# Colour Gamuts – Is Size The Only Thing That Matters?

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Keywords: appearance, colour, images, psychophysics, rendering

## Abstract

Today's inkjet printers are capable of producing colour images of very high quality. However, in inkjet printing, the substrate has a large influence on the quality of a printed image. In addition, the large variety of inkjet substrates increases the complexity of the colour reproduction in inkjet printers. Even when high-quality substrates are used, colour management is required when the input data is represented in any of the RGB colour spaces used today. Moreover, colour gamut transformations are inherent as the colour gamut of colour reproduction systems differ in size and shape. In this study, three colour rendering attributes associated with image quality – colour gradation, colour gamut volume and sharpness have been varied prior to printing in a set of test images. In real life, variations in these colour rendition attributes can be caused by different substrate properties, inappropriate printer settings for a specific substrate or the result of shortcomings in colour management. Whatever the cause may be, the effects of these variations can be observed in inkjet-printed images. The colour gamut volume, colour gradation and sharpness were varied simultaneously according to a statistical experimental design thus producing a subset of modified versions for each image in the test set. Furthermore, a visual assessment study was carried out in order to study the effect of the modifications on the perceived impression of the colour rendition in the printed images. Finally, the data from the visual assessment study was analysed in order to reveal how the different attributes influenced the perceived colour rendition.

## Introduction

The colour gamut of a printing system is the range of colours that can be reproduced for the combination of a printer and a substrate. The range will depend on the physical properties of the substrate, the colorants used and the properties of the print engine, such as adopted halftoning method.

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In addition, the conditions under which the printed substrate is viewed or measured will influence the perceived or measured range of colours. Moreover, the reproducible colour gamut for the combination of a substrate and a printer can be represented as an irregular solid in the CIELAB colour space for which the volume can be calculated. A widely established opinion regarding inkjet printing is that a large reproducible colour gamut for the combination of a printer and a substrate automatically yields high print quality. However, critics to this view may claim that a large colour gamut is useless unless in-gamut colours are correctly reproduced and the colour quantization is carried out with high precision in order to enable a good colour gradation. Furthermore, studies have shown that the size of the reproducible colour gamut for the combination of a printer and a substrate is one of the most important print quality attributes in high quality inkjet printing when relating objective print quality measurements to the visual appearance of a printed image (Gidlund 2005). On the other hand, other studies have shown that the visual appearance of a printed image is not only related to the size of the gamut but also to a high extent to attributes such as colour gradation, colour accuracy and image sharpness (Hunt 2004, Dahlberg 2005). The influence of these parameters will, in turn, also be related to the actual composition of the image.

## Background

It is widely known that the print quality in inkjet printing is heavily dependent of the substrate used. The difference in print quality between an ordinary office paper and a high-quality inkjet paper is considerable, but in turn, so is the difference in price. It is expected that an affordable inkjet paper capable of delivering high print quality will be a highly anticipated paper grade, at least on the European paper market. This type of improved office paper grade should be capable of producing a visually pleasant print quality to a reasonable price – a combination which is believed to lead to high usage. For paper producers, this type of paper grade could be produced in large volumes thus resulting in low production costs. On the other hand, obtaining a distinctively higher print quality (better colour rendition and higher sharpness) to a low cost is a challenging task. Furthermore, papermaking does in most cases imply compromising between different paper properties and also production costs. Therefore, it is wise to find out what properties to give priority to when designing the paper. In this study, the objective was to get an understanding of what properties of an inkjet-printed image that would have the largest effect on the perceived colour rendition for a paper grade of this type. A commonly used way to obtain this understanding is to acquire a large number of paper grades of similar type, print them on several printers and carry out a large visual assessment study. However, in visual assessment studies were several different substrates are involved, differences in substrate properties separate from the objective of the study often have a tendency to skew the study away from its intended target. In this study, a different approach to this problem was used. A single paper grade with suitable properties was used to create an experimental printer-substrate combination, thus simulating an improved office paper. With this simulated paper grade as a starting point, different colour rendition attributes were manipulated in test images prior to printing. Moreover, these attributes were varied according to a statistical experimental design, which was utilised to find out how the attributes influenced the perceived colour rendition. The attributes that were varied in this study – colour gradation, colour gamut size and sharpness are all attributes that can be associated with actual inkjet printing issues related to paper properties, such as ink absorption, ink spreading and surface roughness.

## Method

Consider an optimization process of a product such as paper for inkjet printing with numerous input parameters. An often used approach to a problem of this type is to change one input parameter at a time until no further improvement is achieved in the output. This is however a very inefficient approach. In fact, already a hundred years ago, it was proven that this approach does not necessarily lead to a maximum in the response (Eriksson 2000). In this study, the objective was to study how three colour rendition attributes – colour gradation, colour gamut volume and sharpness influenced three responses – the perceived colour rendition quality of three printed motifs. It was designed as a screening experiment aiming to explore the three attributes (factors) in order to reveal their influence on perceived quality of the colour rendition and in addition, to identify their proper ranges and determine the relations between them. To understand how factors and responses related to each other and to reveal which factors were most influential for on the responses, polynomial models were calculated. These local models functioned as approximations of how the attributes affected the perceived colour rendition quality of the printed images within the ranges specified in the confined experimental region. Multiple linear regression based on the principle of least squares analysis was used to analyse the data. The result was models consisting of regression coefficients, which, in turn were used to detect interactions and interpret the influence of the factors on responses. With a designated paper grade and a well-controlled high-end inkjet printer as a basis, a consistent printer-paper combination with a colour reproduction similar to the target, an improved office paper, was simulated with the use of printer linearisation, ink limitations and colour management. This simulated printer-paper combination was, in turn, used as the starting-point for manipulation of test images thus simulating different colour rendition attributes supposedly caused by differences in paper properties.

## Experimental Design

A full factor screening design with three factors in a symmetrical distribution of experimental points around a centre-point experiment was used. Experiments were carried out in all possible corners of the locally defined colour rendition quality space. In the centre-point, three replicate experiments were carried out to investigate the experimental error.

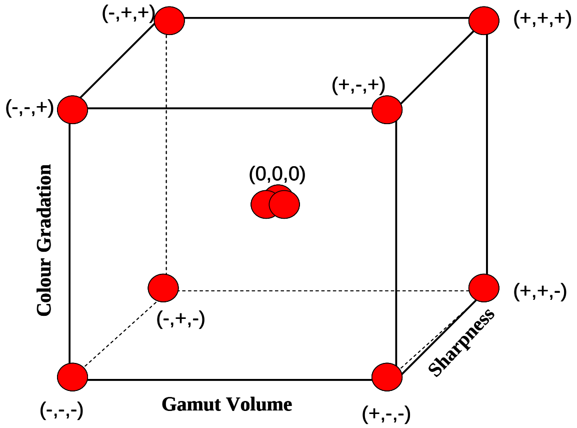

*Figure 1: The three-factor full factorial design with eight corner-point experiments and three replicate experiments in the centre-point*

The corner-experiments corresponded to eight images having different settings of the three varied colour rendition attributes. The factor intervals were chosen on basis of experience. Along with these eight images, the centre-point-image was printed three times, thus resulting in a set of eleven printed images per motif. These image sets provided as the material for the visual assessments. The responses were constituted by the results from the visual assessment studies – the colour rendition quality assessed by a panel of observers.

*Table1: Experimental design plan*

| ID | Sharpness | Gamut Volume | Gradation | Sharpness | Gamut (kColours) | Gradation (bits) |
|---|---|---|---|---|---|---|
| **1** | low | low | low | Low | 90 | 7 |
| **2** | low | low | high | Low | 90 | 9 |
| **3** | low | high | low | Low | 113 | 7 |
| **4** | low | high | high | Low | 113 | 9 |
| **5** | high | low | low | High | 90 | 7 |
| **6** | high | low | high | High | 90 | 9 |
| **7** | high | high | low | High | 113 | 7 |
| **8** | high | high | high | High | 113 | 9 |
| **9** | zero | zero | zero | Medium | 101 | 8 |
| **10** | zero | zero | zero | Medium | 101 | 8 |
| **11** | zero | zero | zero | Medium | 101 | 8 |

### Images

Three images, represented in 16-bit CIEXYZ-coordinates – “Pier”, “Flowers” and “Threads” were chosen from the ISO 12640-2 image set. The ISO-images are well-defined and widely recognised images of high quality. Furthermore, the three images all have characteristics with the potential to reveal the influence of the varied attributes – colour gradation, colour gamut volume and sharpness.

**Pier** **Flowers** **Threads**

*Figure 2: Images used in the visual assessment study.*

### Paper and printing

A matte-coated inkjet paper was used in this study. It was verified that the combination of paper and printer was well adapted to its use with a satisfactory interaction between paper and ink. In addition, this paper had properties very similar to the earlier discussed improved office paper. Moreover, paper grades with matte appearances are well suited for visual assessment studies since the viewing conditions becomes less critical regarding glare effects. All images and test targets were printed on a high-end inkjet printer. The printing system included an advanced RIP that allowed calibration and ink limitations. Prior to printing the test images in the experiment, an ICC-profile was calculated for the used printer-substrate combination. The printer was linearised, and the maximal ink amount and total ink coverage were determined for the paper grade used in this study. The ECI2002 colour chart was printed and measured according to the ISO 13655 specifications and finally, the profile was calculated with commercial software. In the printing of the images for the experiment, all images and test charts were printed with the same settings as the ECI2002 colour chart. A control strip was printed along with all images used to verify the consistency of the printing process. Furthermore, all printed images were measured and compared to the digital data to assure that there were no colour failures. In addition, it was confirmed by the panel of observers that all the printed images had a natural looking appearance. All printing was carried out in a climate controlled environment, with a relative humidity of 40% and a temperature of 21˚C.

### Simulating the printer-substrate combinations

Initially, the CIEXYZ-defined images were downsampled to 2048 x 1536 pixels. When printed with a resolution of 300 ppi, this resulted in printed images having size of 174 x 130 mm, a format suitable for the visual assessment studies. In order to create the simulated printer-substrate combinations, the set of images for the visual assessment study was produced through the following steps:

1. The images were transformed from CIEXYZ-coordinates to CIELAB-coordinates using D50 illumination and 2° standard observer.
2. The ICC-profile generated for the utilised printer-paper combination was used to convert the images defined in CIELAB-coordinates to device CMYK-coordinates using perceptual rendering intent.
3. The generated ICC-profile was used to convert the CMYK-coordinates back to CIELAB-coordinates with relative colorimetric rendering intent, thus resulting in the starting-point image for the image manipulations.
4. Outgoing from the starting-point image, the different manipulations were applied, thus producing a set of nine images according to the experimental design plan.
5. Finally, the generated set of manipulated images was once again converted to device-space CMYK-coordinates using relative colorimetric rendering intent, and then printed thus resulting in eleven printed images.

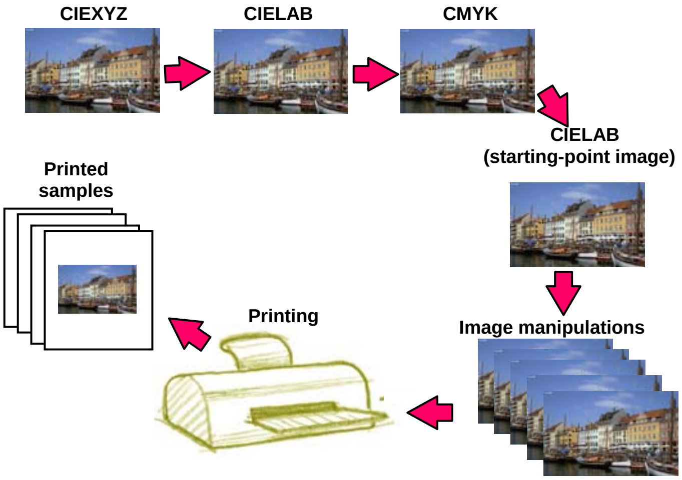

*Figure 3: Producing the simulated printer-substrate combination.*

Image manipulations

The gamut volume was varied by a scaling in the ab-plane of the starting-point image CIELAB coordinates. A test image defining the sRGB gamut boundary was processed the same way as the other test images and the three scale-factors were applied. The printed samples were measured with a spectrophotometer and the colour gamut volumes were calculated. The resulting colour gamut volumes were calculated from the assumption that one colour is defined by a cube in the CIELAB colour space with the dimensions 1L* x 1a* x 1b*.

*Table 2: Scale-factors and corresponding colour gamut volumes*

| Level | Scale-factor | Gamut Volume |
|---|---|---|
| low | 0.9 | 90,000 colours |
| medium | 0.95 | 101,000 colours |
| high | 1.0 | 113,000 colours |

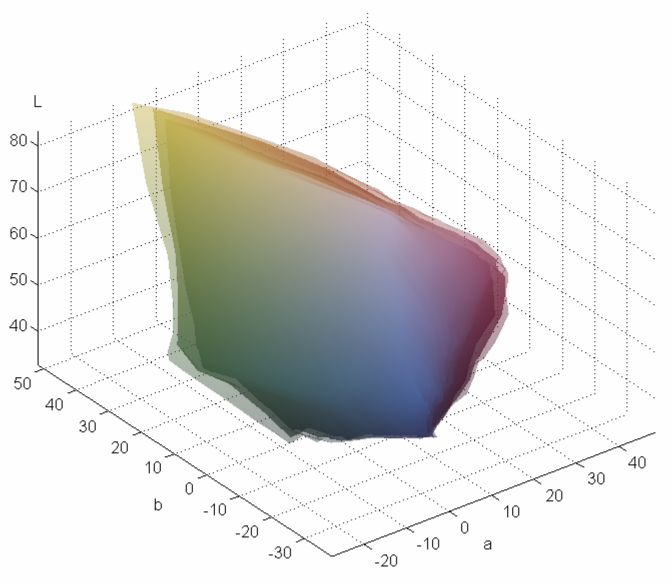

*Figure 4: Colour gamuts corresponding to the three different scale-factors.*

The images sharpness was varied by applying a Gaussian low-pass filter to the 2048 x 1536 pixel CIEXYZ-images. The highest sharpness was obtained for the original 2048 x 1536 pixel image, the medium level corresponded to the filter being applied once and to create the lowest level of sharpness, the filter was applied twice.

| | | |
|---|---|---|
| 0.011 | 0.083 | 0.011 |
| 0.083 | 0.619 | 0.083 |
| 0.011 | 0.083 | 0.011 |

*Figure 5: The Gaussian low-pass filter used to vary the sharpness of the images.*

The colour gradation was varied by quantization of the CIELAB-coordinates of the starting-point image prior to conversion to device CMYK-coordinates.

*Table 2: C*olour *gradation levels and quantisation of CIELAB-coordinates*

| Gradation level | Quantisation (bits) |
|---|---|
| low | 7 |
| medium | 8 |
| high | 9 |

## Visual Assessment

A visual assessment study of the printed samples was carried out in order to relate the influence of the colour rendition attributes to the visual response. To determine the appropriate method to use, a pre-study was carried out using the sets of printed samples. The pre-study indicated that there were small differences between samples in the sets, thus resulting in a high degree of confusion. This finding in combination with the relatively low number of samples made the paired-comparison method most suitable (Engeldrum, 2000). In the paired-comparison method, samples are presented to the observers in pairs. The observer task is then to select the preferred sample with respect to the given instructions. This procedure is repeated for all possible combinations of sample pairs. A separate study was carried out for each motif, each one consisting of eleven samples whereas three samples where identical. These replicate samples corresponded to the experimental centre-point and were used to estimate the variation of the judgements. The visual assessment study was carried out at normal viewing distance in a viewing booth using D50 illumination without external light from surrounding light sources or windows. All wall coverage and tables in the room were neutral grey. The printed images were mounted on white cardboard and a neutral grey frame was mounted on top of the image as a surrounding mask, hence providing a constant visual reference. The grey frame was also used to prevent the Bartleson-Breneman effect (Lindberg 2004) where the reflectance of the surround influences the perceived tone and colour reproduction. The samples were randomly ordered and labelling was put on the back of the sample to avoid obstruction of the judgements. The observer panel consisted of sixteen persons mixed in age, sex and experience in judging printed samples. The observers were instructed to select the preferred sample with respect to the colour reproduction quality. Turnstone's law of comparative judgement with the statistical assumptions of a *case V* solution (Engeldrum, 2000) was applied to the data in order to obtain an interval scale of the samples. The paired-comparison index (PC-index) scales the samples from 0 to 200. High values correspond to samples perceived as having a good perceived colour rendition, while low values correspond to samples perceived as having a poorer perceived colour rendition. The PC-index was calculated according to *equation 1*.

$$PC-index = \frac{\sum_{i=1}^{n} v_i}{2x(n-1)} * 200 \qquad \text{(Equation 1)}$$

where $n$ is the number of observers and $v_i$ is the value given by observer $i$.

A consistency coefficient was calculated for each observer, this coefficient expresses the ration of illogical triads made by the observer. An example of an illogical triad is, if an observer ranks sample A as being better than sample B, sample B better than C, but then ranks C as being better than sample A. All observers with a coefficient of consistence lower than an acceptance level were excluded from the study. Three observers were removed from the "Pier" image study, one observer was removed from the "Flowers" image study and none from the "Threads" image study.

## Results Visual Assessment

The results from the visual assessment differed between the tree motifs. An important finding was the small variation and centred positioning for the replicate centre-point samples. With a variation in the three replicates that is much smaller than the variation in the entire investigation series, the replicate error will not complicate the data analysis. In addition, it gives an indication whether the defined experiment region is skewed or not.

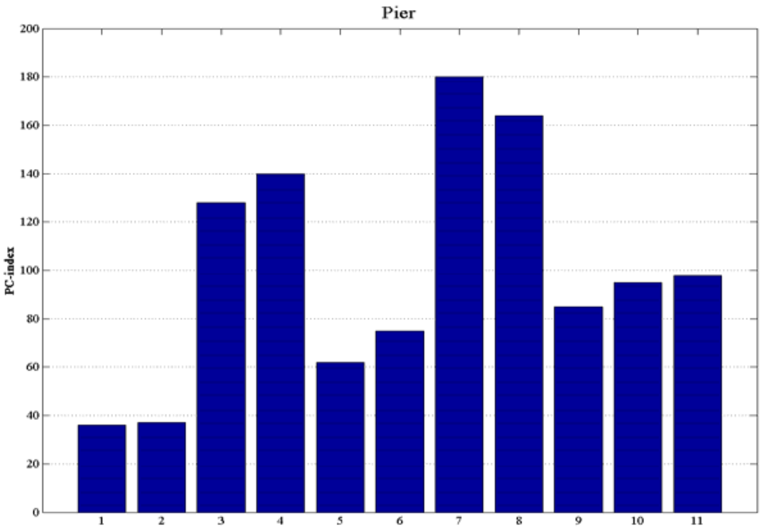

*Figure 6: PC-index of the visual assessment of the "Pier" motif. Higher PC-index corresponds to a better colour rendition. The sample characteristics are presented in table 1.*

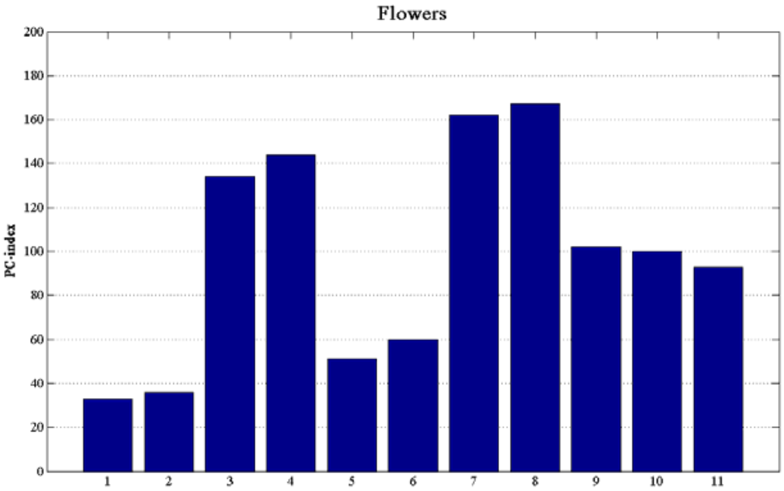

*Figure 7: PC-index of the visual assessment of the "Flowers" motif. Higher PC-index corresponds to a better colour rendition. The sample characteristics are presented in table 1.*

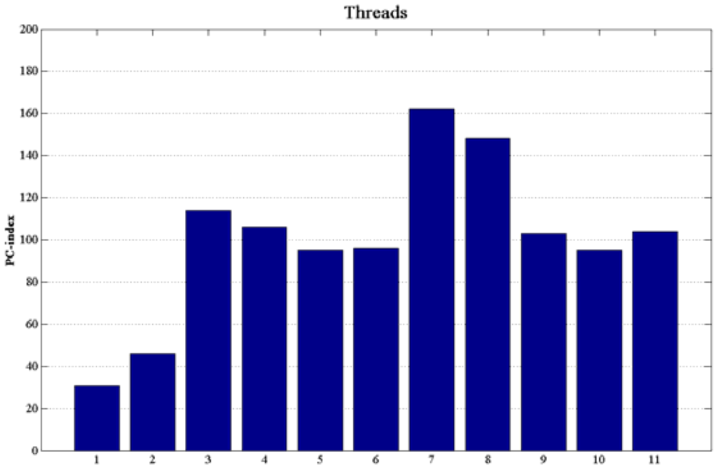

*Figure 8: PC-index of the visual assessment of the "Threads" motif. Higher PC-index corresponds to a better colour rendition. The sample characteristics are presented in table 1.*

## Results

The results from the regression were polynomial models which were used to interpret the influence of the factors. The objective was to find models using the same factors and interaction terms that fit to the responses from all three motifs. Singular value decomposition (SVD) was used to solve the system of equations:

$$Y = X * B + E \qquad \text{(Equation 2)}$$

where Y is a n*m matrix of responses and the extended design matrix X an n*p matrix, p is the number of terms in the model including the constant term and B the matrix of regression constants, E is the matrix of residual response variation not explained by the model (Eriksson, 2000). In the interpretation, the confidence intervals were used to estimate the uncertainty in coefficients and effects. *R2* is goodness of fit and describes how well the model fit to the data. *Q2* is the goodness of prediction and estimates the predictive power of the model. Given a certain fit, this is a more realistic and useful performance indicator. The scaled end centred representation in the graphs should be interpreted as follows; a regression coefficient corresponds to the change in response when a factor is raised from its zero level to its high level. In this study, this implies gamut volume changes at approximately ten-thousand colours, gradation changes represented by one bit higher quantization level and a sharpness difference corresponding to the effect of applying the Gaussian filter in *figure 5* once.

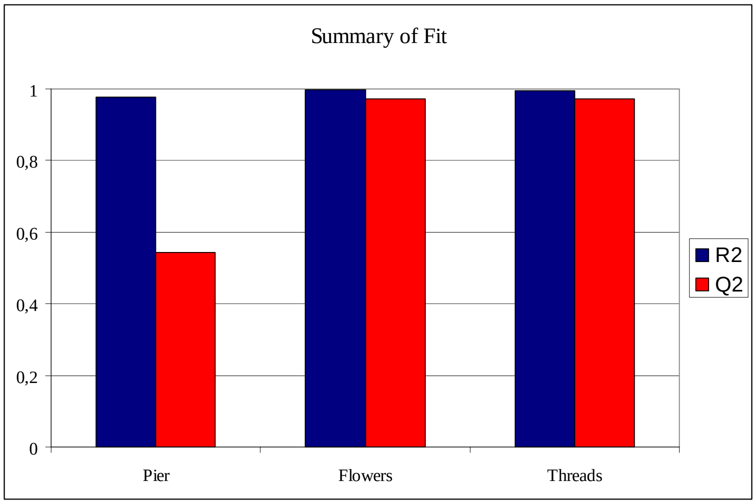

*Figure 9: Summary of fit and prediction ability for models obtained for the three motifs.*

Initially, all factors and their interactions were used in the regression. As shown in *figure 9*, very good models were obtained in terms of goodness of fit and prediction ability. The exception was the low prediction ability for the "Pier" image.

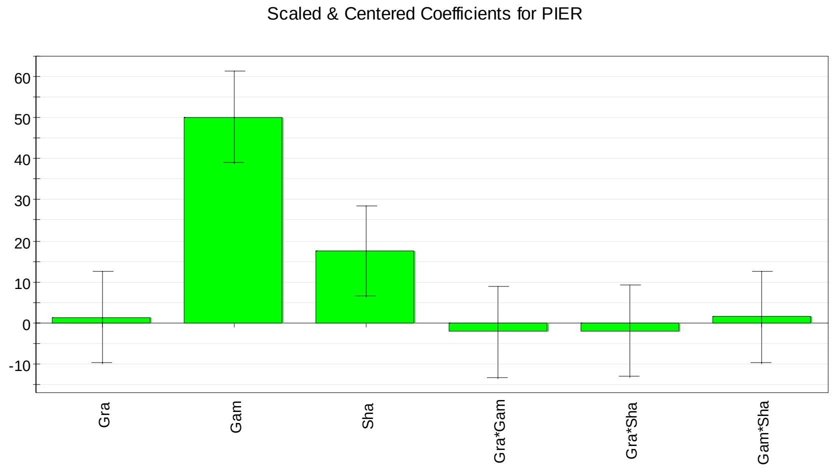

*Figure 10: Regression coefficients for "Pier" image*

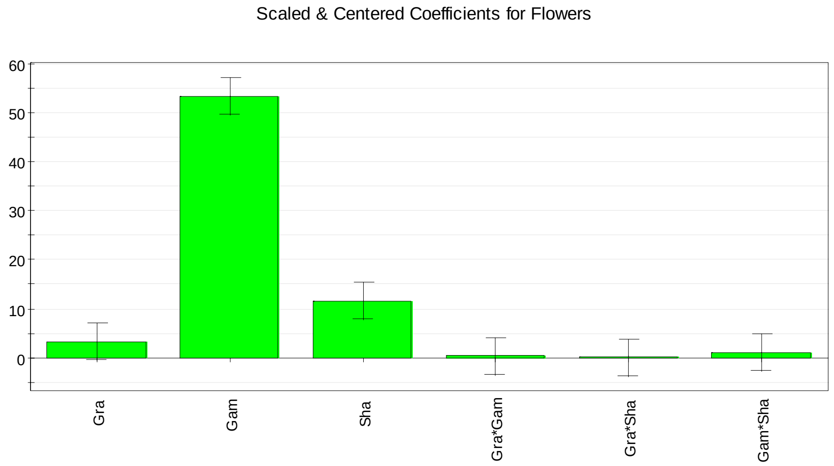

*Figure 11: Regression coefficients for “Flowers” image*

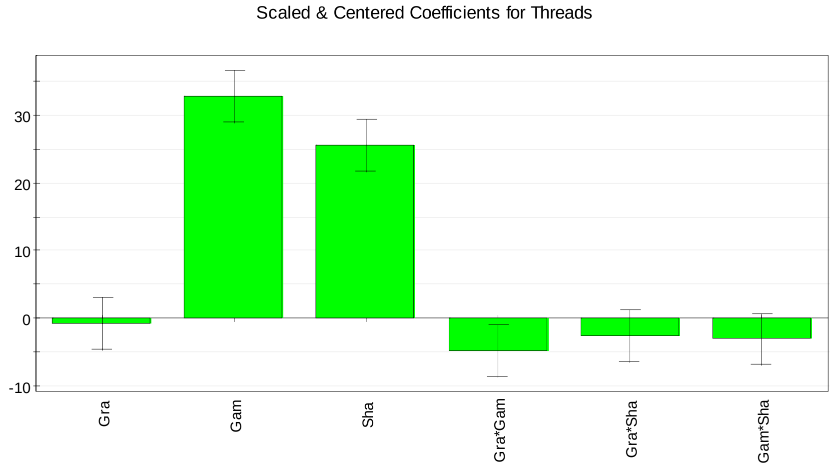

*Figure 12: Regression coefficients for “Threads” image*

When analysing the regression coefficients, it was observed that the gamut volume and sharpness were the most influent factors. The colour gradation had a very small effect on the responses when varied within the range specified for this experiment. A tendency to an exception could be observed for the “Flowers” image where the regression coefficient for gradation was significantly large. However the coefficients’ uncertainty was too large to draw any further conclusions from this. The only observed interaction of significance was the one between gradation and gamut volume for the “Threads” image, the contributions from other interactions could be regarded as noise. All response contour plots had the same appearance although the gamut volume – sharpness relationship differed between the three motifs.

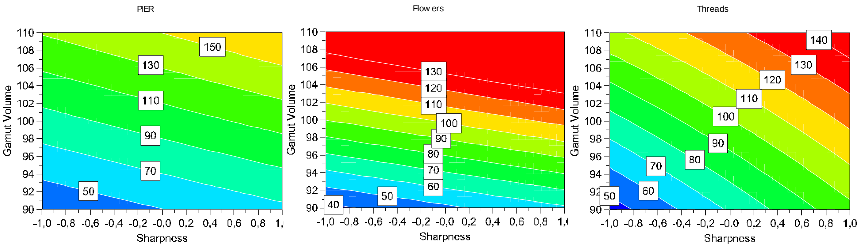

*Figure 13: Response contour plots for the three motifs*

In order to improve the prediction ability for the “Pier” image model, the models were pruned from interaction terms insignificant in all models. The result was significantly improved prediction ability for the “Pier” image and otherwise negligible impairments. In addition, less complex models were achieved, which is preferable as long as a good fit and a high goodness of prediction is maintained.

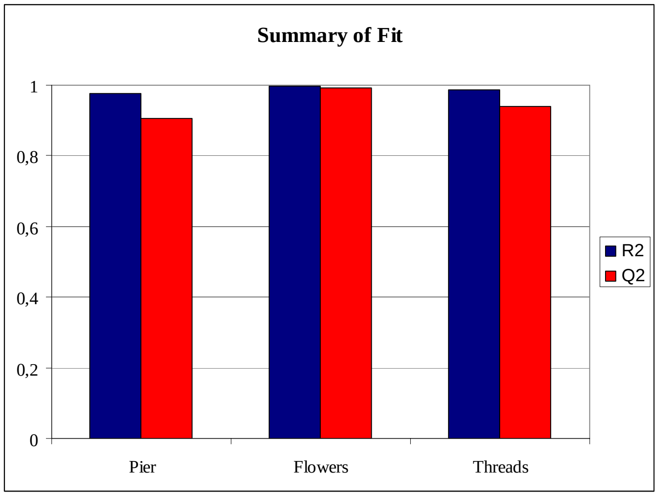

*Figure 14: Summary of fit and prediction ability for the pruned models*

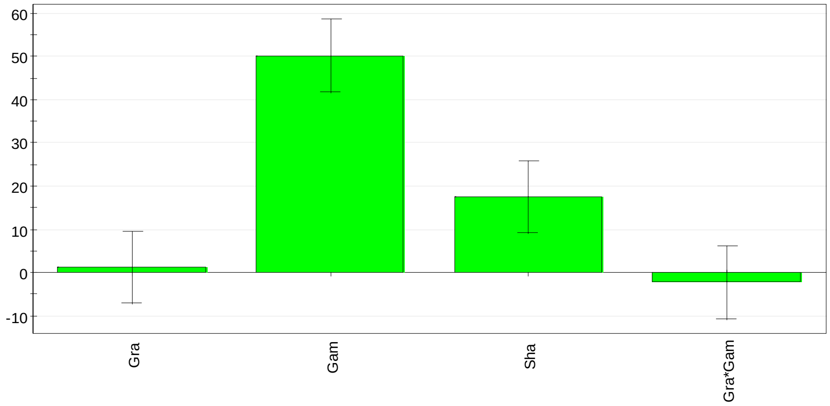

*Figure 15: Regression coefficients in pruned model for "Pier" image*

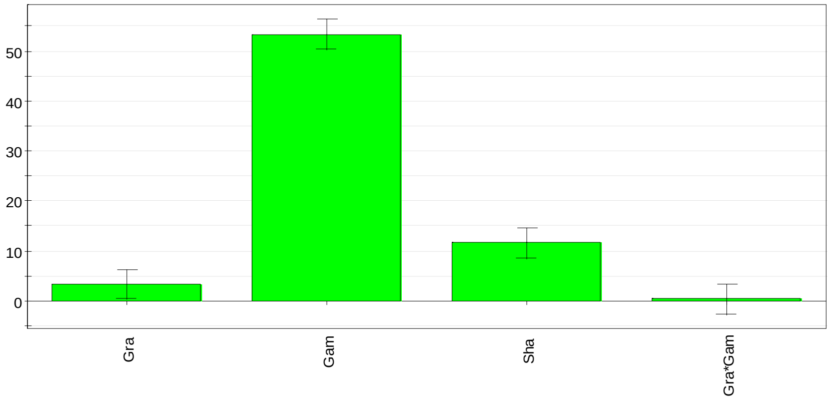

*Figure 16: Regression coefficients in pruned model for "Flowers" image*

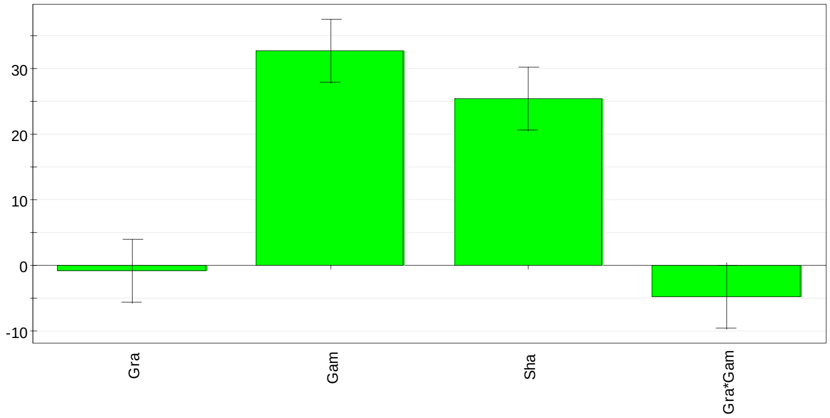

*Figure 17: Regression coefficients in pruned model for "Threads" image*

All response contour plots maintained the same appearance as before the pruning of the model. Moreover, the model prediction plots indicate linear relationships between observed and predicted responses. These results are in agreement with the high R2 and Q2 values obtained for the models.

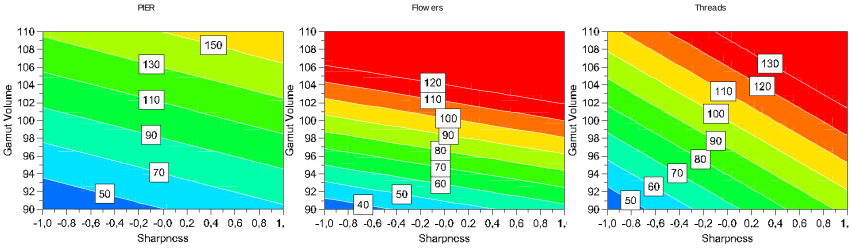

*Figure 18: Response contour plots for the three motifs using the pruned models*

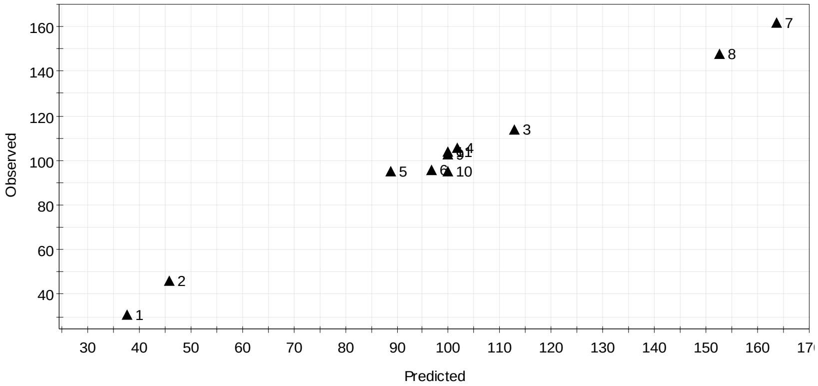

*Figure 19: Predicted vs. observed response plot for "Threads" image and pruned model*

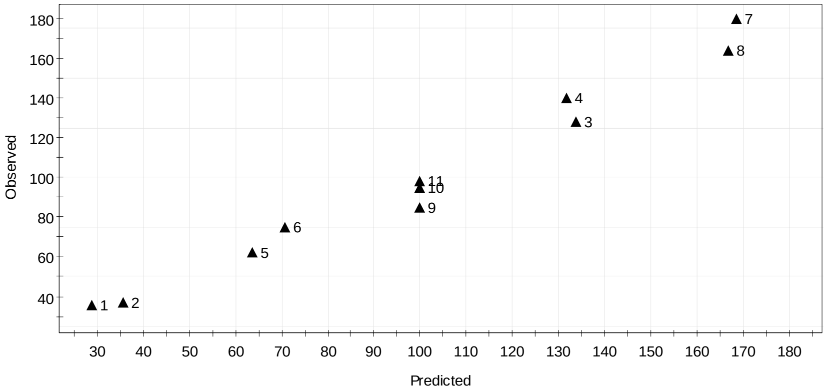

*Figure 20: Predicted vs. observed response plot for "Pier" image and pruned model*

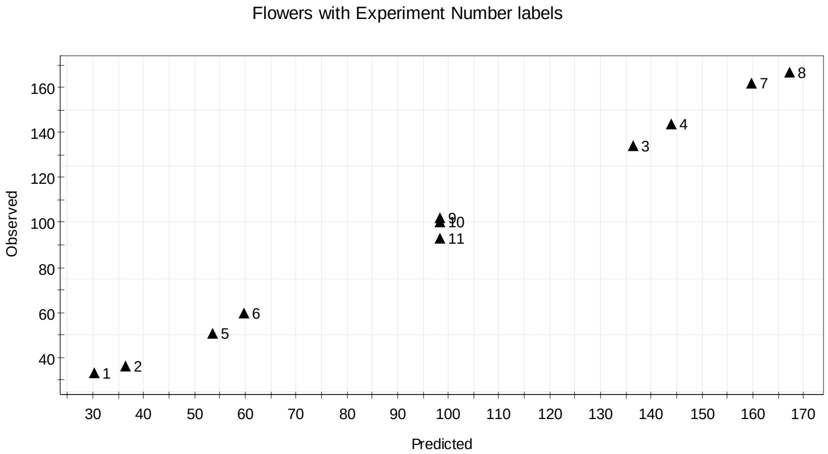

*Figure 21: Predicted vs. observed response plot for "Flowers" image and pruned model*

## Conclusions

The findings in this study show that relatively small differences in colour gamut volume and sharpness can cause noticeable differences in the visual assessment of a printed image. Furthermore, the perceived colour rendition quality was highly correlated with the size of the colour gamut. Therefore, the colour gamut volume is arguably the single best objective parameter for quantization of colour reproduction quality in inkjet printing. This is supported by the fact that very large differences in colour gamut volumes can be observed for different printer-substrate combinations. Moreover, the influence of the sharpness was noticeable. Three different images were used and as expected, it could be observed that the visual assessments were influenced by the motif. All response contour plots had the same appearance although the gamut volume – sharpness relationship differed between the three motifs. For the colour gradation, the findings indicate that as soon as the colour gradation reaches a certain level it becomes a non-influential factor. In this study, the gradation was varied in a range where its effect on the perceived colour rendition was negligible.

## Discussion

The developed models were sufficiently good and provide a good basis for further studies and the future design of an improved inkjet paper. The influence of sharpness was significant but subordinate to the influence of the colour gamut volume, and consequently, in this case, the size of the colour gamut did matter. The effect of the colour gradation was not sufficiently explored in this study. Intuitively, there should be a relation between gamut volume size and gradation.

For example, a printer-substrate combination which is able to reproduce a very large colour gamut would most likely require more in-gamut levels than a printer-substrate combination with a smaller gamut to avoid gradation problems such as contouring and loss of close-colour details. If a glossy high quality inkjet substrate with a significantly larger gamut volume was used instead, the result might have been different. Another consideration is whether the printed motifs, with the printer-substrate combination and specified attribute ranges used actually contained areas whereas the gradation was visible for the observers. In the model for the “Threads” image, the interaction between colour gamut and gradation had a small but significant negative contribution, but this was the only indication of this relationship. Furthermore, it is possible that the gradation range used in this experiment was not properly tuned to the relatively small colour gamuts of approximately a hundred-thousand colours which are typical when applying colour management to this type of printer-substrate combination. Another issue is whether the gradation could have been varied in another way than in this study, there are probably better ways to express gradation steps than in powers of two.

## Acknowledgements

The work presented here has been performed within the Swedish national research program, T2F. The financial support and the fruitful collaboration within T2F are gratefully acknowledged. The support and encouragement from colleagues at M-real Corporation, MoRe Research and Mid Sweden University are also highly appreciated. Furthermore are we grateful to all the experimental observers for their engagement and patience.

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