Factors Affecting The Appearance Of Print On Opaque Substrates

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Keywords: Appearance, Color Measurement, Print, Substrate, Printer

Abstract: This paper aims to consider factors affecting the appearance of print on opaque substrates. In particular it looks at factors from 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. 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 in 'plain paper', 'glossy paper' or 'newsprint' states). 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 versus an alternative way. The results for factors are then viewed both individually and by grouping all factors of a given category together. Finally the results show how big a change 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.

Introduction

At the highest level digital printing can be seen a 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 very dynamic. As various factors are involved in a printing process as well as in the viewing of the resulting print, there is great potential for variation.

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A typical practical scenario is having a given digital image printed in two different locations. If the printing was 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 as well as industrial environments and the need for quantifying the contributing factors is very high.

Before trying to come up with 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 is then viewed in a certain environment under a certain light source and results in a certain appearance for a viewer. Changes to any parameters, settings or properties of any of the elements involved in the above workflow then have a potential to alter the appearance corresponding to a given digital input.

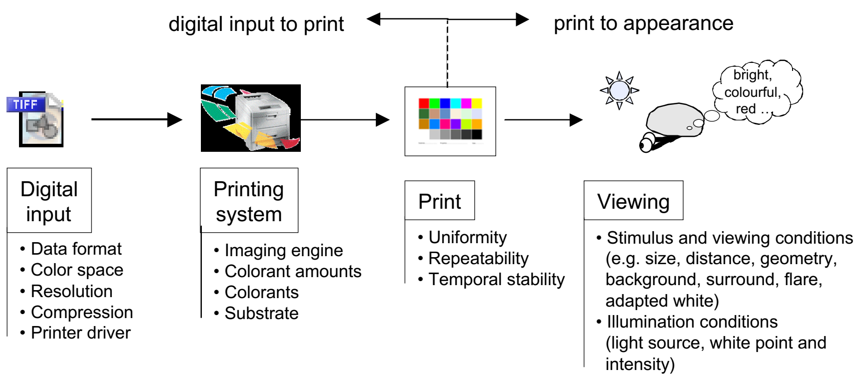

Figure 1. From digital input to appearance.

The different types of factors can therefore be categorized in two areas where the first one determines the print resulting for a given digital input and the second determines the color appearance of a given print (Figure 1). Some of these factors might not have the same potential as others in terms of influencing a print's appearance. For example, can viewing geometry cause greater differences than print resolution?

The aim of the present work is therefore to develop a list of factors ordered in terms of the magnitude of their potential impact on print appearance for opaque substrates. The final result will be a list of factors ordered in such a way and it could be used as a checklist for those involved in the making and servicing of printing systems.

Before discussing how the above aim is going to be achieved, it is worth noting that even though various studies have been done on individual topics pertinent to the present paper (e.g., Rasmussen, 2000; Marcu, 1998;

Green, 1999; Morovic and Sun, 2000; Cui and Weed, 2000), no work was found that investigates the relative magnitudes of visual differences corresponding to changes in factors affecting print.

The next section of this paper 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. Note that more detail on the present work as well as its extension to transparent substrates can be found in Morovic and Nussbaum (2003).

Experimental method

The method used here relies on identifying a range of factors that have the potential to affect the appearance of prints corresponding to a given RGB input. These factors can have alternative states (e.g. the light source factor can be in 'A', 'D65' or 'office lighting' states).

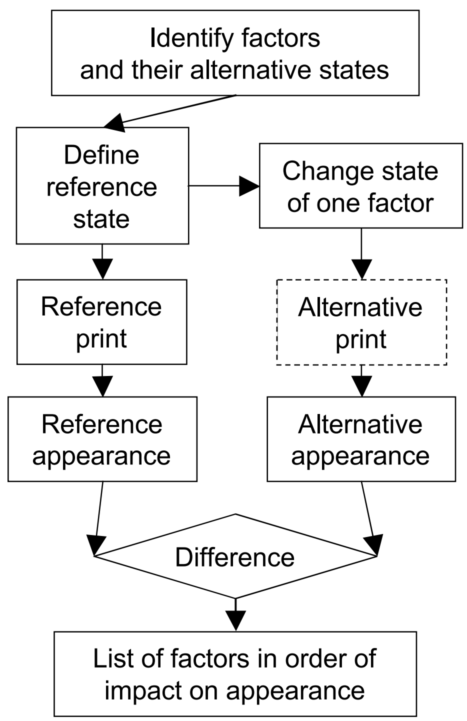

Figure 2. Overview of method.

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 way (Figure 2). This section will therefore provide details of the various aspects of the method used here.

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 contains a gray scale which will show how tone rendering is affected by various factors. The size of color patches in the chart (Figure 3) was chosen so as to be measurable under the various viewing geometries studied here.

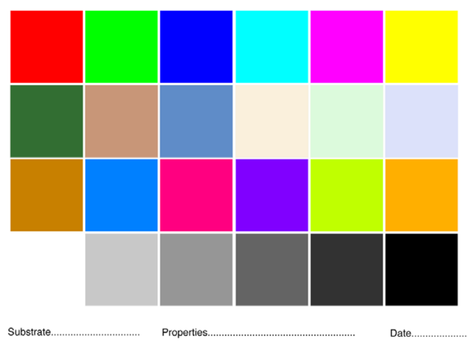

Figure 3. Digital RGB test image with 24 color patches in RGB color space (Patch size is 4.5 x 4.5 cm).

Reference condition

Given the digital test chart, a reference condition was determined under which the test chart was printed, viewed and measured. 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 substrate used for the reference print was commercial one, recommended by Oki Europe, who supported this study in terms of useful comments and technological support. The viewing set up for reference is based on the standard condition of the graphic art industry (ISO, 1999), vertical geometry 45°, background gray, light source D50 simulator, light intensity 100% (Figure 4).

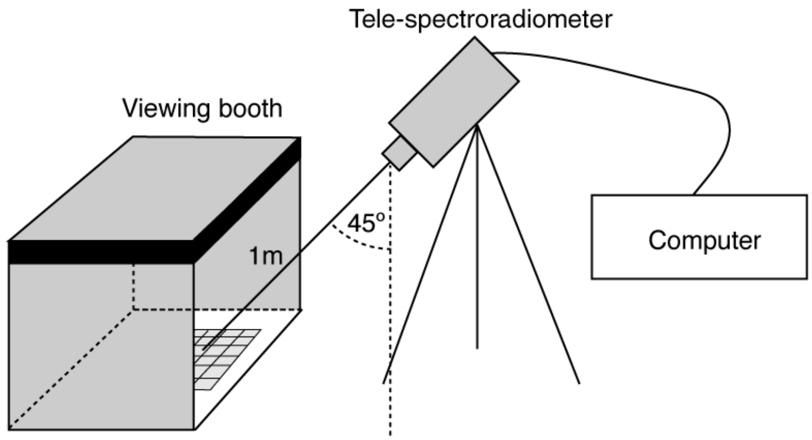

Figure 4. Measuring set-up for opaque substrate.

It is worth pointing out that the chosen reference condition is not meant to represent the best or ideal situation but instead to be a state to which to compare the variations obtained by changing the various factors. The measurement results obtained from the reference condition was then 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 (Mackle, 2002) and therefore also represents options relevant to industry. Next a description will be given of the various factors considered here.

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", followed by the setting "Image Color Matching: PostScript CRD Color Matching". 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 last chosen setting was "ICM Method: ICM Handled by Host System" was applied before PCL was used as an alternative driver setting.

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 pro files were then applied as alternative: 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 setting were distributed together with the digital test chart.

Substrate. Various substrates commonly used in the office marked were printed on. Apart from common office copier paper ("out of the tray"), coated, uncoated and recycled papers were selected.

Print

Printer repeatability. To quantify the effect of the printer's repeatability, the digital test chart was printed on 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. First prints were measured at an angle of 60° and then 30°.

Horizontal geometry. For prints on the opaque substrate one alternative state at 45° was used in terms of horizontal geometry in addition to the 0° reference.

Background. The background in the viewing cabinet where the reference print was viewed was also changed for the prints on the opaque substrate. As alternative states white and black backgrounds were used when measuring the print.

Surround. For the surround factor one alternative state, with the ambient light on was used for measuring the print.

Illumination

Light source. Six alternative states of light sources were evaluated for the opaque substrate: Cool White Fluorescent (CWF) at 4200K, Standard illuminant A at 2800K, actual office lighting, actual day light at the following times: 8 am (cloudy), noon (cloudy) and 4 pm (cloudy/sunny).

Intensity. The intensity of the light source was reduced to three alternative levels 25%, 50% and 75% respectively. The intensity was reduced by fine screen layers placed in front of the light source (black and white film material with 25%, 50% and 75% opacity).

Color measurement

As mentioned previously a telespectroradiometer (Minolta CS-1000) was used for measuring 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°) (CIE, 1986) was used for computing CIE XYZ values. As the measurement method involved a variable measuring geometry, its repeatability was evaluated closely. Overall the results showed that there was an average repeatability error of 0.05 ΔE^*_{ab} with a 95th percentile of 0.11 and a maximum of 0.14 ΔE^*_{ab} units. Hence the repeatability of the instrument can be considered to be very high.

More critical than the testing of the instrument was an evaluation of the repeatability of setting up the measurement and illumination geometry. Here the mean repeatability error for prints on the opaque substrate was 0.4 with a 95th percentile of 0.83 and a maximum of 0.89 ΔE^*_{ab} units, which can again be considered to be a very good degree of repeatability.

Data analysis

After collecting all the color measurements of prints made on opaque 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) and ΔE^*_{94} values (CIE, 1995) are computed between reference and alternative state patches. The arithmetic mean, 95th percentile and maximum of the resulting color difference distributions are the computed. The reason why the 95th percentile is used is that it was found in earlier studies that high percentile values correlate better with the perceptibility threshold than mean color differences (Uroz *et al.*, 2002).

In this work the perceptibility thresholds for complex images obtained in psychophysical experiments by Uroz *et al.* (2002) are going to be used. Uroz *et al.* conclude in their findings that in 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.

As the present paper 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 (Luo and Hunt, 1998). Here CIECAM97s Jab color appearance predictors were first computed from XYZs 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 the average surround option (for stimuli of less than 4° angular subtense) was used.

Results

As has been said above 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. First, however, it is useful to look at the ordering of factor categories, which can be seen in Figure 5. There it can be seen that the "printing system" category has the largest impact on print appearance. On the other hand the "print" category can causes a small color difference.

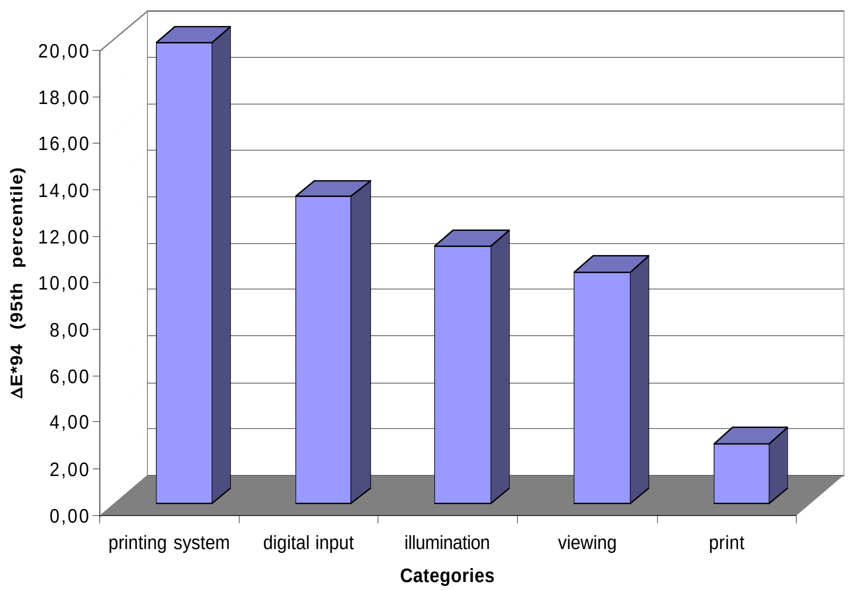

Figure 5. Categories and magnitudes of their potential impact on print appearance.

Next, Figure 6 shows the impact of individual factors on print appearance.

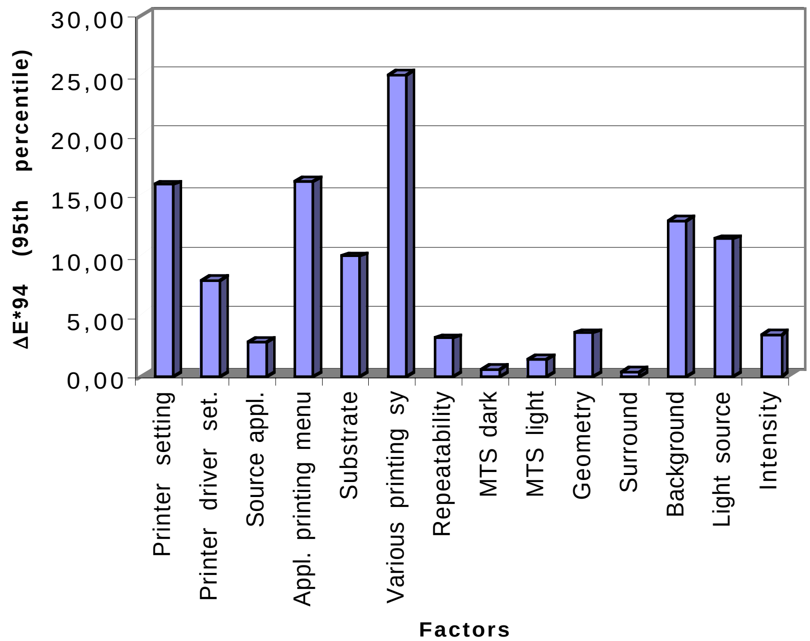

Figure 6. Impact of individual factors on print appearance.

Ranking list of factors

Table 1 shows the ranking of factors listed according to the 95th percentile of ΔE^*_{94} distributions and the table also shows the category of each factor listed in it. 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 "printer" and "substrate") and "digital input" (with the factors "profile" and "calibration") determine the appearance of print most strongly, whereby the factor "printer" is ranked highest in this study.

Categories	Factors	Mean	95th perc.	Max.
Printing system	printer	10.77	25.12	27.47
Digital Input	profile	5.54	16.20	24.65
Digital Input	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	3.90	9.98	24.59
Digital Input	driver	2.42	8.00	27.52
Viewing	geometry	1.69	3.62	5.70
Illumination condition	intensity	1.94	3.57	4.41
Print	repeatability	1.67	3.22	4.06
Digital Input	source app.	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

Table 1. List sorted by 95^{th} percentile of ΔE^*_{94} distributions between reference state and alternative states of individual factors for prints (double line indicates perceptibility threshold for complex images and triple line for single colors).

Below the perceptibility threshold in complex images, factors such as "medium temporal stability" (dark condition and day light condition) and "surround" will not influence the appearance of print due to the small color differences changes in them can cause. "Medium temporal stability" (dark condition) and "surround" condition are even below the perceptibility threshold for single colors.

Further it can be noted in Table 1 that there is a noticeable gap in terms of color differences between the factor "driver" (ΔE^*_{94}=8.00) and the factor "geometry" (ΔE^*_{94}=3.62). Although these factors (geometry, intensity, repeatability and source application) are above the perceptibility threshold the impact on print appearance due to their changes can be considered moderate. It needs to be kept in mind that the results of all the experimental work in this study have an element of uncertainty caused by the inaccuracy of the measurement set-up's repeatability.

Effect on color gamut

The effect of changes to factors can also be considered in terms of its impact on the color gamut and color gamut volume of resulting prints. A color gamut is a 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 and a 2D version of the Segment Maxima gamut boundary descriptor (Morovic and Luo, 2000) will be used. 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 the determine the gamut boundary. 2D color gamut boundaries were computed for those alternative states that gave perceptually significant differences from the reference and those with the smallest and largest gamuts were compared with the reference.

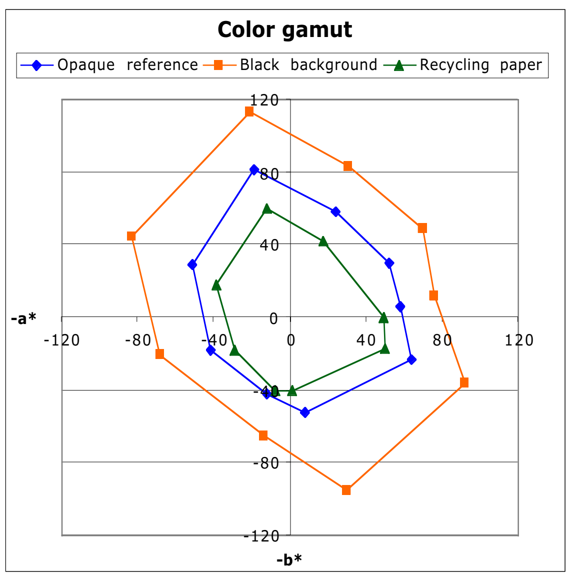

Figure 7. Comparison of smallest, largest and reference 2D color gamuts on opaque substrate.

Figure 7 shows the 2D color gamuts of the reference state, the alternative "black background" state and the alternative "recycling paper" state. It can be seen that the color gamut of the "black background" state is twice as big as the gamut of the reference state due the increase in chroma that results from viewing against black backgrounds (MacDonald *et al.*, 1990).

Also shown is the reduction of the color gamut when using a low-grade substrate such as recycled paper.

Discussion

The results shown in the previous sections indicate which factor has the most and least impact on print appearance. .

As could be seen previously the "printing system" category with the factor "printer" has the most affect on opaque print appearance. Further the factor "substrate" has almost no effect. Regarding digital input the factors "application printing menu" (e.g. applying ICC profiles) and "printer setting" (calibration) influence print appearance more whereas "printer driver setting PPD" (e.g. Color Control) their effect on print appearance is not so significant.

It seems that the factor "application used for printing" (source app.) does not affect print appearance much and this is good news when attempting to control printers from various pieces of software. However, this might be so as the test chart used in this study was created in Adobe Photoshop and stored as a TIFF image that was then imported into and printed from other software. Maybe colors specified in the source application itself 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.

It is further of interest to note that the "surround" factor only caused differences that were below the perceptibility threshold for single colors. Moreover the geometry and light intensity did not influence the appearance of print significantly and resulting color differences were close to the perceptibility threshold in complex images. Similarly medium temporal stability (MTS) under dark and day light conditions caused differences below the perceptibility threshold in complex images. However, if paper with different properties had been used for the opaque reference, such as recycled paper which contains more wood cellulose, the result for the MTS under day light conditions could have been different.

During the experiment it has been observed that most of the prints have 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.

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.

After an introduction to the subject of this study a literature survey was given to illustrate existing work on this topic. Then an experimental overview, defining a digital test chart and reference condition, was given. Various factors, which were thought to potentially influence the appearance of print, and their alternative states were next defined. For each alternative state a new print or new color measurement was performed and compared to the reference state.

The results of the above method demonstrated that the factor "printing system" had the greatest effect on print appearance, whereas the "surround" condition did not cause any change. Furthermore the color differences obtained in this study were compared to 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.

As such the findings of the work described here offer a clear comparison of the relative impact that different factors can have on print and as such they can give an empirical basis for developing more robust printing solutions in the future and for trouble-shooting current printing systems.

Acknowledgements

The authors would like to thank Prof. Ronnier Luo for his generous help and Oki Europe for supporting this study in terms of helpful comments and technological support. We would particularly like to thank Philip Mackle of Oki (UK) Ltd for his constructive advice and interest in this study and Vidar Øierås of Oki Norway for his time spent printing all the test charts.

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Appendix-A

Overview of the reference condition (gray column) for prints on the opaque substrate and the various states chosen for each of the investigated factors. In addition to the reference state, the chosen variables re quired 26 new prints and a total of 46 sets of 24 measurements.

Opaque substrate	Rey Success 100g	Alternative	Alternative	Alternative	Alternative	Alternative	Alternative	new	new
Factors	Reference setting	state	state	state	state	state	state	print	measurement
Digital input									
Printer setting	Default	Visual calibration	mis-calibr. 1 extr. magenta	mis-calibr. 2 extr. blue				3	3
Printer driver setting PPD	Default	Color Control	Image color matching	Black Finish	ICM Method	PCL		5	5
Application used for printing	Adobe Acrobat	Adobe Photoshop	MS PowerPoint	MS Word	MS Excel			4	4
Application printing menu	Default Acrobat	Individual ICC	Standard OKI ICC	Newspaper ICC				3	3
Printing system									
Various printing system	C7400 Oki Norway	C7400 Oki Scottland	C7400 Oki CII					2	2
Substrate properties	Oki recommendation	"Munken" "out of the tray"	Silk 250g	Carton 250g	Recycling	Business card		5	5
Print									
Printers repeatability	1. Week	2. Week	3. Week	4. Week				3	3
Mediums temporal stability in dark condition	1. Week	2. Week	3. Week	4. Week					3
Mediums temporal stability in day light condition	1. Week	2. Week	3. Week	4. Week				1	3
Viewing									
Geometry vertical	45°	60°	30°						2
Geometry horizontal	0°	45°							1
Background	grey	white	black						2
Surround	Ambient light off	Ambient light on							1
Illumination conditions									
Light source	Day 5000K	CWF 4150K	A 2856K	normal office light condition	real daylight morning	real daylight noon	real daylight afternoon		6
Intensity	100 %	75 %	50 %	25 %					3
	reference=one print +one measurement						Total	26	46