Quality Space for High-Quality Inkjet Prints

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Abstract

The high-quality inkjet market is expanding and a large number of printers and print substrates are available. This makes the ability to analyse current print quality and quantify improvements increasingly important. For print quality evaluations, technical measures are preferred since they are repeatable and less time consuming than visual assessments. The question is which print quality factors that best describe the overall visual appearance of an inkjet print? The aim of this investigation is to identify those factors and thus define a quality space that characterises the print result in relation to visual appraisal. Sample material has been obtained by printing on nine different inkjet papers in three desktop inkjet printers. Technical quality factors assumed to be relevant for inkjet print quality, such as gloss, mottle, sharpness, grey balance, density and colour gamut have been obtained from the printed samples using technical measurements. Visual assessments have been made by a panel to determine the general visual quality. The relationship between the technical measures and the visual appraisal has been analysed using correlation coefficients, regression analysis and Principal Component Analysis. Among the factors studied here, the most important quality factor was the colour gamut. Further, colour raggedness and green mottle seem to be of importance. These three quality factors seem to determine a quality space for high-quality inkjet prints satisfactorily ($0.90<R<0.97$), at least at quality levels similar to those evaluated here.

Introduction

Inkjet printing technology is showing a rapid development. This versatile technique is capable of delivering different ink types in varying amounts onto very different substrates. Development are going in different directions, e.g. optimising for high-speed printing using relatively large droplets or optimising for high print quality in terms of sharpness, smoothness and colour, in which

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case the desire is for smaller droplets and more than four process inks (Klaman and Wedin, 2003). The high-quality potential of inkjet is verified by its use in proofing systems to emulate other print processes as well as its use as a means of producing prints replacing traditional photographs. The printers intended for this purpose need not to be very expensive, but the inks and speciality papers for this high colour quality have so far been quite costly. The market is however now expanding and a multitude of printers and print substrates are available. This calls for a comprehensive way of analysing the quality outcome of different paper-ink-printer combinations, which is the theme of the present investigation.

Print quality is a subjective measure and it can really only be determined by the viewer. Visual assessments are often carried out to determine the general visual quality. However, these assessments are time-consuming and not directly reproducible. In production control, objective quantitative measurements are preferred, as being both faster and repeatable. Perception studies nevertheless play an important role by providing the basis for the technical measurement methods.

Gloss, mottle, sharpness, grey balance, density and colour gamut are quality factors known to affect inkjet print quality. The question is which print quality factors best describe the overall visual appearance of an inkjet print? If print quality could be defined by only a couple of factors - the fewer the better - print quality evaluations would be fast and easy to perform.

McFadden and Donigian (1999) consider print density and colour-to-colour bleed the most important visual print factors for inkjet prints. This has been adopted by others (Svanholm and Ström, 2004; Superka and Janson, 2000), who evaluate inkjet prints in terms of these factors.

The aim of this study was to identify the most important print quality factors for high-quality inkjet prints. From these factors a quality space that characterises the print result in relation to the visual appraisal can be defined. The research approach was to perform a practical trial and hence acquire a significant quantity of evaluation material. From the printed material, quality factors could be obtained and visual assessments could be carried out. The technical quality factors could then be set in relation to the visual appraisal and the relevance of the print quality factors could be determined. The performance of the inkjet papers on the printers could then be investigated in terms of this quality space.

Material

Nine commercially available coated inkjet papers with different optical and physical properties were used. Eight brands were labelled *glossy* whereas one was labelled *matte*. However, visually the one labelled matte had a pearly appearance rather than a matte. The characteristics of the papers are given in Table 1.

Table 1. Paper characteristics.

Paper	Label	Grammage [g/m^2]	Surface roughness PPS [µm]	Gloss 75º [%]
1	Glossy	171	1,42	85
2	Glossy	214	1,51	79
3	Matte	243	2,56	55
4	Glossy	241	0,83	94
5	Glossy	255	0,49	63
6	Glossy	226	1,66	92
7	Glossy	184	1,87	50
8	Glossy	201	0,97	85
9	Glossy	262	0,65	70

The desktop inkjet printers used were Epson Stylus Photo 950, Canon Bubble Jet i950 and HP DeskJet 5550. All three printers were moderately priced desktop photo inkjet printers at the time of the investigation (end of 2003). The characteristics of the printers are given in Table 2.

Table 2. Printer characteristics.

Printer	Technology	Min. droplet size [pl]	Resolution [dpi]	Ink type	Colours
Epson Stylus Photo 950	Piezo	4	2880x1440	Dye	CMYK, light C and light M
Canon Bubble Jet i950	Thermal	2	4800x1200	Dye	CMYK, light C and light M
HP DeskJet 5550	Thermal	4	4800x1200	Dye	CMYK, light C and light M

The test form consisted of three test images for visual evaluation and test charts for technical measurements. The images used are shown in Figure 1 and the specifications are presented in Table 3. The test charts contained colour patches for gloss, mottle, sharpness, grey balance, density and colour gamut measurements. The test form was printed on the nine papers in the three inkjet printers. In the printing trials no calibration, profiles or exclusive settings were generated. For each printing, the setting was adjusted to give the highest print quality on the chosen paper type. The printers were placed in the same office area and were connected to the same computer.

Figure 1. The three images used for visual evaluation; Silver, Baby Boy and Girls.

Table 3. Specifications of the images used for visual evaluation.

File name	**Resolution** [pixels]	**Colour space**	**Format**	**Characteristics/purpose**
Silver	4096x3072	RGB	Tiff	grey balance, sharpness
Baby Boy	3000x2000	RGB	Tiff	skin tones, memory colours
Girls	2272x1620	RGB	Tiff	skin tones, grey balance, memory colours

Technical evaluation

To obtain the colour gamut, colour patches representing the colour gamut surface were measured with a GretagMcBeth spectrophotometer. The measurements were performed using standard illuminant D50, observer angle 2° and the neutral filter. The CIELAB values obtained were then used to calculate and visualise the colour gamut using a Matlab® routine at MoRe Research.

The test areas for mottle, sharpness and density were scanned using a desktop scanner, AgfaArcus1200, and the measures of these quality factors were calculated using a Matlab® image analysis routine at M-real Technology Centre Örnsköldsvik. Mottle was measured in full-tone black and in full-tone green. The mottle values were obtained by transforming the scanner RGB-values in the measurement area into CIELAB-values and then computing the variance of the L* for the size class 2,0–8,0 mm in wavelength. Sharpness was measured from two regions, a black line on yellow background and a black line on an unprinted area. From each region two measures were obtained, raggedness and blurriness. Four sharpness metrics were thus produced, referred to as black raggedness, black blurriness, colour raggedness and colour blurriness. Raggedness was defined according to ISO 13660 (2001), i.e. as the standard deviation of the distance from a calculated ideal smooth edge. Blurriness was calculated as the mean width of the edge zone. The edge zone is that part of the image having a reflectance factor in the range of 1/3 - 2/3 of the total reflectance range.

Density was measured in full-tone cyan, full-tone magenta, full-tone yellow and full-tone black. The density value was calculated using the scanner signal, which is proportional to the reflectance factor, in the density formula

$$D = \log(R_{\text{bg}} / R_{\text{print}}) \qquad [1]$$

where R_{bg} is the reflectance factor value for the background and R_{print} is the reflectance factor value for the printed area.

Gloss is commonly measured at 75˚, but when the aim is to discriminate between papers with high gloss levels, other angles could be more significant and distinguish the papers better (Pauler, 2002). Therefore, measurements were performed at three different angles; 20˚, 60˚ and 75˚ using a Zehntner gloss meter. Measurements were made at 75˚according to ISO 8254-1 (1999) and at 60˚ and 20˚ according to ISO 2813 (1994). Print gloss was measured in full-tone black and full-tone green. Each print was measured twice (once in each perpendicular direction) on two different sections of the test region. The gloss value was taken as the mean value of these four values.

The CIELAB values for a 40% CMYK-grey printed patch were obtained with a GretagMcBeth spectrophotometer, using standard illuminant D50, observer angle 2° and the neutral filter. The grey balance was defined as the chroma value, C_{ab}.

$$C_{ab} = \sqrt{a*^2 + b*^2} \qquad [2]$$

This value gives gave an indication of how much the colour differed from neutral grey (a*=b*=0). The larger the chroma value the less neutral is the colour.

Visual assessment

The Epson, Canon and HP prints were evaluated separately using pair comparison (Bristow and Johansson, 1983). For each set, the three images Silver, Baby Boy and Girls, were used. The prints were mounted on cardboard and presented to the panel of observers in a standard daylight viewing illumination, D50. Each observer had to say which print he/she preferred in terms of overall print quality. In each evaluation, ten to seventeen observers performed the pair comparison.

The prints used in the study all were high-quality and hence produced low values for the technical quality disturbance factors. The quality factors black raggedness, colour raggedness, green mottle and black mottle were analysed and the just detectable value was determined. The assessment was performed using the Method of Limits – Absolute Threshold as described by Engeldrum (2000). For each quality factor, a sequence of test areas from the printed material was selected. The prints were chosen so that their values gave as broad a range as possible and they were as equally spaced as possible. The prints were presented to the panel of observers in a standard daylight viewing illumination, D50. In each evaluation, eleven observers performed the assessment. For five of them the series was presented in ascending order and for six the series was presented in descending order.

Correlation analysis

Correlation coefficients between the different technical measurements and between the technical measurements and the results of the visual evaluation were calculated. The calculations were performed in Matlab®, using the predefined function *R=corrcoef(X).*

$$R(i,j) = \frac{C(i,j)}{\sqrt{C(i,i)C(j,j)}} \qquad [3]$$

where C(i,j) is the covariance of i and j.

A multiple regression analysis was carried out as a complement to the calculated correlation analysis. The regression was performed using the analysis tool in the Microsoft Excel® software. The method was used to determine the degree of correlation between the results of the visual assessments and combinations of two or three independent print quality factors. The result is presented as a table of regression statistics and the weighting coefficients, which describe the meaning and importance of the variables.

With Multivariate data analysis a large data set can be analysed and similarities, differences, correlations and influences can be shown. The data set is organised into a matrix where each row represents an *object* and each column a *variable*. When a Principal Component Analysis (PCA) is performed, the data are reorganized into so-called components. The aim is to describe several variables with only a few new components. The result is presented as a *score* and a *loading* graph. The PCA is interpreted by a combined evaluation of these two. In the score graph the positions of the objects in the new dimensions are shown. Hence, the relation between the objects can be determined and groups of objects as well as outliers can be identified. In the loading graph, the significance of the variables is revealed and correlations between variables can be found.

A PCA model was created to identify the correlation structure between the measured print quality factors and the results of the visual evaluation. Each print represented one object and the measured print quality factors and the result of the visual evaluation were set as variables. The multivariate data analysis was performed using the Extract software.

Results

Some general differences could be seen between the prints from the three printers. Obvious differences were seen in colour gamut and grey balance. The Canon prints had larger colour gamuts than the other prints. The Epson prints had the poorest grey balance and were in general more bluish than the others. The HP printer gave the most neutral result in terms of colour. These findings should be regarded as specific for these three individual printers and shall not be assumed to apply to other printers from these manufacturers.

The combination paper-ink-printer was of great importance. Different combinations gave different levels of print quality. The performance of a particular printer or a particular paper can vary significantly when used in different combinations. Some of the papers seemed to be incompatible with, or not optimized for, the Epson printer. Papers 3, 4 and 6 differed significantly in some of the quality factors. This was especially noticeable in green mottle and colour raggedness. The incompatibility resulted in poor print quality , which was easily visible to the naked eye and could primarily be described as grainy prints.

The outcome of a visual assessment depends on the motif used (Field, 1999), which was clearly seen in the visual assessment. Paper 5 printed in the HP printer gave very varying results for the three motifs, being ranked from almost best to almost worst. Rather than using an unrepresentative mean value, this print was excluded from the correlation analysis.

The just detectable black raggedness, colour raggedness, green mottle and black mottle values are presented in Table 4.

Table 4. Just detectable quality values.

Quality factor	Just detectable value
Black raggedness	4,0 µm
Colour raggedness	4,0 µm
Black mottle	0,1
Green mottle	0,1

The correlation coefficients between the different technical quality factors when the prints from all three printers were analysed together are presented in Table 5. In this table, the density values are excluded since they were closely related to the colour gamut and therefore did not add any information. Print gloss measured in green is not included either, since black and green print gloss correlated strongly. The correlation coefficients for each set separately, are presented in Appendix A. The correlation coefficients between the different technical quality factors and the results of the visual assessment are presented in Table 6. The results of the multiple regressions when colour gamut is combined with raggedness and/or mottle are presented in Table 7.

Table 5. Correlation coefficients between the technical quality factors.

All prints	Colour gamut	Black mottle	Green mottle	Black raggedness	Black blurriness	Colour raggedness	Colour blurriness	Print gloss black 75°	Print gloss black 60°	Print gloss black 20°	Grey balance
Colour gamut	1,00										
Black mottle	-0,07	1,00									
Green mottle	0,32	0,62	1,00								
Black raggedness	-0,49	0,48	0,16	1,00							
Black blurriness	0,18	0,16	-0,03	0,10	1,00						
Colour raggedness	-0,24	0,67	0,64	0,79	0,04	1,00					
Colour blurriness	-0,28	0,63	0,37	0,84	0,33	0,86	1,00				
Print gloss black 75°	0,26	-0,33	0,15	-0,61	-0,21	-0,28	-0,42	1,00			
Print gloss black 60°	0,20	-0,32	0,18	-0,47	-0,27	-0,16	-0,31	0,98	1,00		
Print gloss black 20°	0,29	-0,40	0,13	-0,40	-0,30	-0,17	-0,28	0,88	0,93	1,00	
Grey balance	0,15	0,31	0,55	0,23	-0,27	0,42	0,24	0,14	0,18	0,19	1,00

Table 6. Correlation coefficients between the technical quality factors and the result of the visual assessment.

Visual appraisal	Colour gamut	Black mottle	Green mottle	Black raggedness	Black blurriness	Colour raggedness	Colour blurriness	Print gloss black 75°	Print gloss black 60°	Print gloss black 20°	Grey balance
- Epson	0,67	-0,67	-0,19	-0,71	-0,14	-0,59	-0,67	0,60	0,53	0,55	-0,36
- Canon	0,84	-0,05	-0,21	-0,72	0,19	-0,77	-0,29	0,05	-0,10	-0,01	-0,19
- HP	0,94	-0,71	-0,21	-0,72	0,50	-0,85	-0,74	0,27	0,12	0,09	0,06

Table 7. Multiple regression coefficients for the technical quality factors and the result of the visual assessment.

Visual appraisal	Colour gamut/ Green mottle	Colour gamut/ Black mottle	Colour gamut/ Black raggedness	Colour gamut/ Colour raggedness	Colour gamut/ Green mottle / Black raggedness	Colour gamut/ Green mottle / Colour raggedness	Colour gamut/ Black mottle / Black raggedness	Colour gamut/ Black mottle / Colour raggedness
- Epson	0,87	0,94	0,81	0,89	0,91	0,90	0,94	0,95
- Canon	0,84	0,87	0,85	0,85	0,95	0,94	0,87	0,88
- HP	0,95	0,95	0,96	0,97	0,97	0,97	0,97	0,97

The PCA loading graph for the Canon prints, when all the measured factors and the visual appraisal were used as variables, is presented in Figure 2. The corresponding loading graphs for the Epson and HP prints are presented in Appendix B. All three loading graphs indicate that colour gamut, black raggedness and colour raggedness were significant factors. Colour gamut had a positive correlation with the visual appraisal, whereas black raggedness and colour raggedness had a negative correlation. For the Epson prints, print gloss and black mottle seemed to be of some significance as well. Black mottle seemed also to be significant for the HP prints.

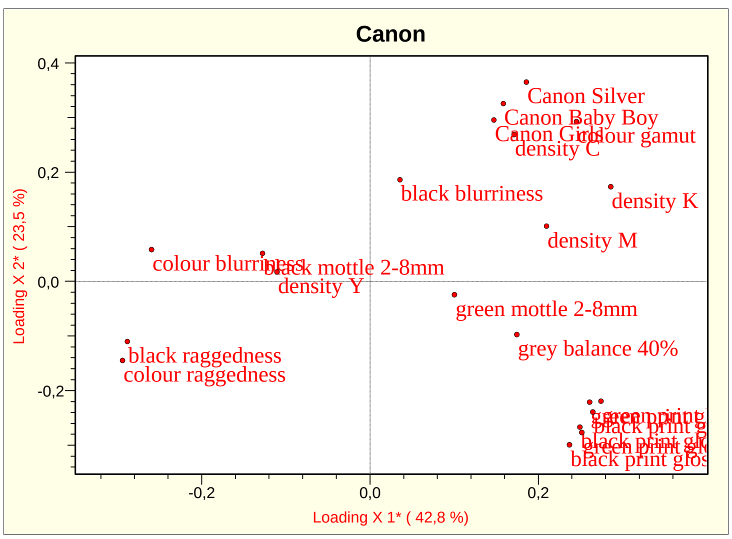

Figure 2. PCA loading graph for the Canon prints, using all quality factors as variables.

The PCA loading graphs for all three printers, when only colour gamut, black raggedness, colour raggedness, black mottle, green mottle and the mean visual appraisal were used as variables are presented in Figure 3.

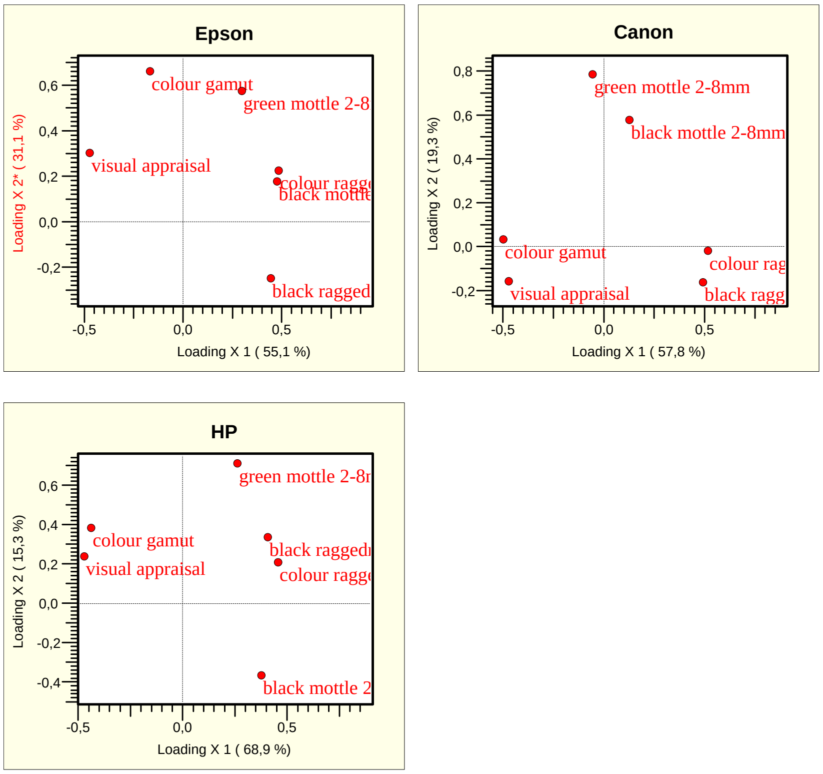

Figure 3. PCA loading graphs with reduced number of variables for the Epson, Canon and HP prints respectively

Discussion

The differences in colour reproduction found between the Epson, Canon and HP prints were expected, since no ICC-profiles were used. The colour reproduction could be improved and more similar colour appearance could be attained. However, the differences in colour reproduction had no effect on the visual evaluation since this was performed individually within each set of prints.

The importance of the paper-ink-printer combinations is well known. In this investigation the incompatibility of some combinations printed in the Epson printer was problematic. Some prints had quality factor values that differed significantly from all the others, which affected the correlation analysis.

The threshold values for just detectable black raggedness and just detectable colour raggedness was found to be equal. This was also the case for the threshold values for just detectable black mottle and just detectable green mottle. This indicates that the observers were equally sensitive to the two raggedness factors and the two mottle factors. Since many prints had values lower than the threshold this might affect the correlation analysis, so that these factors appeared less influential than what they are over a wider quality range.

Both raggedness and blurriness are measures of sharpness and they could be assumed to covary to some extent. However, they had no significant correlation for these sets of high-quality inkjet prints.

In general, the correlations varied between the printers. The Canon and the HP printer gave more similar results. This might be due to the fact that they both use the thermal technique to create droplets, whereas the Epson printer uses the piezo technique and therefore has a different ink composition. The incompatibility of some of the Epson prints also made it more difficult to analyse the correlations for these prints.

According to the correlation analysis, the most significant factor seemed to be the colour gamut. Especially for the Canon and HP prints, the colour gamut characterised the visual appraisal well, as shown in Figure 4-5.

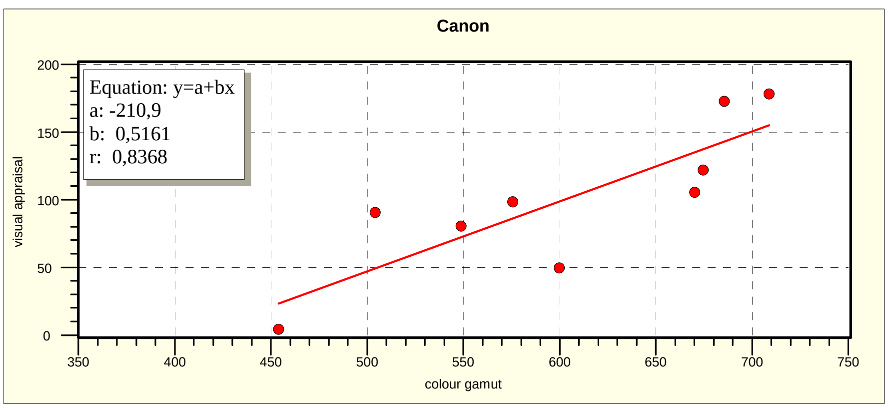

Figure 4. Visual appraisal vs. measured colour gamut volume (10^3) for the Canon print.

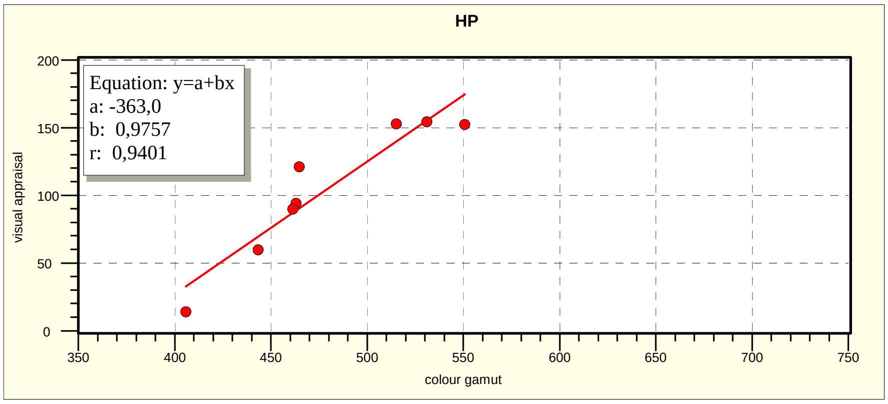

Figure 5. Visual appraisal vs. measured colour gamut volume (10^3) for the HP prints.

Although the correlation was only slightly improved when the colour gamut was combined with one or two additional quality factors, other factors were still found to be of importance. Both black raggedness and colour raggedness gave a relatively good correlation with the visual appraisal. The prints that were judged to have the poorest print quality mainly had small colour gamuts, high colour raggedness and high black raggedness. The black raggedness and colour raggedness values correlated strongly and to use both factors would therefore be redundant. Colour raggedness gave a slightly better correlation in combination with colour gamut than black raggedness. Since the main application for high-quality inkjet printing is image reproduction, a colour-to-colour measure like colour raggedness was considered to be preferable. Furthermore, the number of prints having values greater than the threshold was larger for colour raggedness than for black raggedness.

Print mottle is a generally feared quality defect. No clear correlation between raggedness and mottle was found, meaning that mottle could be used as a third independent quality factor. The two mottle measurements, green mottle and black mottle, showed no apparent correlation. This may be because of the low number of prints having visible black mottle. Far more prints had green mottle values that were higher than the just detectable value. Therefore, green mottle here determines the print quality of these high-quality inkjet prints better than black mottle. Using green mottle rather than black mottle also makes it possible to detect incompatible prints, since green is a secondary colour, produced by two process colours, cyan and yellow, which increases the risk of mottle.

The three quality factors colour gamut, colour raggedness and green mottle seems to determine a quality space for high-quality inkjet prints. Together, these

three characterise the print result in relation to visual appraisal to a great extent (0.90<R<0.97).
The findings thus fit well with McFadden and Donigians's results, which state that print quality can be defined by print density and colour-to-colour bleed. In this investigation, colour gamut and colour raggedness was determined as the two most significant quality factors, although the quality factors were used were not exactly the same. Further, it was found that green mottle was also important and should be included in a quality space for high-quality inkjet prints. Even if mottle had no great effect on the over-all print quality here, mottle is known to be a significant factor in other printing techniques. Hence, it deserves to be included in a quality space for inkjet prints over a wider quality range.

A quality factor that has not been analyzed is gloss variations. Its influence on the visual appraisal is not therefore known. Large variations in this quality factor could have an effect on the general visual appraisal.

Conclusions

The paper-ink-printer combination strongly affects the print quality. Some combinations in this investigation were even found to be incompatible. These prints mainly had significantly higher green mottle and colour raggedness values.

The observers seemed to be equally sensitive to black raggedness and colour raggedness, as well as to black mottle and green mottle when high-quality inkjet prints were studied. Raggedness disturbances smaller than 4 µm and mottle disturbances smaller than 0.1 could not be detected and hence did not influence the visual appraisal.

Among the factors studied here, the most important print quality factor for high-quality inkjet prints was the colour gamut. The colour gamut characterises the print result in relation to visual appraisal to a large extent (0.67<R<0.94). Further, colour raggedness and green mottle were found to be of importance. These three quality factors determine a quality space for high-quality inkjet prints satisfactory (0.90<R<0.97), at least at quality levels similar to those evaluated here.

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Appendix A - Correlation coefficients

Table A1. Correlation coefficients between the technical quality factors for the Epson prints.

Epson prints	Colour gamut	Black mottle	Green mottle	Black raggedness	Black blurriness	Colour raggedness	Colour blurriness	Print gloss black 75°	Print gloss black 60°	Print gloss black 20°	Grey balance
Colour gamut	1,00										
Black mottle	-0,02	1,00									
Green mottle	0,45	0,63	1,00								
Black raggedness	-0,45	0,58	0,07	1,00							
Black blurriness	0,07	0,36	-0,06	0,42	1,00						
Colour raggedness	0,01	0,70	0,71	0,67	0,31	1,00					
Colour blurriness	-0,29	0,63	0,34	0,91	0,52	0,86	1,00				
Print gloss black 75°	0,42	-0,64	0,14	-0,70	-0,34	-0,22	-0,44	1,00			
Print gloss black 60°	0,37	-0,61	0,19	-0,56	-0,36	-0,10	-0,29	0,98	1,00		
Print gloss black 20°	0,44	-0,63	0,13	-0,45	-0,42	-0,12	-0,28	0,89	0,94	1,00	
Grey balance	-0,20	0,13	0,25	0,20	-0,40	0,24	0,13	-0,03	0,03	0,10	1,00

Table A2. Correlation coefficients between the technical quality factors for the Canon prints.

Canon prints	Colour gamut	Black mottle	Green mottle	Black raggedness	Black blurriness	Colour raggedness	Colour blurriness	Print gloss black 75°	Print gloss black 60°	Print gloss black 20°	Grey balance
Colour gamut	1,00										
Black mottle	-0,32	1,00									
Green mottle	0,24	0,12	1,00								
Black raggedness	-0,73	0,04	-0,16	1,00							
Black blurriness	0,31	0,21	0,36	-0,07	1,00						
Colour raggedness	-0,81	0,23	-0,10	0,97	-0,07	1,00					
Colour blurriness	-0,54	0,40	-0,32	0,68	0,43	0,70	1,00				
Print gloss black 75°	0,19	-0,18	0,21	-0,63	-0,03	-0,57	-0,58	1,00			
Print gloss black 60°	0,06	-0,24	0,17	-0,48	-0,10	-0,42	-0,53	0,98	1,00		
Print gloss black 20°	0,17	-0,47	0,06	-0,46	-0,13	-0,44	-0,56	0,91	0,95	1,00	
Grey balance	0,35	-0,40	0,81	-0,20	0,07	-0,24	-0,63	0,40	0,40	0,38	1,00

Table A3. Correlation coefficients between the technical quality factors for the HP prints.

HP prints	Colour gamut	Black mottle	Green mottle	Black raggedness	Black blurriness	Colour raggedness	Colour blurriness	Print gloss black 75°	Print gloss black 60°	Print gloss black 20°	Grey balance
Colour gamut	1,00										
Black mottle	-0,73	1,00									
Green mottle	-0,09	0,15	1,00								
Black raggedness	-0,60	0,35	0,42	1,00							
Black blurriness	0,62	-0,05	0,04	-0,21	1,00						
Colour raggedness	-0,73	0,52	0,45	0,95	-0,23	1,00					
Colour blurriness	-0,59	0,56	0,20	0,83	-0,01	0,90	1,00				
Print gloss black 75°	0,25	-0,25	-0,12	-0,73	-0,14	-0,62	-0,72	1,00			
Print gloss black 60°	0,13	-0,23	-0,09	-0,58	-0,25	-0,48	-0,61	0,98	1,00		
Print gloss black 20°	0,14	-0,30	-0,23	-0,47	-0,34	-0,45	-0,52	0,86	0,92	1,00	
Grey balance	-0,13	-0,39	-0,27	0,02	-0,41	0,01	-0,12	-0,13	-0,12	-0,22	1,00

Appendix B - PCA loading graphs

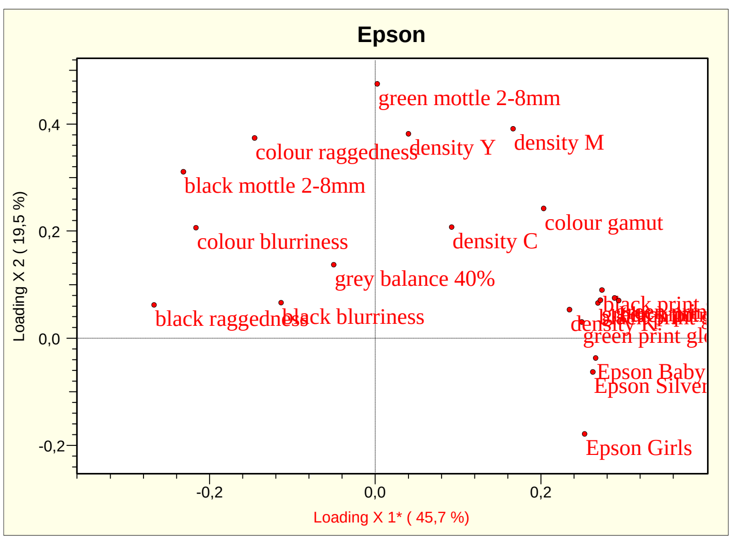

Figure B1. PCA loading graph for the Epson prints, using all quality factors as variables.

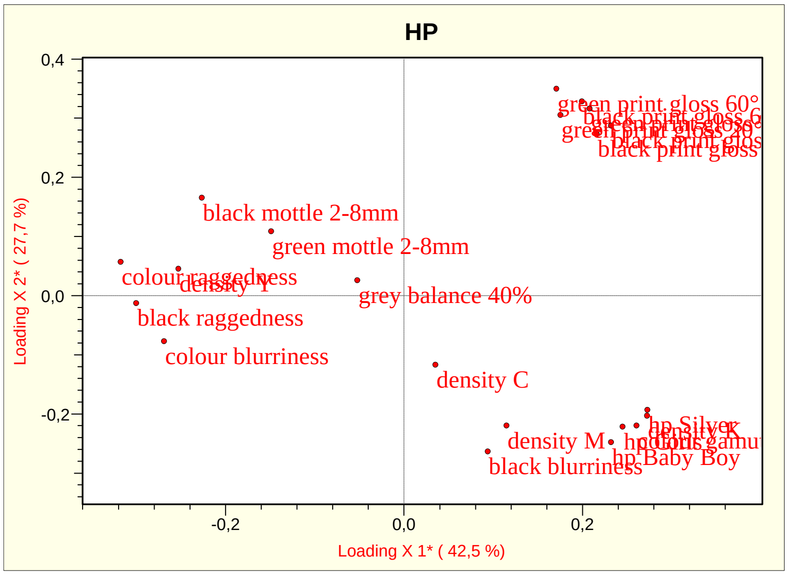

Figure B2. PCA loading graph for the HP prints, using all quality factors as variables.