The Effect of Paper Properties on Print Quality

M. Péralba[1, 2], M. Dubé[2], L. Cormier[3], P. Mangin[2]

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Abstract: We study the impact of paper surface on ink jet print quality. We first visually rank an ensemble of complex images and explain this ranking in terms of the print attributes (color rendering, mottle and edge raggedness) of the different papers. In particular, we find that heavy print mottle is more damaging to quality than poor color rendering. We then consider in more details these attributes and relate them to the specific chemical and physical properties of paper (permeability, roughness, formation and sizing). We show that permeability has the largest influence on both color rendering and print mottle, followed by paper roughness. Sizing and paper formation have however only limited effects.

Introduction

Ink-jet printing is now a popular process and is continuously spreading due in large part to its link with the flourishing development of computer technology. Ink-jet printing is now present, not only on desktop, but also in the printing plant. The technology has become faster and more efficient, giving the possibility to personalize each print and to decrease the number of stage between the conception of a print and the printing itself. Ink-jet is however a non contact printing process, with a different technology than more traditional processses such as offset printing, and an understanding of this new technology requires different parameters (Buczynski, 1999), together with different ink formulations. Many papers have explored ink-jet print quality, in particular with relation to coating structure (Chapman, 1997) and surface chemistry (Svanholm, 2004). However, there are many uncoated (but generally highly filled) papers used in ink-jet printing, and the relationship between the properties of these papers and ink-jet print quality is still poorly understood.

[1] École Française de Papèterie et des Industries Graphiques, BP 65, 38402 Saint-Martin-d'Hères Cedex, France.
[2] Centre Intégré en Pâtes et Papiers, Université du Québec à Trois-Rivières, 3351 Boul. Des Forges, Trois-Rivières, Québec Canada G9A 5H7.
[3] Paprican, 570 boul St-Jean, Pointe-Claire, Québec, Canada H3R 3J9

Moreover, the very notion of print quality is becoming more and more important in the print room, since it is linked to the customer expectations. It is not obvious that print quality can be properly defined in terms of “good” or “bad”, but the development of a metric of print quality would help to achieve this goal. This is of course a difficult task since print quality includes both objective concepts such as darkness of shades, print gloss, brightness of colors, sharpness of edges, etc, and a subjective part due to the human eye. For instance, the human eye detects more easily a non uniform aspect of the print than a steady default (Kajanto, 1990). Through a literature search, we have found that the dimension space of print quality could be decomposed as five dimensions related to the image itself (color, uniformity, rendering, interface and frequency) and two to the printing process (defect, operation) (Mangin, 2006). In this respect, it is interesting to study ink-jet print quality since it can minimize the loss of quality due to the printing process itself. This article is the thus the beginning of a study on print quality, its main aspects, its human perception, and its quantification, focusing for now on the effects of paper properties on ink-jet print quality.

We studied the principal paper physical and chemical properties that are supposed to influence ink-jet print quality. Particularly, we studied roughness at the scale of the drop size together with sizing, permeability and gloss. Print quality was assessed by visual ranking of a set of images and we show that color rendition and print mottle are the main properties that can differentiate the prints. We then show that color rendition is mostly related to the permeability of paper while print mottle can be related to the roughness of the paper, although there are no clear causes for this particular print attribute. The outline of this paper is as follows: we first describe the material (printer, paper) used in this study, as well as the measured paper properties. We then describe the print quality study, beginning with the objective evaluation of the principal print attributes, followed by the overall image ranking of the prints. We then discuss separately the influence of color rendition and print mottle on the print, together with the paper properties that influences them.

Print and scanning devices

The images were printed with a high (proofing) quality Epson ink jet printer (Epson Stylus Pro 4800), which uses a pigmented ink with finest drops of 3,5 pL of volume (i.e. about 10 μm of diameter) and high resolution (720 dpi). After printing, the images were acquired with an Epson scanner (Epson expression 10000XL), with high resolution (up to 12800 dpi), and high depth of colors (48 bits). All images were printed under the setting “plain paper” and all image enhancement features were deactivated for the scans.

Papers: physical and chemical properties

The study used 7 commercial office papers from different suppliers, with common basis weight of 90 g/m^2 and TAPPI brightness ranging between 90 and 94. The papers were either coated (medium or lightweight coated) or simply filled (mostly with calcium carbonate). Both sides of the papers were similar, but we always consistently chose the same paper side. Paper 1 and the paper 2 are the same paper (same supplier) but with different levels of calendaring, and likewise for paper 3 and paper 4. The measured physical properties are roughness, air permeability and gloss. The chemical properties of the surface were assessed by measuring the degree of resistance of the paper surface to water penetration. In addition, the overall formation of paper was measured.

Roughness

Paper roughness obviously affects a contact printing process such as offset (Chapman, 1997), but it can also affect ink-jet printing. A typical ink-jet drop has a radius of a few microns, which is of the same order as the paper roughness. This will obviously affect gloss (Xu, 2005), together with the spreading and absorption of ink, and will thus have an effect on print quality. It is however important to discuss the scale at which roughness is measured. Roughness can be divided in micro and macro scale (Yang, 2003). The limit is still at the center of discussions, but macroroughness can be defined as the roughness of at the scale of the fiber length and microroughness as the roughness at the scale of fiber width and fines. Two different types of measuring devices are used:

i) Macroroughness is measured with the Parker Print Surf instrument It measures the air flow through the surface under constant pressure, on a scale of about 100 μm.

ii) Microroughness. We measured the roughness at small scales with a Wyco NT 1100 optical interferometer. Surface profiles were measured at resolution of $\Delta x = 1.67\ \mu$m over a surface of 1.0 mm^2. A convenient measure of roughness is the standard deviation *Rq(l)* over a given scale *l*, defined as

$$Rq(l) = \frac{1}{l^2} \sum_{x,y<l} (h(x,y) - \bar{h})^2 \qquad (1)$$

where *h(x,y)* is the surface profile at position *x,y* and $\bar{h}$ is the average value of the surface profile. The scale *l* ranges from the spatial resolution Δx to the total length of the scan.

Gloss

Closely related to roughness is gloss, caused by light reflection and diffusion from the paper surface. Gloss was measured with a Technidyne glossmeter at an angle of 75 º.

Sizing

Sizing refers to the process wherein chemical additives are introduced into the bulk of the paper (internal sizing), or directly coated on paper (external sizing) in order to make it more water-repellent. Sizing has a large influence on ink absorption and hence on print quality. Paper sizing was measured with a Mutek EST instrument. This device works with ultrasound sent through the paper. Since ultrasound transparency of the paper changes with liquid content, it can easily measure water penetration. Sizing is then defined as the time needed for paper to begin to absorb water, as shown in table 1.

Permeability

Permeability is the capacity of a paper to let air or fluid flow though it. Permeability is closely related to porosity (the ratio of pore volumes to the overall volume) but there are no straightforward relationships between the two since an average capillary radius must also be considered. For the present study, permeability is measured as the volume of air that flow though the paper under a given time at constant pressure.

Formation

The term formation refers to the overall density of paper. Typically, a paper sheet is not uniform but presents random variations in density. It is known that formation will greatly influence print quality for an offset of flexographic processes. Paper formation was measured with an optical scanner (Kaptra vision 9000+) and the metric of formation corresponded to the standard deviation in the intensity of light received by the scanner.

Table 1 summarizes the properties of the paper, which we now discuss in more details. Figure 1 shows this behavior for the papers considered. At small values of l, Rq(l) has a small value but increases steadily with until *l* it reaches a value ξ_l, the correlation length. After this length, *Rq (l)* saturates to a constant value, well correlated with the macroroughness measured with the Parker Print Surf.

Paper	Paper 1	Paper 2	Paper 3	Paper 4	Paper 5	Paper 6	Paper 7
Ash content	Coated (30 %)	Coated (33 %)	LWC (23 %)	LWC (25 %)	Filled (10%)	LWC (20 %)	LWC (17 %)
Calendering	Low	High	Low	High	High	Mid	Mid
Gloss	5	31	5	10	11	8	7
Roughness PPS (µm)	5	2	7	4	3	4	5
Roughness Profilometer (µm)	4	3	6	4	4	5	5
Permeability (ml/min)	38	7	835	499	272	867	728
Water penetration time (s)	2	0,9	0,3	0,3	1,1	0,7	1,3
Formation	41	46	49	56	39	46	59

Table 1: Physical and chemical characteristics of the papers. Gloss and permeability and sizing measurements are accurate to 1%, roughness measurements to 0.2 µm while permeability and formation measurements are accurate to 5%.

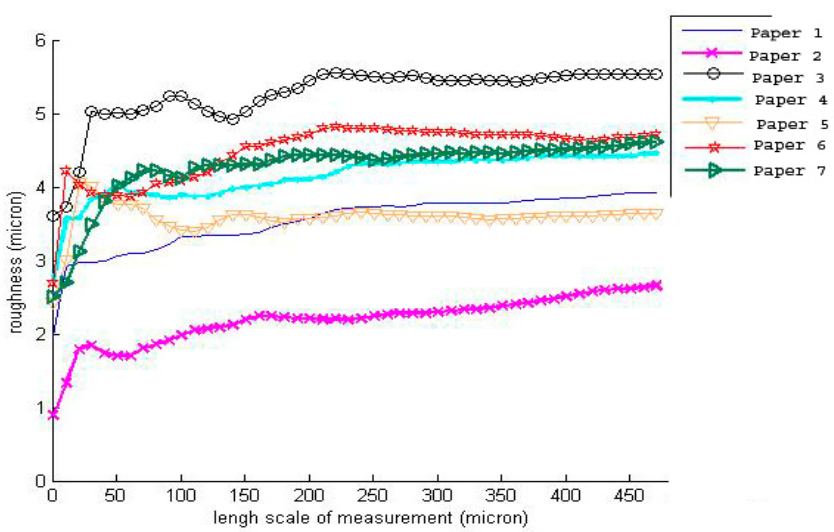


Figure 1 : Surface roughness of the papers measured at different scales with an optical interferometer

Images, print attributes and overall ranking

The images consisted of the set of 8 images developed for preprint (ISO-12640-1), shown in Appendix 1. This is a small set to study print quality, but the diversity of the images allows us to observe the influence of the various print attributes. In addition to the overall ranking of the images, we measured in details three print attributes, i.e., color rendition, print mottle and edge raggedness. Table 2 summarizes the results.

	Color rendering (ΔE*)			Edge raggedness	Mottle	
	Cyan	Magenta	Yellow		Index1	Index2
Paper 1	20,5	19,5	19,6	10,6	9,4	30
Paper 2	18,9	12,5	17,5	4,6	9,3	230
Paper 3	21,7	17,9	22,6	1,7	5,6	2
Paper 4	23,3	21,1	26,4	2,5	7,6	3
Paper 5	21,9	16,2	22,6	1,9	5,6	2
Paper 6	23,6	20,6	24,6	1,8	5,7	2
Paper 7	22,1	20,4	24,9	2,2	7,1	3

Table 2: Evaluation of the principal print attributes for the set of papers. All measurements are accurate to 1%.

Color rendering

Color rendering was assessed by a measure of the *L*a*b* coordinates of solid prints in cyan, magenta and yellow on each paper. To eliminate the difference of color due to the printing device, we used an Epson photo quality paper, printed under the appropriate setting, as reference. Color rendering is then defined as the ΔE*-value between the photo quality paper and the papers of the study. For simplicity we concentrate on 100% solid coverage. The ranking of the papers, shown in Table 2, is similar at all coverage and for the 3 primary color. From these measures, paper 2 comes out as having the best rendering, papers 1, 3 and 5 are ranked as averages and papers 4, 6 and 7 have the poorest color rendering.

Edge raggedness

Edge raggedness describes the linearity of the limit between inked and non inked areas. Solid black squares were printed on each paper and scanned with a high resolution (3200 dpi). A Matlab® program was used to determine a grey level histogram, from which a threshold level was chosen. The raggedness of the threshold was then assessed by calculating the standard deviation (roughness) of this threshold line with respect to an ideal limit of a straight line. It should be noted that edge smoothness was not considered in itself, since it participates to edge raggedness. Table 2 shows the ranking of the papers with respect to this print attribute. Papers 3, 5 and 6 have the best linearity while paper 10 has the worst line quality.

Mottle

Print mottle is a common defect, intuitively defined as graininess in print solids. The solid print is composed of several zones of lighter or darker areas around a certain mean, and the sizes as well as orientation of these zones are stochastic. The causes of mottling are various; it may arise from uneven ink transfer or penetration, which is in turn influenced by the formation and transverse (z-directional) structure of the underlying base stock and/or coating color. Solid black squares of 8 cm by 8 cm were printed on each paper at a resolution of 720 dpi and subsequently scanned at 1200 dpi. We define the print as the grey level $I(x,y)$ at pixel position x,y. Mottle was quantified using two methods.

i) Index 1: The simplest method is to calculate the standard deviation in grey levels obtained from the scanned images, ie.,

$$Rq = \frac{1}{L^2}\sum_{x,y}(I(x,y)-\bar{I})^2 \qquad (2)$$

where L is the size of the image and $\bar{I}$ is the average value of grey levels. The ranking of the papers according to this method are shown in Table 2. Papers 1 and 2 have the strongest mottle, while papers 3, 5 and 6 have the most uniform prints.

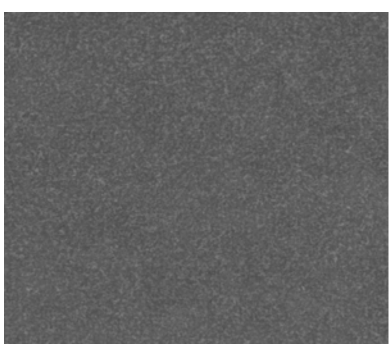
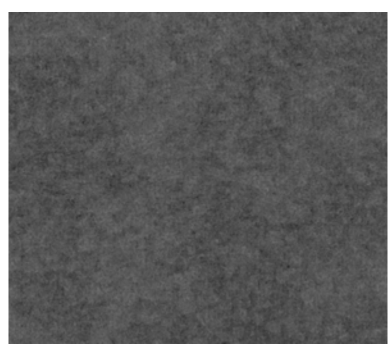
Paper 1	**Paper 2**
	

Figure 2: Scanned images of solid prints on paper 1 and paper 2 showing mottling.

ii) Index 2: It is however well known that simply calculating grey level variations is not sufficient since it does not take into account the spatial arrangements of these variations. In typical situations, the human visual system is most sensitive to variations at certain scales and certain contrasts. Noise with extremely rapid scale fluctuations is not perceived while smooth transitions are not disturbing. It is possible to evaluate mottle taking into account those aspects of human visual system (Béland (2000), Cormier (2005)). The classification using the Paprican Mottle Index is shown in Table 2, high numbers corresponding to more mottled prints. With the visual perception taken into account, differences between papers 3, 5, 6, and between paper 4 and 7, are too small to be noticeable. Contrary to the ranking with standard deviation of grey level, paper 2 is now classified as being worst than the paper 1. This is due to the spatial dispositions of the print variations. Figure 2 shows that the "patches" on paper 2 are more apparent than those of paper 1.

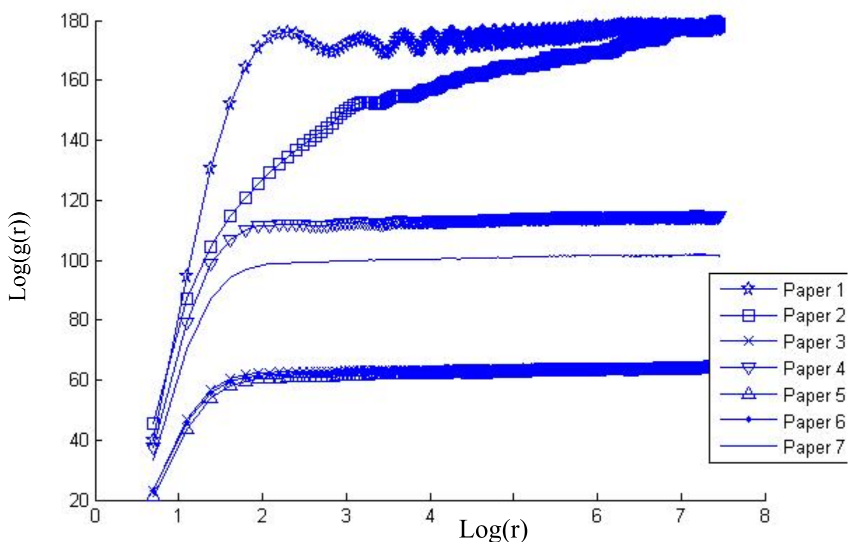


Figure 3: Correlation function of printed papers. The distance *r* is expressed in pixels.

The spatial correlations between the variations in print density *I(x',y')* at position *(x',y')* and the print density *I(x+x'y+,y')* at position *(x+x'y+,y')* may be measured through the correlation function:

$$g(x,y)=\sum_{x',y'}\left(I(x'+x,y'+y)-I(x',y')\right)^2 \quad (3)$$

where the summation is over all pixels separated by a distance *(x,y)* and normalized accordingly. This function is of course closely related to the scale-dependent roughness given by Eq. (1). Figure 3 shows the angular average of the correlation function for the printed papers. It clearly shows that the correlations of paper 2 extend to a larger distance than all other papers, which explain the ranking of Table 2. Since all papers, except paper 2, have similar correlations functions, we can suppose that the mottle mechanism on paper 2 is different than for the other papers. We shall come back to this point below.

Overall evaluation of the print

The overall evaluation of the 8 ISO images was performed by a jury composed of 10 persons from different countries, and of different ages and sex. Images were printed images on the 7 papers of the study and also on Epson quality photo. Four images were printed twice on paper 7 (paper 7 and paper 7') in order to test the judge's classification. Each judge was presented each image on the different papers and the print was ranked with the merge and sort method. Table 3 and Appendix 2 show the classification of the papers for the 8 images from better to worst, with in bracket the average rank of the image.

Fruits	Young girl	Cafeteria
Photo paper (1)	Photo paper (1,2)	Photo paper (1,9)
Paper 5 (2,25)	Paper 5 (2,5)	Paper 3 (2,5)
Paper 3 (3,3)	Paper 3 (3)	Paper 5 (2,5)
Paper 7 (4,75)	Paper 7 (4,1)	Paper 6 (4,6)
Paper 7' (5)	Paper 6 (5,2)	Paper 4 (4,9)
Paper 6 (5,4)	Paper 4 (5,6)	Paper 7 (5,7)
Paper 4 (6,4)	Paper 2 (7,1)	Paper 2 (7)
Paper 1 (8,4)	Paper 1 (7,6)	Paper 1 (7,4)
Paper 2 (8,6)		

Table 3: Classification by judges of print quality of papers for each studied image

The results show essentially three groups within the papers. Papers 3 and 5 consistently come on top of the ranking, papers 1 and 2 at the bottom and papers 4, 6 and 7 are ranked as average. To understand these results, we focus on the images of the fruits, young girl and cafeteria.

The first image, the fruit can discriminate the papers in terms of sharpness and color rendering, but also in terms of mottle, since there are large portions of solid prints. Table 3 shows that the papers with more mottle (Paper 1, Paper 2) are poorly ranked. Despite the fact that paper 2 has very good color rendition, it is ranked below paper 1. This indicates that the visual perception of print mottle is extremely important. The other papers are classified according to their color rendition. Thus, an image with bright color and important mottle will be judged worst than an image with lower color rendition but better print uniformity.

The young girl image is supposed to give a good idea of light color rendering thanks to the face. Table 3 shows that paper 1 is considered as the worst paper in this particular case. In fact, the judges did not like the rendering because of a blurred impression, in particular in the young girl's eye. The glance is important for a face, and paper 1 present the worst edge raggedness, and hence the blurry impression in fine details. Paper 2 also has large edge raggedness and is also poorly ranked, again despite its good color rendering. As for the fruit image, the others papers are classified in order of color rendering.

Finally, we examined the cafeteria image, which presents many details. Table 3 shows that the paper ranking almost follows the edge raggedness index except for papers 4 and 7.

Physical causes of print attributes

We now try to link the print attributes of the papers (color rendering, edge raggedness and print mottle) to the underlying physical and chemical properties of the papers. We focus on color rendering and print mottle since Table 2 shows that the properties of the papers with edge raggedness essentially follow the grey levels variations of solid prints.

Color

There is a large difference between colors printed on an Epson photo quality paper and other papers (cf., Table 2). We studied the *La*b** coordinates in order to know precisely which coordinate causes the observed difference. Table 4 shows those coordinates for magenta, other colors had the same behavior.

	Photo paper	**Paper 1**	**Paper 2**	**Paper 3**	**Paper 4**	**Paper 5**	**Paper 6**	**Paper 7**
L	48	60	56	60	61	59	62	61
a*	68	53	59	54	52	56	52	52
b*	-5	-4,2	-3,9	-4,2	-5,5	-3,2	-4,7	-3,6

Table 4: La*b* coordinates for magenta at 100% coverage for the papers under study.

Except for paper 3, the most permeable papers give light colors, and the less permeable papers give colors closest to the photo quality paper. Pigments are thus in large part absorbed by the most permeable papers. The behavior of paper 3 can be explained by its large roughness, leading to less homogeneous pigment absorption.

Mottle

In order to study the causes of print mottle, we used the standard deviation of grey level, since it is probably more representative of what may occur when ink is deposited on paper. Figure 4 and Figure 5 first show that there are no clear relationships between print mottle, sizing and paper formation. However, there are slight correlations between print mottle and microroughness on one hand, and with permeability on the other hand.

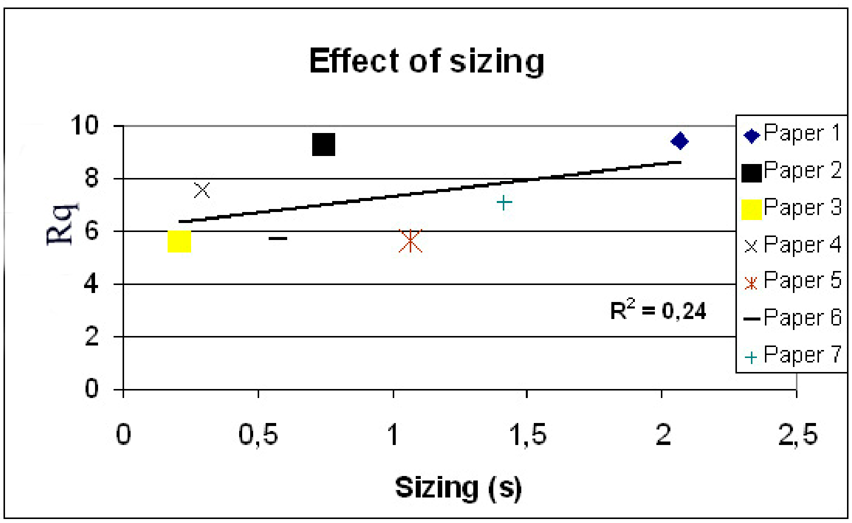


Figure 4: Influence of sizing on print mottle.

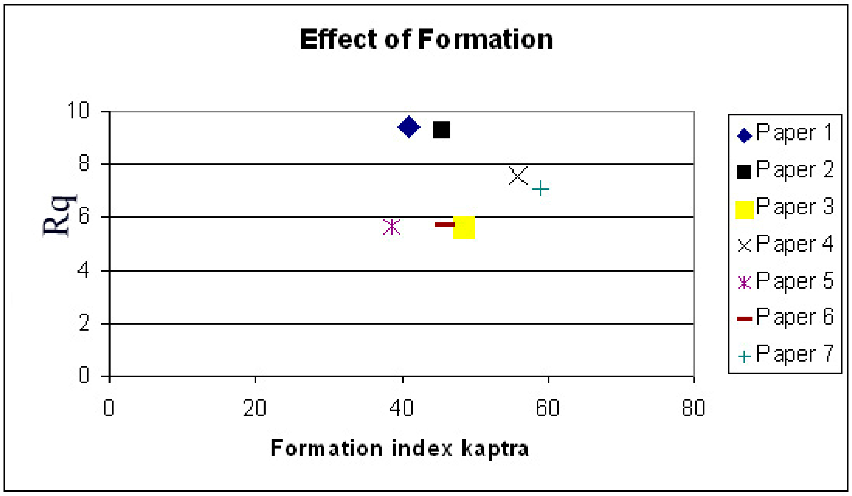


Figure 5: Influence of paper formation on print mottle

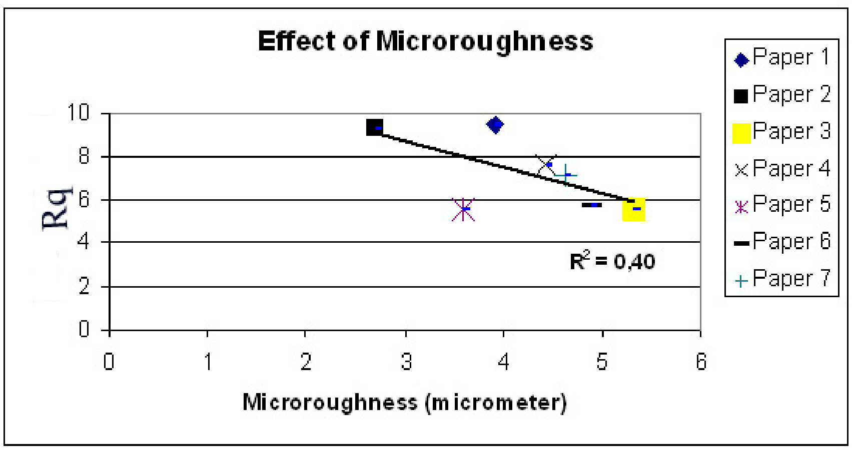


Figure 6: Influence of microroughness on the mottle

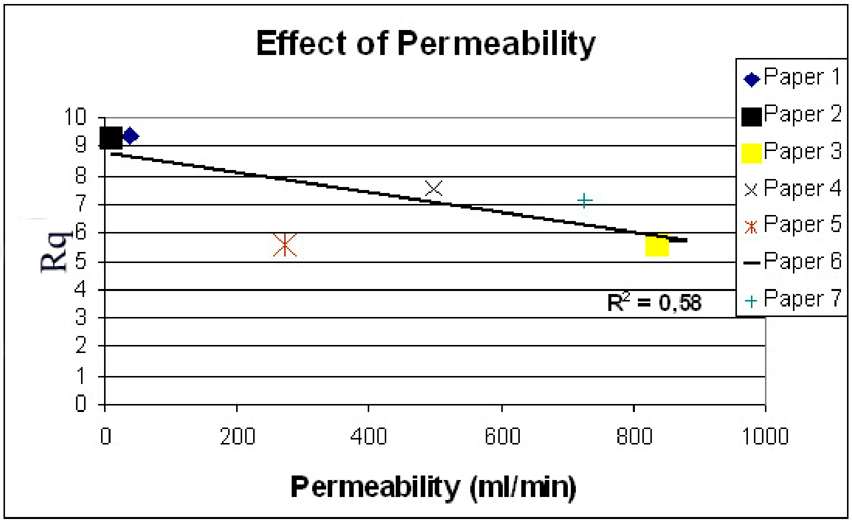


Figure 7: Influence of permeability on print mottle

The results indicate that more permeable and smoother papers present less print mottle, but there are no clear relationships that emerge. It is more probable that all these properties interact in a complex way to form mottle. It is particularly interesting to see that formation has absolutely no influence on mottle, but this may simply reflect the fact that formation is a very difficult quantity to measure.

Print mottle and ink volume

Paper 2 is characterized by a high mottle index, whether it is measured through the standard deviation of grey level or visual perception. It is also much different of the other papers. Its permeability is very low (7,3 ml/min) and it is particularly smooth. We can thus suppose that the time needed to absorb ink is more important for this paper, and that ink spread then causes mottle. To have a confirmation of this idea, we printed black solid squares again on the seven papers, but at lower resolution (360 dpi).

	Paper 1	**Paper 2**	**Paper 3**	**Paper 4**	**Paper 5**	**Paper 6**	**Paper 7**
Density (360 dpi)	0,73	0,77	0,68	0,63	0,67	0,63	0,68
Density (720 dpi)	0,88	0,94	0,84	0,77	0,83	0,79	0,82

Table 4: Density of black solids at 360 dpi and at 720 dpi for the different papers

Table 4 shows that the density of the paper printed to 360 dpi is smaller than the density of the paper printed at 720 dpi, which may indicate that the print requires less ink. Figure 8 shows the correlations functions of the print solids at 360 dpi. It is now clear that paper 2 has the same print density correlations as the other papers, a strong indication that print mottle for this particular paper is caused by an excessive amount of ink for its specific permeability.

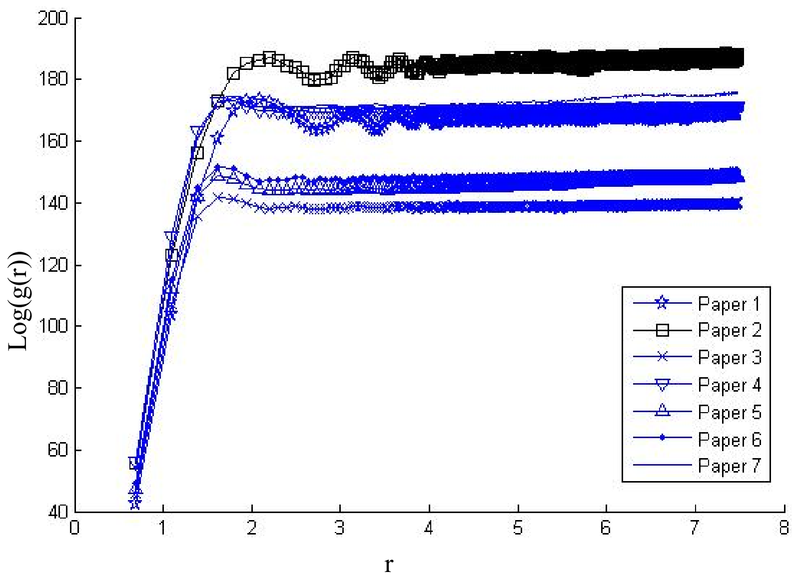


Figure 8: Correlation function of printed paper at 360 dpi

Conclusion

In conclusion, we explored the print quality complex images with three metrics: print mottle, edge raggedness and color rendering. These metrics each correspond to a dimension space of print quality and can be used to evaluate the quality of a given print. We then tried to relate these 3 print attributes to the physical and chemical properties of the paper. Although no definite relationships between paper properties and print attributes were established, we showed that bad color rendering was associated with high permeability while print mottle and edge raggedness were present with papers with low permeability. There is also a slight but noticeable correlation between print mottle and paper roughness. Rough papers have lower print mottle, which may be due to the fact that roughness will hinder ink spreading and thus lead to a more uniform print.

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Appendix 1

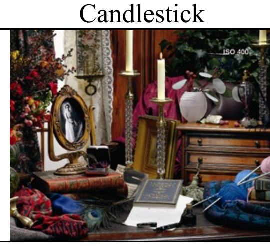
Fruits	Young girl	Cafeteria
		
Wine	**Musicians**	**Bicycle**
		
Orchids	**Candlestick**	
		

Figure 10: Images ISO used for print quality classification

Appendix 2

Vine	Musicians	Bicycle	Orchids	Candlestick
Photo paper (1)	Photo paper (1,5)	Photo paper (1)	Photo paper (1)	Photo paper (1)
Paper 3 (2,5)	Paper 5 (2,5)	Paper 3 (2,9)	Paper 3 (2,6)	Paper 5 (2,6)
Paper 5 (2,7)	Paper 3 (3)	Paper 5 (3)	Paper 5 (3,6)	Paper 3 (3,1)
Paper 6 (4,6)	Paper 6 (4,2)	Paper 6 (4,6)	Paper 6 (4,6)	Paper 6 (5,2)
Paper 7 (5,1)	Paper 7 (4,8)	Paper 7 (4,7)	Paper 7 (4,8)	Paper 7 (5,7)
Paper 4 (5,5)	Paper 4 (5,8)	Paper 7' (5,4)	Paper 7' (5,2)	Paper 7' (6)
Paper 2 (6,8)	Paper 1 (6,9)	Paper 4 (7,1)	Paper 4 (6,3)	Paper 4 (6,3)
Paper 1 (7,7)	Paper 2 (7,2)	Paper 2 (7,8)	Paper 1 (8,4)	Paper 2 (6,7)
		Paper 1 (8,6)	Paper 2 (8,6)	Paper 1 (8,4)

Table 4: Classification of the paper in function of their print quality for each image