Factors Affecting the Appearance of Print on Opaque and Transparent Substrates

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This study aims to investigate factors affecting the appearance of print on both opaque and transparent substrates. In particular it looks at factors from five categories: the digital input, the printing system, the print, the illumination under which the print is viewed and the viewing environment in which it is viewed. The key method underlying the work described here relies on identifying a range of factors in these categories and having alternative states for each factor, e.g., the substrate factor can be 'plain paper', 'glossy paper' or 'newsprint'. A reference state is then defined for each factor and alternative states are compared with the reference one factor at a time. The comparison is in terms of color differences between patches of a test chart obtained in the reference and an alternative state. The results for factors are then viewed both individually and by grouping all factors of a given category together. Finally the results indicate the magnitude of the change that can be expected due to a given factor or category and this makes it possible to order factors in terms of the magnitude of visual difference they can cause when altered. Having such an ordered list is then of use both in improving printing systems and in dealing with customer service queries.

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Introduction

At the highest level digital printing can be seen as having digital data as its inputs and a visual stimulus as its output. The relationship between the digital data and the corresponding visual stimulus, i.e., a print viewed in a certain way, can be highly dynamic. As various factors are involved in the printing process as well as in the viewing of the resulting print, there is great potential for variation.

A typical scenario is a given digital image printed in two different locations. If the printing is done on the same type of device and the appearance of the two prints is not equal, which factors have caused the mismatch? This is a common question in office and industrial environments, therefore the need for quantifying the contributing factors is very high.

Before attempting to formulate a list of relevant factors, let us first look at a generic digital printing workflow. The starting point here is a digital image, which is sent to a printer from some software application using a certain printer driver. The instructions from the printer driver are sent to the printing system's imaging engine, e.g., LED, inkjet, dye-sublimation, which deposits colorants on a substrate. The final print, when viewed in a certain environment under a certain light source, results in a certain appearance for a viewer. Any change to the properties of any of the elements involved in the above workflow has the potential to alter the final appearance corresponding to the digital input.

The different factors can be categorized into two classes. Those that determine the resulting print for a given digital input, and those that determine the color appearance of a given print (Fig. 1). Some of these factors might not have the same potential as others in terms of influencing a print's appearance; for example, does viewing geometry cause greater differences than print resolution?

The aim of the present work is to develop a list of factors ordered in terms of the magnitude of their potential impact on print appearance both for opaque and transparent substrates. This list could be used as a checklist for those involved in the construction and servicing of printing systems.

Before discussing how the above aim is going to be achieved, a brief survey of existing literature dealing with this topic will be given. Even though various studies have been carried out on individual topics pertinent to the present study, no work was found that investigates the relative magnitudes of visual differences corresponding to changes in factors affecting print.

Rasmussen,[1] for example, concluded that from a technical point of view there are a vast number of parameters that determine color image quality. However, he

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Supplemental Materials—An Appendix containing a full list of the factors considered in this study can be found on the IS&T website (www.imaging.org) for a period of no less than two years from the date of publication.

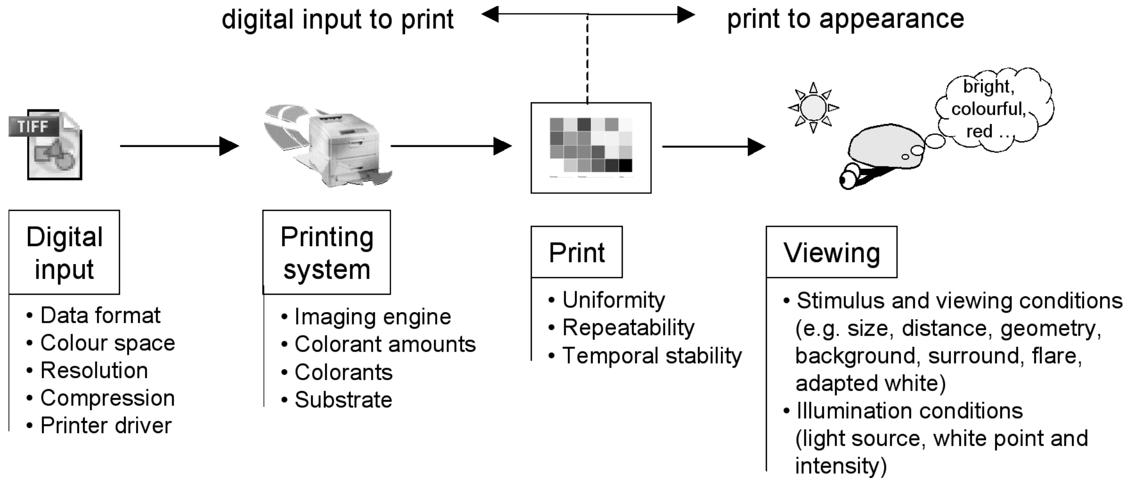

Figure 1. From digital input to appearance.

points out that from the viewer's point of view, there are a limited set of important attributes. Furthermore these attributes can be described in appearance terms and without the need to reference technical parameters. Marcu[2] then deals with various factors that determine print quality such as printing technology, colorant/media interaction, geometric resolution, halftoning, separation, black generation, UCR, GCR and tone reproduction. These technical parameters are discussed without reference to their impact on the final appearance of print. On the other hand, Green[3] points out the importance of viewing conditions for color appearance. He concludes that standard viewing conditions should be used when comparisons between originals, proofs and prints are made to ensure accuracy. Morovic and Sun[4] illustrate the effect, and magnitude, of varying viewing and illumination conditions as well as substrates on the color gamut of prints as well as other media. Cui and Weed[5] highlight factors affecting projected transparent prints, listing stray light, sample scattering, and projector optical design limitations as being of importance. Furthermore, they illustrate the factors that contribute to the process of color calibrating an overhead transparency projection system. As can be seen there are numerous papers that either list factors affecting print or study one or a small number of them, but there is no work that compares factors of different categories side-by-side.

Finally, the perceptibility and acceptability of color differences in printed images is also essential for interpreting the results of the work presented here. Uroz et al.[6] derived thresholds for these and argued that in general the perceptibility threshold of color changes for a particular image depends on its content and composition.

The next section of this article will introduce the experimental method used for evaluating the visual differences caused by varying a number of factors. Then the data analysis performed on the experimentally obtained data will be described, followed by a presentation of the results. Finally the implications of the results will be discussed and ideas will be suggested for future work.

Experimental Method

The method used here relies on identifying a range of factors that could potentially affect the appearance of prints corresponding with a given digital input. These factors can have alternative states, e.g., the light source can be 'A', 'D65' or 'office lighting'. A reference state is also defined for each factor. Then alternative states are compared with the reference, changing one factor at a time. The comparison is in terms of color differences between patches of a test chart obtained in the reference versus an alternative state (Fig. 2). This section will provide details of the various aspects of the method used here.

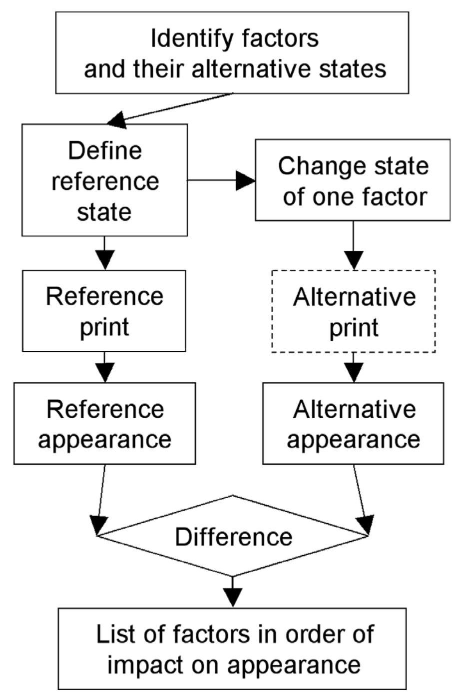

Figure 2. Overview of method.

Digital Test Chart

The test colors used for evaluating the impact of various factors were selected so as to contain memory colors such as those of skin, grass and sky. Furthermore pastel colors and colors from the RGB-cube's surface have also been chosen to give information about the print's color gamut. The last row of the test chart con-

Figure 3. Digital RGB test image with 24 color patches in RGB color space. (Patch size is 4.5 × 4.5 cm.)

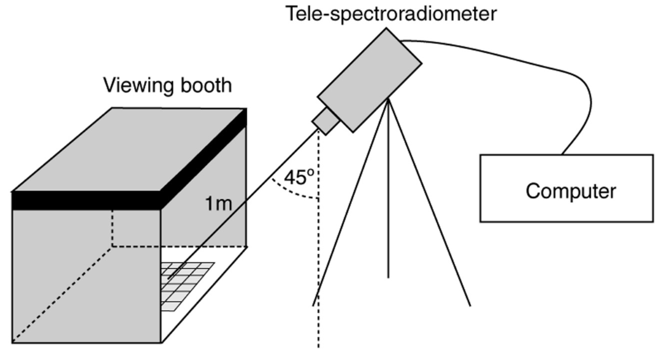

Figure 4. Measuring set-up for opaque substrate.

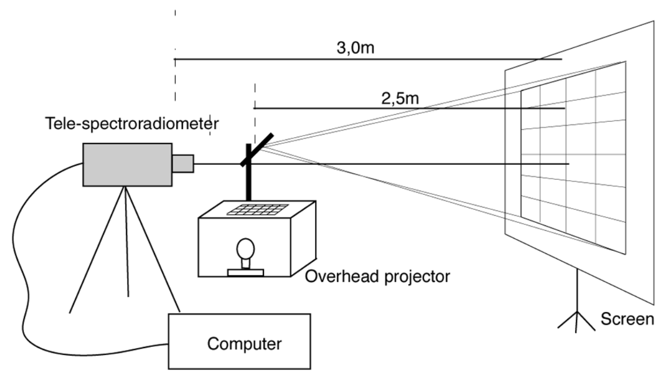

Figure 5. Measuring set-up for transparent substrate.

tains a gray scale, which will show how tone rendering is affected by various factors. The size of color patches in the chart was chosen so as to be measurable under the various viewing geometries studied here. Note also that the same digital test chart (Fig. 3) was used for both opaque and transparent substrates.

Reference Conditions

Given the digital test chart, reference conditions were determined under which the test chart was printed, viewed and measured both for opaque and transparent substrates. In particular, the reference print was based on the default settings of the printing system used in this study. The application used to print the test chart was Adobe Acrobat and the substrates used for both opaque and transparent reference prints were commercial ones, recommended by Oki Norway. The viewing set up for the opaque reference is based on the standard condition of the graphic art industry,[7] vertical geometry 45°, background gray, light source D50 simulator, light intensity 100% (Fig. 4). The reference viewing condition for the transparent substrate is defined by the projector and the corresponding geometry and is not related to any standard (Fig. 5).

It is worth emphasizing that the chosen reference conditions are not meant to represent the best or ideal situations but instead are a reference state with which to compare the variations obtained by changing the various factors. The measurement results obtained from the reference conditions were used as the standard with which measurements from all other conditions were compared.

Factors Determining the Appearance of Print

The test chart and viewing conditions defined above can now be used to evaluate the changes caused by a number of factors being in different states. Each of these factors was varied one by one and the result measured using a telespectroradiometer (TSR). The factors considered in this study belonged to the following five categories: the digital input, the printing system, the print, the illumination under which print is viewed and the viewing environment in which it is viewed. As will be shown in the following sections, a number of factors were considered in each category and each of these factors was set to a number of alternative states. Note that some factors required both new prints and new measurements for their alternative states, e.g., changes to printer driver settings, whereas others required only new measurements to be made, e.g., changes to viewing conditions. The final list of factors evaluated here was arrived at with the help of Oki Europe and therefore also represents options relevant to industry. A description will be given of the various factors considered here (for a full list, see the *Appendix published as Supplemental Material on the IS&T website (www.imaging.org) for a period of no less than two years from the date of publication).*

Digital Input

Digital input is the first category in the print process, which might affect the appearance of a print, and four factors will be considered here:

Printer Setting. The Oki C7400 printer used in this study is color balanced when it is manufactured and it allows for manual color balance adjustment. As the first alternative state a visual calibration was performed under office lighting conditions (with a correlated color temperature of approximately 3500K). Two mis-calibrations were also executed, whereby the first mis-calibration was adjusted towards magenta and the second one towards blue. These two mis-calibrations can be seen as common user mistakes.

Printer Driver Setting. Five different Printer Driver settings were applied on the basis of Oki Norway's experiences and feed–back from their customers. First, a test print was made using the PostScript printer driver setting “Color Control: No Color Matching”. “No Color Matching” transmits the color data as it is without printer color calibration. Subsequently the Printer Driver Setting “Image Color Matching: PostScript CRD Color Matching” was applied. The third setting was based on “Black Finish: Matte”, which means that all 100% black areas of an image is printed with black toner only, not a mixture of cyan, magenta and yellow. The fourth setting, “ICM Method: ICM Handled by Host System,” resulted in the host computer controlling the printer’s software colour profiles. PCL was used as an alternative driver to the PostScript one.

Application Used for Printing. Five common applications were used for printing the test chart. For the reference print Adobe Acrobat 5.0 was used. Adobe Photoshop 6.0, Microsoft Office 2001 (Word, Excel and PowerPoint) were used for obtaining the alternative states.

Application Printing Menu. The default settings of Adobe Acrobat 5.0 were used for printing the reference test chart. Three different ICC profiles were then applied as alternatives: a custom ICC profile generated by Oki Norway, the standard ICC profile distributed by Oki for the printer used, called “Oki C7400 1200dpi(PS)” and an ICC profile generated for newsprint.

Printing System

Various Printing Systems. Three printing systems in different locations were used whereby the printer types, the digital input parameters and the substrates were identical in all three cases. To avoid differences in the settings, written instructions based on the reference settings were distributed together with the digital test chart.

Substrate. Various substrates commonly used in the office market were printed on. Apart from common office copier paper (“out of the tray”), coated, uncoated and recycled papers were selected. For the transparent substrate only one alternative was printed on and measured.

Print

Printer Repeatability. To quantify the effect of the printer’s repeatability, the digital test chart was printed on both opaque and transparent reference substrates three times at weekly intervals.

Print Temporal Stability Under Dark Conditions. To characterize the temporal stability of prints, four measurements were made at weekly intervals. Between the measurements the prints were stored without being exposed to light.

Print Temporal Stability Under Day Light Conditions. Here a print was again measured at weekly intervals but it was left exposed to daylight under office conditions.

Viewing

This category and the next one only require different measurements to be made of the reference print under various viewing or illumination conditions.

Vertical Geometry. Two different vertical geometries were used for the prints on the opaque substrate; prints were measured at an angle of 60° and then 30°. As prints on transparent substrates are typically viewed under a fixed vertical geometry no alternative states were applied in this case.

Horizontal Geometry. For prints on the opaque substrate one alternative state at 45° was used in addition to the 0° reference. In the transparent case two alternatives were used: 30° and 60°.

Background. The background in the viewing cabinet where the reference print was viewed was also changed for the prints on the opaque substrate. Alternative states of white and black backgrounds were used when measuring the print. For prints on the transparent substrate the background factor was not used.

Surround. For the surround factor one alternative state, with ambient light, was used for prints on both substrates.

Illumination

Light Source. For the alternative states, six light sources were evaluated for the opaque substrate: Cool White Fluorescent (CWF) at 4200K, Standard illuminant A at 2800K, actual office lighting, actual daylight at the following times: 8 am (cloudy), noon (cloudy) and 4 pm (cloudy/sunny). For the transparent substrate only two light sources were used – a second backlight projector (being of the same model as the reference) and a reflection projector.

Intensity. For both substrates the intensity of the light source was reduced to three alternative levels. For prints on the opaque substrate they were 25%, 50% and 75%. For prints on the transparent substrate the same levels were used, except that the back light projector was set to reduce intensity internally to 50% instead of having the 75% reduction applied externally. The intensity was reduced by black and white film material with 25%, 50% and 75% transmittance in front of the light source.

Screen. The screen onto which prints on the transparent substrate were projected was also altered by selecting two different screens as alternatives to the reference state.

Color Measurement

As mentioned previously a telespectroradiometer (Minolta CS-1000) was used to measure the spectral radiance of each color patch on the test chart under different conditions. In addition, each measurement set (24 colors of the test chart) also included a measurement of the calibration tile, which is a nearly perfect diffuser. The *CIE Standard Colorimetric Observer* (2°) was used for computing CIE XYZ values.[8] As the measurement method involved a variable measuring geometry, its repeatability was evaluated closely.

Repeatability of the Measuring Instrument

Repeatability, as defined by Hunter and Harold,[9] represents the degree to which a single instrument gives the same reading on the same sample at different times. To evaluate repeatability, three different color patches from the test chart (paper white, skin tone and black) were measured under experimental conditions eight times at short intervals. The measured spectra were first transformed to CIE XYZ and then CIE LAB (CIE, 1986) values, whereby the reference white was that measurement with the highest luminance.

The averages of the eight LAB values were then obtained and ΔE^*_{94} color differences between the average and each individual color were computed. This was repeated for each of the three colors. Overall the results showed that there was an average repeatability error of 0.05 ΔE^*_{94} with a 95th percentile of 0.11 and a maximum of 0.14 ΔE^*_{94} units. Hence the instrument can be considered to have a high degree of repeatability.

Repeatability of the Reference Measuring Set-Up

More critical than the testing of the instrument was an evaluation of the repeatability of setting up the measurement and illumination geometry. Therefore the following procedures were defined for setting up the measuring geometry and instrument:

Reference Set Up for Opaque Substrate:

- Place the target in the center of the viewing cabinet, cover it with a gray card having a square opening in its center, exposing only a single color patch at a time.
- Set a horizontal angle of 45° between the target and the measuring instrument.
- Set a distance of 1 m between the target and the measuring instrument.
- Leave a warm-up time of 30 minutes for the measuring instrument and the viewing cabinet.
- Focus the measuring instrument.

Reference Set Up For Transparent Substrate:

- Place the target in the center of the back light projector; cover it with a black card having a square opening in its center, exposing only a single color patch at a time.
- Set a horizontal angle of 0° between the target and the measuring instrument.
- Set a distance of 3 m between the target and the measuring instrument.
- Leave a warm-up time of 30 minutes for the measuring instrument and the back light projector.
- Focus the measuring instrument and the projector.

At the beginning of each measuring session the measurement values of the calibration tile from the reference set were first matched, before new measurements were taken. The new measurement values of the calibration tile were informally compared with the reference set in terms of tristimulus values. For the opaque substrate a variation in the tristimulus units of 2.0% was deemed acceptable and for the transparent substrate 10.0% variation was considered to be reasonable. Furthermore the measuring instrument and its geometry was fixed and the target patch of the test chart was moved into the center of the measuring instrument's field of view. Hence the issue of illumination non-uniformity was highly reduced and is not part of the discussion in this study.

The procedure for calculating the measurement uncertainty of the above set-up is similar to the measurement of instrument repeatability. Thirty-one measurements of the calibration tile were taken under equal reference conditions at various times throughout the process of collecting data for this study. The mean repeatability error for prints on the opaque substrate was 0.4 ΔE^*_{94} units with a 95th percentile of 0.83 ΔE^*_{94} units and a maximum of 0.89 ΔE^*_{94} units, which is a very good degree of repeatability.

The same procedure was used for prints on the transparent substrate whereby 14 calibration tile measurements were made at various times. The results for this test had a mean error of 1.0 ΔE^*_{94} unit, a 95th percentile of 2.4 ΔE^*_{94} units and a maximum of 4.2 ΔE^*_{94} units. The worse repeatability in this case is due to the geometry being more difficult to repeat exactly. Also the light source of the overhead projector is not as stable as that of the viewing cabinet. Nonetheless, this repeatability is still acceptable as the 95th percentile of color differences due to repeatability error (2.4 ΔE^*_{94} units) is close to the discriminability threshold for complex images, as will be discussed later.

As these repeatability errors are an inherent property of the results presented in the following sections they will be the basis of computing confidence intervals for these results. Where an alternative state is obtained simply by measuring the reference print under non–reference conditions the above mean errors, which represent the standard deviation of the measuring process, will be used to compute the standard error at the 95% confidence level using the following formula: $\pm 1.96\sigma/(n^{1/2})$ where σ is the mean error and n is the number of measurements involved in a particular result.

For alternative states where an alternative print is used, the standard error will be obtained in the same way as detailed above but instead of using the mean error of setting up reference conditions the mean printer repeatability will be used instead as this incorporates variation of the printing system as well as of setting up the reference conditions. For prints on the opaque substrate this mean repeatability is 1.67 ΔE^*_{94} and for prints on the transparent substrate it is 3.01 ΔE^*_{94}.

Data Analysis

After collecting all the color measurements of prints made on opaque and transparent substrates, the data analysis described in this section was performed to determine color differences between the reference state and various alternative states. First spectral measurements are converted to XYZ and then to LAB (with the calibration tile near-perfect diffuser as the reference white). Then ΔE^*_{94} values[10] are computed between reference and alternative state patches. The arithmetic mean, 95th percentile and maximum of the resulting color difference distributions are then computed. Previous research[6] has shown that high percentile values correlate better with the perceptibility threshold than mean color differences, hence the use of the 95th percentile.

As the present study also intends to deal with the effects of different backgrounds, surrounds and light source chromaticities and intensities, it is necessary to use a color appearance model that can predict their effects. As CIELAB is not able to do this, the CIECAM97s color appearance model was used.[11] Here CIECAM97s *Jab* color appearance predictors were first computed from XYZ values under alternative state conditions and XYZ for the reference state were computed from them. The reference states had a ratio of background to adapted white luminance of 0.2 and in the opaque case the average surround option (for stimuli with angular subtense of less than 4°) was used whereas for the transparent case the dim surround option was used.

Difference Thresholds

When considering color differences two types of visual assessments are most prevalent—perceptibility and acceptability.[12] First, perceptibility thresholds indicate what magnitude of color difference is a just noticeable difference (JND). Moreover, the perceptibility threshold for complex images differs from the perceptibility

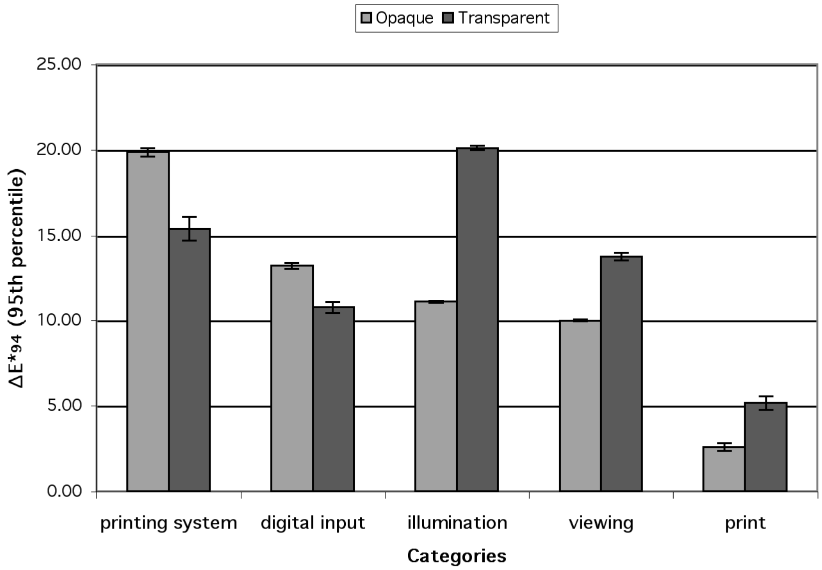

Figure 6. Categories and magnitudes of their potential impact on print appearance. The error bars express measurement inaccuracies in terms of standard error.

threshold for single colors due to the content and texture of the more complex stimuli. The perceptibility threshold for complex images used in this work was empirically derived by Uroz et al.[6] Uroz et al.[6] conclude that for complex images the perceptibility threshold expressed as the 99th percentile of ΔE^*_{94} (1:1:1) difference distributions is approximately 2.6 ΔE^*_{94} units. The results of Stokes et al.[13] also support this figure. Due to the fact that single colors may not have texture or content the perceptibility threshold is smaller than that for complex images. Color difference formulae are set such that their units correspond to JNDs – hence any color difference below 1 unit is predicted as not being perceptible.

Second, the acceptability threshold can be seen as a less concrete concept and one that depends strongly on application and industry. For example in the work of Stokes et al.[13] an acceptability threshold of approximately 6 ΔE^*_{ab} was found for their experimental images and observers. However, as acceptability depends greatly on the experiences and expectations of observers as well as the application for which the color stimuli are intended, the above threshold is only one of many possible ones. Finally, a further quality metric, which could be more suitable for the printer market, would be a tolerance threshold and this issue could be the subject of future research.

Results

The aim of this work is to obtain a list of factors ordered in terms of the magnitude of their potential impact on print appearance. From the experimental results for the two substrate classes, opaque and transparent, two such lists were obtained. First, however, it is useful to look at the impact on print appearance of the factor categories, which can be seen in Fig. 6. The "digital input" category has almost the same impact on print appearance for both substrates. On the other hand the "illumination condition" category can cause a larger color difference in the transparent case. Further it can be seen that the "printing system" category can cause a larger color differences in the opaque case.

Next, Fig. 7 shows the impact of individual factors on prints made on both substrates. The factor "various printer" is most important in the opaque case and the factor "light source" in the transparent case.

Prints on Opaque Substrate

Table I shows the ranking of factors listed according to the 95th percentile of ΔE^*_{94} distributions, and each factor's respective category. The table also shows the perceptibility thresholds for complex images and for single colors. Firstly, it can be seen that approximately 75% of the tested factors are above the perceptibility threshold for complex images, i.e., changes to them will be seen in printed images. The categories "printing system" (including the factors "various printer" and "substrate properties") and "digital input" (with the factors "application printing menu" and "printer setting") determine the appearance of print most strongly; the factor "various printer" is ranked highest in this study.

Below the perceptibility threshold in complex images, factors such as "medium temporal stability" (dark condition and day light condition) and "surround" do not influence the appearance of print due to the small color differences that changes in them can cause. "Medium temporal stability" (dark condition) and "surround" condition are also below the perceptibility threshold for single colors. Further it can be noted in Table I that there is a noticeable gap in color difference between the factor "printer driver setting" ($\Delta E^*_{94} = 8.00$) and the factor "geometry" ($\Delta E^*_{94} = 3.62$). Although these factors (geometry, intensity, printers repeatability and application used for printing) are above the perceptibility threshold their impact on print appearance can be considered moderate. It should be noted that the results of all the experimental work in this study have an element of uncertainty due to the repeatability of the measurement setup.

Prints on Transparent Substrate

Table II shows that all but one of the factors for prints on the transparent substrate cause differences that lie above the perceptibility threshold in complex images.

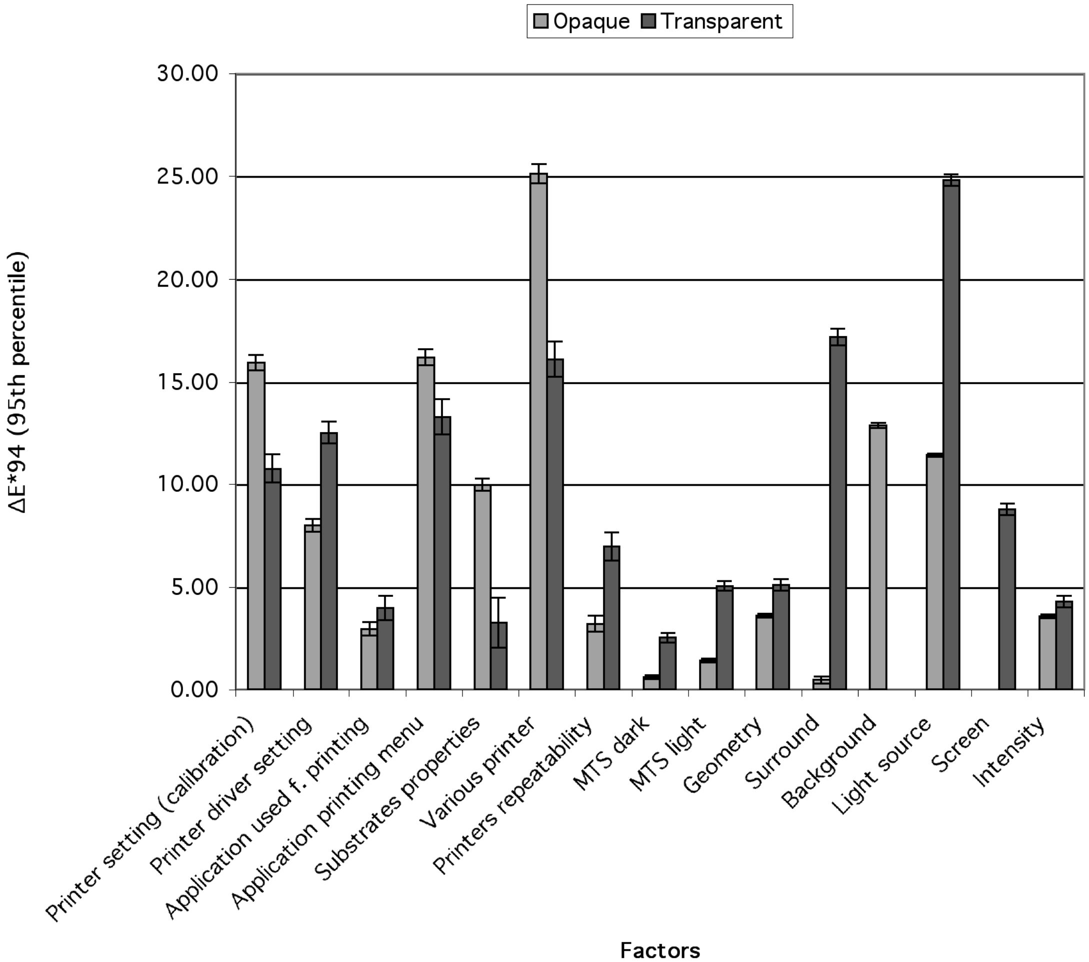

Figure 7. Impact of individual factors on print appearance for both substrates.

TABLE I. List sorted by 95th percentile of ΔE^*_{94} distributions between reference state and alternative states of individual factors for prints on opaque substrate (double line indicates perceptibility threshold for complex images and triple line for single colors).

Categories	Factors	Mean	95th perc.	Max.
Printing system	Various printer	10.77	25.12	27.47
Digital Input	Application printing menu (Profile)	5.54	16.20	24.65
Digital Input	Printer setting (Calibration)	6.89	15.93	19.83
Viewing	Background	6.58	12.87	16.68
Illumination condition	Light source	4.93	11.42	15.89
Printing system	Substrate properties	3.90	9.98	24.59
Digital Input	Printer driver setting	2.42	8.00	27.52
Viewing	Geometry	1.69	3.62	5.70
Illumination condition	Intensity	1.94	3.57	4.41
Print	Printers repeatability	1.67	3.22	4.06
Digital Input	Application used for printing	1.44	2.96	3.33
Print	MTS light	0.57	1.41	2.09
Print	MTS dark	0.34	0.59	0.79
Viewing	Surround	0.31	0.47	0.60

As predicted, the factor “light source” has the highest impact on print appearance. Note that in this work a common reflector projector has been used as an additional light source. Compared with the back light projector (the reference), the different light source technologies affect the appearance of print most, followed by the factor “surround” (ambient light on).

Different transparent substrates, different applications used for printing and medium temporal stability (under dark conditions) affect the appearance of print

TABLE II. List sorted by 95th percentile of ΔE^*_{94} distributions between reference state and alternative states of individual factors for prints on transparent substrate (double line indicates perceptibility threshold for complex images).

Categories	Factors	Mean	95th perc.	Max.
Illumination condition	Light source	10.26	24.80	26.17
Viewing	Surround	9.93	17.19	35.02
Printing system	Various printer	8.27	16.10	20.34
Digital Input	Application printing menu (Profile)	5.15	13.30	22.46
Digital Input	Printer driver setting	3.50	12.52	17.82
Digital Input	Printer setting (Calibration)	5.55	10.77	14.90
Illumination condition	Screen	5.49	8.79	10.61
Print	Printers repeatability	3.01	6.97	9.02
Viewing	Geometry	3.52	5.11	5.75
Print	MTS light	2.36	5.06	5.25
Illumination condition	Intensity	2.33	4.31	5.30
Digital Input	Application used for printing	1.98	3.98	5.89
Printing system	Substrate properties	2.04	3.26	3.36
Print	MTS dark	1.07	2.52	2.92

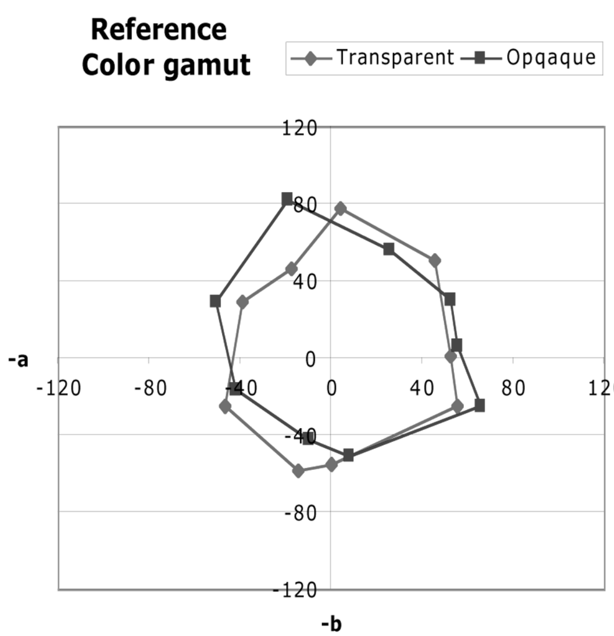

Figure 8. Color gamuts of reference states.

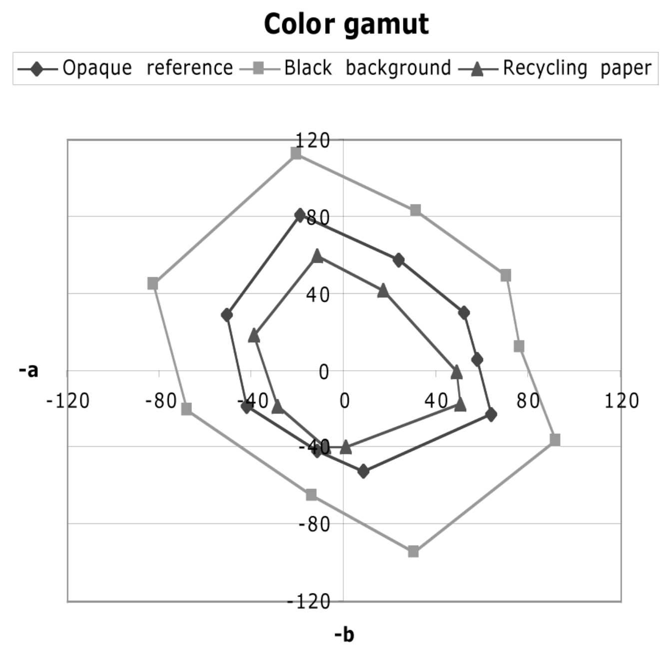

Figure 9. Comparison of smallest, largest and reference 2D color gamuts on opaque substrate.

insignificantly and are close to the perceptibility threshold in complex images. It is interesting to note that no factor has a color difference which is below the perceptibility threshold for single colors, i.e., changes in any of the factors will result in differences that can be seen for individual images. It should be emphasized, however, that the performance in terms of measurement uncertainty for the transparent condition is lower than for the opaque condition and that this uncertainty may have affected the results.

Effect on Color Gamut

The effect of changes to the factors can also be considered in terms of their impact on the color gamut and color gamut volume of resulting prints. A color gamut is the range of colors achievable on a color reproduction medium under a certain set of viewing condition and can be described using a gamut boundary descriptor. In this section the gamut of the reference condition and some alternative states will be described in the a*b* plane of CIELAB. A 2D version of the Segment Maxima gamut boundary descriptor will be used.[14] This is done by segmenting color space in terms of hue and storing the color with the greatest chroma for each segment. The colors stored for each segment they determine the gamut boundary. 2D color gamut boundaries and gamut volume were computed for those alternative states that gave perceptually significant differences from the reference for each substrate and those with the smallest and largest gamuts were compared with the reference.

2D Gamut Boundaries

The difference between the two color gamuts is rather small (Fig. 8); prints on opaque or transparent substrates have very similar gamuts for the printer used in this study.

Figure 9 compares the 2D color gamuts of the opaque reference state, the alternative "black background" state

TABLE III. Alternative States for Opaque Substrate Ordered by Relative Gamut Volumes

Factors	Alternative states	L* range	2D area	%
Background	Background black	67.96	22,282	2.24
Light source	Office light condition	81.79	9,675	1.17
Printer Driver setting	Printer Driver "Color Control"	67.88	10,414	1.05
Opaque reference		67.96	9,928	1.00
Printer setting	Mis-calibration (magenta)	67.99	9,824	0.99
Application printing menu	Individual ICC profile	67.55	7,149	0.72
Various printer	Printer system CII	64.53	7,405	0.71
Substrate properties	Recycled paper	47.92	5,561	0.40

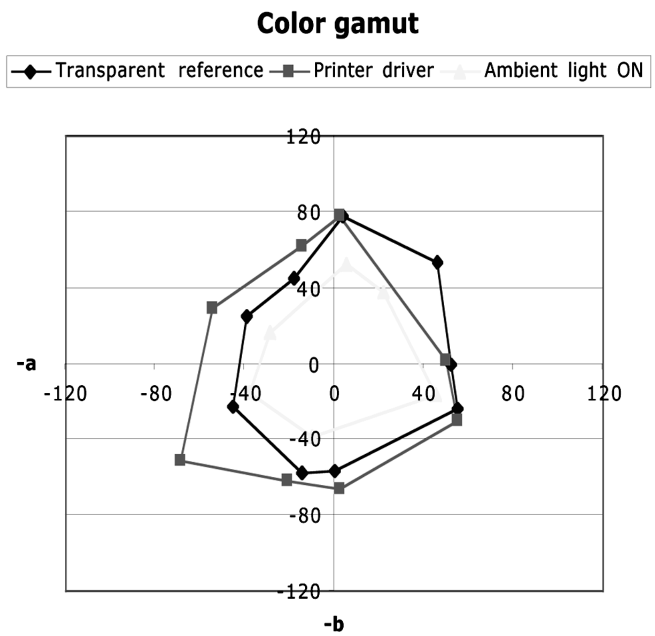

Figure 10. Comparison of smallest, largest and reference 2D color gamuts on transparent substrate.

and the alternative "recycling paper" state. Note that the color gamut of the "black background" state is twice as large as the gamut of the reference state due to the increase in chroma that results from viewing against black backgrounds.[15] Figure 9 also shows the reduction in the color gamut with the use of a low-grade substrate such as recycled paper.

A comparison of 2D color gamuts achievable on the transparent substrate is shown in Fig. 10, for the "printer driver" and "ambient light ON" alternative states. When the printer driver had the "Color Control" option enabled, the gamut of resulting prints expands as compared with the reference; the increase is due to internal color transformation before the data is sent to the printer. On the other hand the alternative state "ambient light ON" has reduced the color gamut as there ambient light interferes with the light projected through the transparent print and the result is lighter and less saturated.

Approximate Relative Gamut Volumes

Another way of looking at the impact of factors on print appearance is to compare approximate relative gamut volumes of the reference states and the alternative states. To obtain an approximation of color gamut volume, the 2D gamut area was multiplied by the lightness range of a given print. The lightness range is simply the difference between the lightness of the paper and the black color patch. Furthermore, dividing the approximate gamut volume of a given state by the gamut volume of the reference condition gives an approximate indication of gamut volume as a percentage of the reference gamut. Note that the aim here is not to compare the actual color gamuts under the various states but to have an approximate metric that can be used to make relative comparisons. While the relative color gamuts are approximations the 2D gamuts and lightness ranges are actual properties of the gamuts in question and similar judgments can be made about these properties and the approximate gamuts computed from them. Note also that the greatest weakness of this approximation is that it does not incorporate differences in the relative shapes of the color gamuts between the various states but assumes that this relative shape is maintained.

Ranking these approximate relative gamut volumes then shows how each condition affects the color gamut. Notice in Table III that the "black background" state has a gamut volume that is more than twice as large as that of the reference. Poor substrate quality, e.g., recycled paper, can, on the other hand, reduce gamut volume to less than half (40%).

Although the alternative state "Mis-calibration (magenta)" has a high impact on print appearance, the relative gamut volume is virtually equal to that of the reference state. This reinforces the fact that color differences say something more specific about individual colors whereas relative gamut volumes refer to their ranges.

Table IV illustrates the alternative states for the transparent substrate again ordered by relative gamut volume. Apart from the "printer driver setting" factor all other factors reduced gamut volume as compared with the reference state. The large reduction in lightness range due to the surround condition changing from the reference to "ambient light ON" is also noteworthy.

Discussion

The results shown in the previous sections indicate which factors have the greatest and least impact on print appearance. Figure 11 separately lists the factors ordered in terms of their impact on print appearance for each substrate. The category of each factor is indicated by its background: digital input (clear), printing system (20% gray), print (50% gray), viewing (70% gray pattern) and illumination condition (black).

As could be seen previously the "printing system" category with the factor "various printer" has the greatest effect on opaque print appearance. Further the factor

TABLE IV. Alternative States for Transparent Substrate Ordered by Relative Gamut Volumes

Factors	Alternative states	L* range	2D area	%
Printer driver setting	Printer driver "Color Control"	81.80	11,064	1.18
Transparent reference		83.25	9,256	1.00
Geometry	Geometry horizontal 60 degree	79.38	8,515	0.88
Printers repeatability	Printer repeatability 4. week	82.29	8,068	0.86
MTS day light condition	MTS day light condition 4. Week	81.28	8,143	0.86
Screen	Screen white board	75.63	8,540	0.84
Printer setting	Mis-calibration (magenta)	81.13	7,177	0.76
Application printing menu	Individual ICC profile	82.31	5,734	0.61
Various printer	Printing system CII	82.29	5,606	0.60
Surround	Surround ambient light ON	57.79	4,447	0.33
Light source	Reflection projector	65.23	3,540	0.30

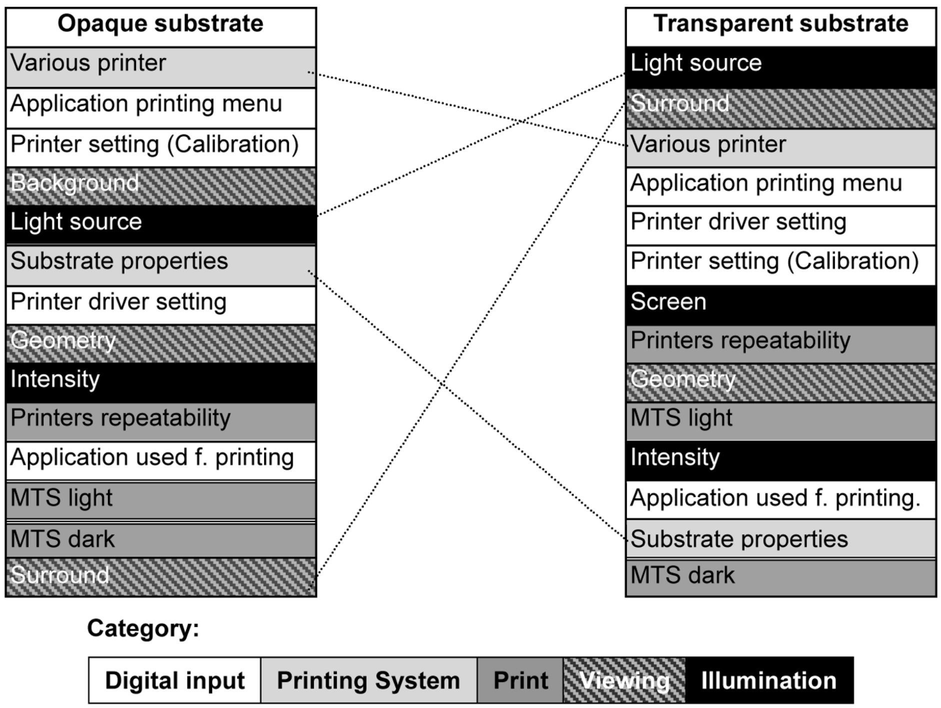

Figure 11. Correlation of factor order between substrates.

"substrate properties" has a larger impact in the opaque case than in the transparent case, where this factor has almost no effect. Regarding the "digital input" category the factors "application printing menu", e.g., applying ICC profiles, and "printer setting" (calibration) influence print appearance more in the opaque case whereas their effect on transparent print appearance is less marked.

It seems that the factor "application used for printing" has little effect on print appearance in either case. This is a positive result for those who are attempting to control printers from different software applications. Note that colors specified in the source application could give different results depending on the color interface between the source application and the PostScript driver. Furthermore the color space in which the digital input is specified could be another factor that might influence the appearance of the resulting print.

As mentioned previously the light source influenced print appearance most in the transparent case and it was found that the reflector projector with its different light sources and illumination geometry resulted in the largest color differences. On the other hand a back light projector (OHP) of the same type as the reference one resulted in color differences that were close to the perceptibility threshold for complex images.

Interestingly the "surround" factor caused differences that were below the perceptibility threshold for single colors for the opaque substrate. For the transparent substrate, however, the surround condition is a key factor which influences print appearance significantly. The geometry and light intensity on the other hand did not influence the appearance of print significantly on either substrate and the resulting color differences were close to the perceptibility threshold in complex images. Similarly medium temporal stability (MTS) under dark conditions caused differences below the perceptibility threshold in complex images for both substrates whereas MTS under day light conditions had a more significant effect for prints on the transparent substrate. However, had paper with different properties been used for the opaque reference such as recycled paper, which contains more wood cellulose, the result for the MTS under day light conditions may have been different.

During the experiment it was observed that most of the prints (opaque and transparent) also exhibited a banding effect in the color patches. Although the effect of banding has been uniform it was most visible in the cyan and gray color patches in most of the prints. Spatial uniformity is another important characteristic of a printed medium that can influence the appearance, however, this factor was not evaluated here.

Strengths and Limitations

Throughout the present study only one factor was changed at a time and the results indicate the extent to which factors and their alternative states affect print appearance. These findings can therefore be considered as a starting point for further research, where more than one factor at the time could be changed simultaneously.

The results obtained in this work could be useful for printer manufacturers in a number of areas. First, the findings could be used as a check list for technical support staff when trying to determine what factor caused an end user reported problem. Second, the list of factors ordered in terms of their potential impact on print appearance can be the basis for making recommendations to customers that could help avoid complaints. Third, the findings of this study can be used for training purposes. Fourth, printer quality control procedures could also be informed by the data presented here.

Many of the observations made throughout this study can also be considered as subjects for future research. First, further data analysis could be conducted to investigate the alternative states and their impact on memory colors and tone reproduction. Second, more research into alternative states, e.g., printer driver, data format and color space of the target, could also improve an understanding of how each setting contributes to print appearance. Third, a help desk solution, based on the decision support system idea from artificial intelligence, could be implemented on the basis of the findings from this study. Finally, extensions to other media, e.g., factors affecting the appearance of displays or digital projection, or models for predicting the appearance of print for various states of factors are also further areas for future research.

Summary

The aim of this study was to evaluate the magnitude of visual differences in prints caused by changes to various factors, with the final result being a list of factors ordered in terms of the size of their potential impact on print appearance.

Various factors, which could potentially influence the appearance of print, and their alternative states were defined. For each alternative state a new print or new color measurement was performed and compared with the reference state.

The results of the above method demonstrated that for prints on opaque substrates the factor "various printing system" had the greatest effect on print appearance, whereas the "surround" condition did not cause any change. On the other hand, the factor "light source" was shown to influence the appearance of prints on transparent substrates most significantly. It was also found that for some factors there is a correlation between the opaque and transparent cases. However, the effects of factors such as "surround", "light source" and "substrate properties" caused a large difference for prints on the two substrate types. Furthermore the color differences obtained in this study were compared with perceptibility thresholds both in complex images and for single colors. Finally, the study illustrated the impact of the various factors on the color gamut boundaries and volumes of prints.

The findings of the work described here offer a clear comparison of the relative impact that different factors can have on print. Therefore they can be used as a basis for developing more robust printing solutions in the future and for troubleshooting current printing systems.

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References

1. R. Rasmussen, Measuring Color Printer Image Quality, *Tutorial Notes*, *IS&T/SID 9th Color Imaging Conference*, IS&T, Springfield, VA, 2000, course SC4.
2. G. Marcu Factors Governing Print Quality in Color Prints, *Proc. IS&T's PICS Conference*, IS&T, Springfield, VA, 1998, pp. 221–225.
3. P. Green, *Understanding Digital Color*, 2nd ed., GATF Press, Pittsburgh, PA, 1999.
4. J. Morovic and P. L. Sun, *How Different are Colour Gamuts in Cross-Media Colour Reproduction?* Colour and Imaging Institute, University of Derby, UK, 2000.
5. Ch. Cui and S. Weed, Measurement Problems for Overhead Projection Transparency Printing Color Calibration, *Proc. IS&T/SID 9th Color Imaging Conference Proc.*, IS&T, Springfield, VA, 2000, pp. 303–309.
6. J. Uroz, J. Morovic and M. R. Luo, Perceptibility Thresholds of Colour Differences in Large Printed Images in *Colour Image Science: Exploiting Digital Media*, L. W. MacDonald and M. R. Luo, Eds., John Wiley and Sons, New York, 2002, pp. 49–73.
7. ISO (1999) *ISO 3664:1999 Viewing conditions - Prints, transparencies and substrates for graphic arts technology and photography.*
8. International Commission on Illumination, *Colorimetry*, 2nd ed., CIE Publication 15.2, CIE, Vienna, Austria, 1986.
9. R. S. Hunter and R. W. Harold, *The Measurement of Appearance,* 2nd ed., John Wiley and Sons, Inc., New York, 1987.
10. International Commission on Illumination, *Industrial Colour–Difference Evaluation*, CIE, Vienna, Austria, 1995, p. 116.
11. M. R. Luo and R. W. G. Hunt, The Structure of the CIE 1997 Color Appearance Model (CIECAM97s), *Color Res. Appl.* **23,** 138–146 (1998).
12. R. S. Berns, *Principles of Color Technology*, 3rd ed., John Wiley and Sons, Inc., New York, 2000.
13. M. Stokes, M. D. Fairchild and R. S. Berns, Colorimetrically Quantified Visual Tolerances for Pictorial Images, *Proc. TAGA* **2,** 757–777 (1992).
14. J. Morovic and M. R. Luo, Calculating Medium and Image Gamut Boundaries for Gamut Mapping, *Color Res. Appl.* **25,** 394-401 (2000).
15. L. W. MacDonald, M. R. Luo and S. A. R. Scrivener, Factors Affecting the Appearance of Coloured Images on a Video Display Monitor, *J. Photogr. Sci.* **38,** 177–186 (1990).