests at 40°, 50% r.h. and 40° 80% r.h. for 7, 14, and 21 days and the density changes for the different patterns were recorded.

Results

The most discriminating test pattern for strong and weak dye diffusion is a square of full color intersected by a grid of white lines which are 2–4 pixel wide (2w–4w) and spaced 4–8 pixels apart (4c–8c). Figure 11 shows the yellow density change for the case of a very diffusion-fast (left) and a very strongly diffusing ink/media combination (right). The other inks showed a very similar behavior.

The test pattern was applied to the study of the humidity sensitivity of the diffusion effect as well as its change over time. The diffusion at 50% r.h. is very weak for all ink/media combinations. The onset of diffusion is a steep function of humidity as shown in Fig. 12. At 70% r.h., the increase of density for all colors was negligible after 3 days of humidity exposure whereas major changes are visible at 80% r.h. The exact onset of the humidity sensitivity seems to vary with the ink/media combination. However, the limited number of ink/media systems available for testing did not allow firm conclusions.

As can be expected, the degree of diffusion is dependent on the time of exposure to the high humidity. Major changes happen in the first 7 days of the exposure to humidity, but the plateau is not reached even after 21 days as can be seen in Fig. 13. Dye diffusion creates a contrast increase (and color shift) that is strongest in the intermediate density range of 0.5–1.5. This should be borne in mind when working on color profiles, color calibrations and color studies. Reference samples need to be measured quickly after full drying and should be stored below 60% r.h.

Ink jet prints are often laminated quickly after printing to protect them. Lateral dye diffusion occurred on such freshly laminated samples underneath the laminate. At least 8h of drying in 50% r.h conditions were needed to stop the diffusion.

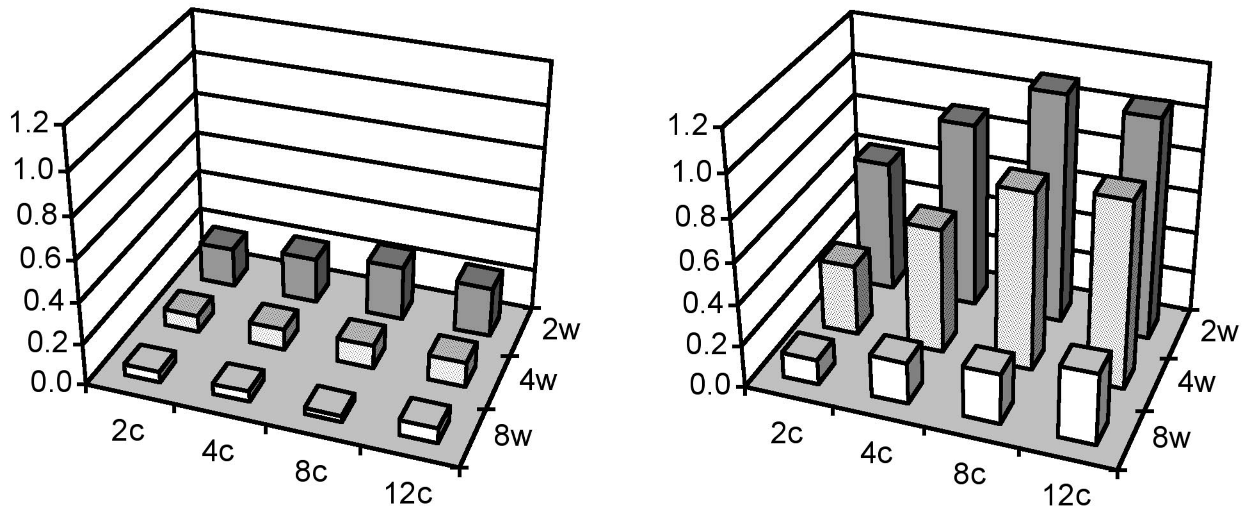

Figure 11. Yellow density change depending on line width (2w–8w) and line spacing (2c–12c) for two different inks

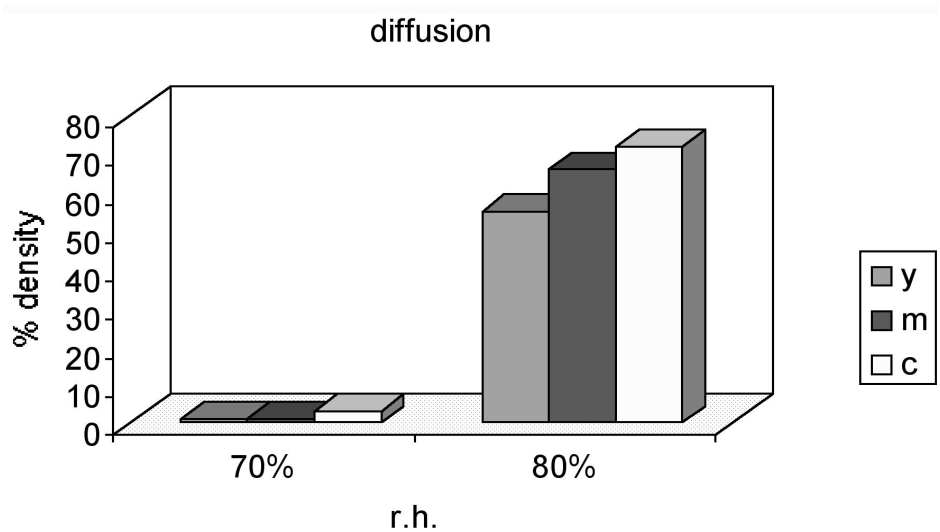

Figure 12. Humidity sensitivity of the diffusion effect

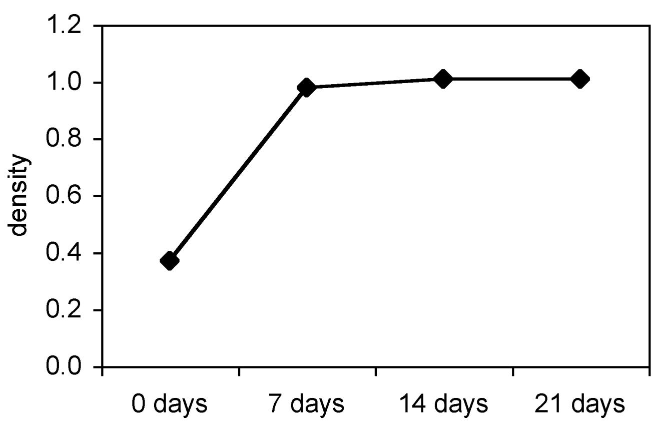

Figure 13. Densities of test pattern after 80% r.h test.

Conclusions

A mesh of experimental gamut surface colors was spectrally interpolated in the equiluminace planes and L*a*b* interpolated in-between planes to provide a detailed view into gamut differences caused by colorant, media or print pattern changes. Due to the spectral interpolation it is possible to use a base set of only 250 experimental points, about a tenth of other gamut visualization methods.[12,13] The semi-empirical method avoids assumptions about the validity of continuous or halftone printing theory for ink jet printing and does not make use of the Neugebauer equations. Ink dilutions and continuous tone versus halftone printing effects on gamut can be investigated. The gamut gain by printing with ink dilutions below 50% of normal ink strength is clearly demonstrated. It is shown that for ink jet prints, the measurement geometry used in the spectral acquisition of the color is of high importance for glossy media and of less importance in matte media. This sensitivity to the measurement geometry, known from graphic arts, is even more important with ink jet prints that may have widely varying surface texture and surface finish.

A small grid test pattern is shown to be suitable for quantifying dye diffusion under high humidity conditions. The target pattern provides a sensitive and reproducible response. Storage of print reference samples in controlled low humidity (around 50% r.h.) is recommended for colorimetric work.

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