JPMTR 093 | 1509
DOI 10.14622/JPMTR-1509
UDC 655.1-021.465:535.3:774.8

Research paper
Received: 2015-11-19
Accepted: 2017-04-29

Print quality and color accuracy of spectral and colorimetric reproduction

Radovan Slavuj[1,2], *Ludovic G. Coppel*[1,3], *Irina Ciortan*[1], *Peter Nussbaum*[1] *and Jon Yngve Hardeberg*[1]

[1] The Norwegian Colour and Visual Computing Laboratory, Teknologiveien 22, 2802 Gjøvik, Norway
[2] Radovan Slavuj, Pavla Micunovica 9, 24300 Backa Topola, Serbia
[3] Ludovic G. Coppel, Bolindervägen 79, SE-17674, Järfälla, Sweden

slavujr@gmail.com
ludovic.coppel@gmail.com
irina.ciortan@gmail.com
peter.nussbaum@hig.no
jon.hardeberg@hig.no

Abstract

When reproducing an image by means of printing, the most common concerns are to have good colors and the least perceivable artefacts. These two concerns are most conveniently conveyed via two common reproduction goals: color accuracy and image quality. The goal of this paper is to evaluate how color accuracy aim relates to printed image quality, the attribute usually tight to the method of halftoning. In order to provide a relation between these two different goals, spectral and colorimetric color management workflows are paired with different halftoning methods. Image quality metrics is employed both on the output from the color separation process and on the print output. Overall, spectral reproduction used in this paper showed higher color accuracy but lower image and print quality score, even if combined with state of the art halftoning methods.

Keywords: reproduction workflow, halftoning, image quality, spectral reproduction, multichannel printing

1. Introduction

A reproduction workflow is comprised of processing steps that transform an input, in a form of spectral reflectance or colorimetric values, to the printer binary information. A print oriented reproduction workflow involves calibration and characterization of the printer, gamut mapping where needed, a separation to compute ink amounts, and halftoning. In the best scenario, input signal, whether it is a spectral reflectance or trichromatic value, is perfectly matched by printing specific ink combinations. Specific ink combination and percentage of each ink in the mixture is determined by the separation process.

Typical separation process involves an inversion of the printer characterization model, either analytically or by some search mechanisms (e.g. interpolation or optimization). Which method to use will depend on invertibility of the characterization function and dimensionality difference between input and output. It follows that colorimetric input, being of three dimensions, could be utilized more directly with a printing system having similar degree of freedom (e.g. CMYK). On the other hand, a workflow that starts with spectral reflectance as the input and having printing system on the output will almost exclusively suffer from dimensionality difference. This suggests that more compromises must be made in spectral reproduction process and especially in separation method. Therefore, an ink combination selected by separation process to print input spectral reflectance might be very different from the one otherwise selected to print colorimetric CIE $L^*a^*b^*$ value.

Common goal of any color reproduction is high accuracy. Colorimetric workflow aims to maximize accuracy under one fixed viewing condition, while spectral workflow aims for illuminant and observer independent match (Tzeng and Berns, 1998; Taplin, 2001; Gerhardt and Hardeberg, 2006). Latter is most conveniently achieved by having a spectral match, that is, a copy of the original with the same physical property to selectively reflect input light. It is well known that a single CIE $L^*a^*b^*$ value can be created out of set of different reflectances. All reflectances that sums up to the same CIE $L^*a^*b^*$ value under the combination of viewing condition and illumination form so called metamere set. This set can be large which makes it difficult to match spectral reflectance. On the other hand, if spectral match was possible, the problem of metamerism would be eliminated. However, in majority of the printing applications, spectral match is not possible due to the limited spectral gamut of today's printers (Urban and Berns, 2011; Morovič et al., 2012). This is partly due to the non-optimal ink set for spectral reproduction (Alsam and Hardeberg, 2004), but moreover it is because the available number of inks is yet too small for additive process such as the ink mixing process. As a consequence, the reproducibility of the real world reflectances highly depends on a given application, where one study (Slavuj, Marijanovic and Hardeberg, 2014) suggests that more than a half of the CIE $L^*a^*b^*$ values of the patches to be printed, have spectral reflectance that is non-printable on a current state of the art multichannel printer.

Limitation induced by non-printable reflectances also leads to different gamut mapping strategies that are applied in spectral versus colorimetric spaces. Moreover, a metric commonly used to quantify spectral difference (e.g. spectral root mean squared error – RMS) does not correlate well with the perceptual difference. One of the practical solutions to this problem is to convert spectral data to colorimetric coordinates where conventional color gamut mapping can be applied (Derhak, Green and Lianza, 2015). If spectral information is now converted to colorimetric encoding, the spectral match is then achieved by ensuring that each point is within a gamut constructed under multiple illuminants (Urban and Berns, 2011). If there is a match between the pair of CIE $L^*a^*b^*$ values under any illuminant, then illuminant metamerism is eliminated and it follows that spectral match most probably exists. Problem with pure spectral approach to gamut mapping and of multi-illuminant gamut mapping is that they are pixel based operations that do not account for neighboring pixels. This, in addition to the weak correlation to the perception gives a rise to noisy images as a result of gamut mapping and separation. This problem was addressed by Samadzadegan and Urban (2013) who reported a significant banding that occurred on separation images as a result of multi illuminant gamut mapping and separation. Therefore, the image quality of the separation images suffers due to the nature of the separation process. On the other hand, a print quality or an image quality of the final print is usually attributed to the process of halftoning.

Well-known source of image quality degradation is noise that can be observed in print as a luminance difference of neighboring dots or in the case of low resolution as a disturbing dot placement on the substrate. Dots overlaps are therefore not desirable and multiple solutions are offered in the literature to solve the problem. The most common one is referred to as Minimal Brightness Variation Rendering (MBVR) by Shaked et al. (1999) which reallocates dots so that the pattern becomes the least perceivable. Other solution would be to maximize dot-off-dot printing within processing block (Lee and Allebach, 2001; Agar and Allebach, 2005; Ortiz Segovia, Bonnier and Allebach, 2012a). However, dot-off-dot algorithms are very computationally expensive (Trager et al., 2011) and rarely used in practice. In Slavuj and Pedersen (2015) a different approach is taken where channel independent halftoning is post processed with so called multichannel Direct Binary Search (MC DBS). This halftoning method takes just fraction of the time used by dot-off-dot algorithms and directly enables it to operate in multichannel printing environment. It is also shown that MC DBS improves image quality in comparison with channel independent (CI) DBS halftoning and that it is a good candidate to enhance spectral reproduction workflow.

All parts of the reproduction system generate noise. There can be noise coming from separation process, whether it is a spectral (Samadzadegan and Urban, 2013) or colorimetric separation (Wang, Aristova and Hardeberg, 2010). Likewise, halftoning in absence of separation can be evaluated for similar image quality attributes (Lee and Allebach, 2001; Ortiz Segovia, Bonnier and Allebach, 2012b). However, all these evaluations do not give a full description of the overall system's noise. In this work we quantify noise of spectral and colorimetric separations and overall noise of the reproduction system; that is of separation and halftoning combined.

The evaluation in this paper is made of the two parts. We first evaluate color accuracy of the reproduction using spectral and colorimetric reproductions, then separation's image quality, and then we evaluate print quality of the spectral versus colorimetric reproduction in combination with different halftoning. Note here that print quality is an image quality metrics applied to the actual print while only image quality is a metric applied to digital image (e.g. image of the ink amounts – separation image).

Color accuracy of the spectral and colorimetric workflows is quantified by measuring of reproduced spectral reflectance or colorimetric values of the textile samples. It is followed by an evaluation of the image quality (with selected noise metric) of spectral and colorimetric separation images. The final comparison is made by halftoning separation images (ink amounts) using different halftoning algorithms, and then applying two image quality metrics that evaluate noise.

2. Methods

The overall description of the method is shown in Figure 1. We have compared the performance of the colorimetric and spectral workflows in terms of color accuracy and print quality for a set of spectral images of natural scenes, a painting and real textile patches. Additionally, separations of both reproduction workflows were compared in terms of the image quality. Three halftoning methods were used to test overall reproduction workflow print quality. The spectral images or reflectance factors, obtained either directly from a database or measured, were firstly used to compute the CIE $L^*a^*b^*$ values under D50 and A illuminants.

The D50 rendering was then gamut mapped to the gamut of the printer. Gamut mapping was therefore the same for colorimetric and spectral workflow and it was done by round-tripping with ICC profile. What was different, was the separation from CIE $L^*a^*b^*$ to the CMYKRGB space of used printer where colorimetric separation was performed with the help of pre-built ICC profile (BToA table) while spectral separation was based on a multi-illuminant separation and spectral gamut mapping algorithm (mapping from illuminant D50 to illuminant A). All colorimetric computations were performed using the 2° standard observer. At this stage, the quality of the two separation methods were evaluated in terms of induced noise in the simulated separation image (before halftoning and printing).

In next phase the separation images (in CMYKRGB space) were halftoned in channel independent manner prior to printing. After printing, color accuracy of the colorimetric and spectral workflows was assessed under both A and D50 illuminants using the measured reflectance factors of selected samples and their respective print reproductions. Halftoning method used for this purpose was CI DBS halftoning method. To finalize our evaluation, we varied halftoning methods applied on separation images and showed image quality score of the final print (or print quality) for selected image quality metrics. Following is the detailed description of the samples used for evaluation, explanation of separation strategies and selected halftoning methods used in this paper, and image quality metrics that were selected for our evaluations.

2.1 Material, printing and measuring equipment

One set of images used for testing were spectral images of natural scenes from the Foster database (Foster et al., 2006) while other set of images was selected from Spectral Image Database for Quality (SIDQ) (Le Moan et al., 2015). In addition, we also used a spectral acquisition of a painting to include an image with smooth gradation. As for the SIDQ images, the spectral image of the painting was acquired using a HySpex line scanning hyperspectral camera VNIR 1600 (Norsk Elektro Optikk AS, Norway). The camera has a spectral resolution of 3.7 nm, interpolated to 10 nm steps for further processing. All selected – acquired images are shown in Figure 2 (encoded in sRGB color space for presentational purpose).

For the evaluation of color accuracy we used homogeneous textile samples made of wool and polyethylene (Figure 3). The dyes in colored fabrics have similar

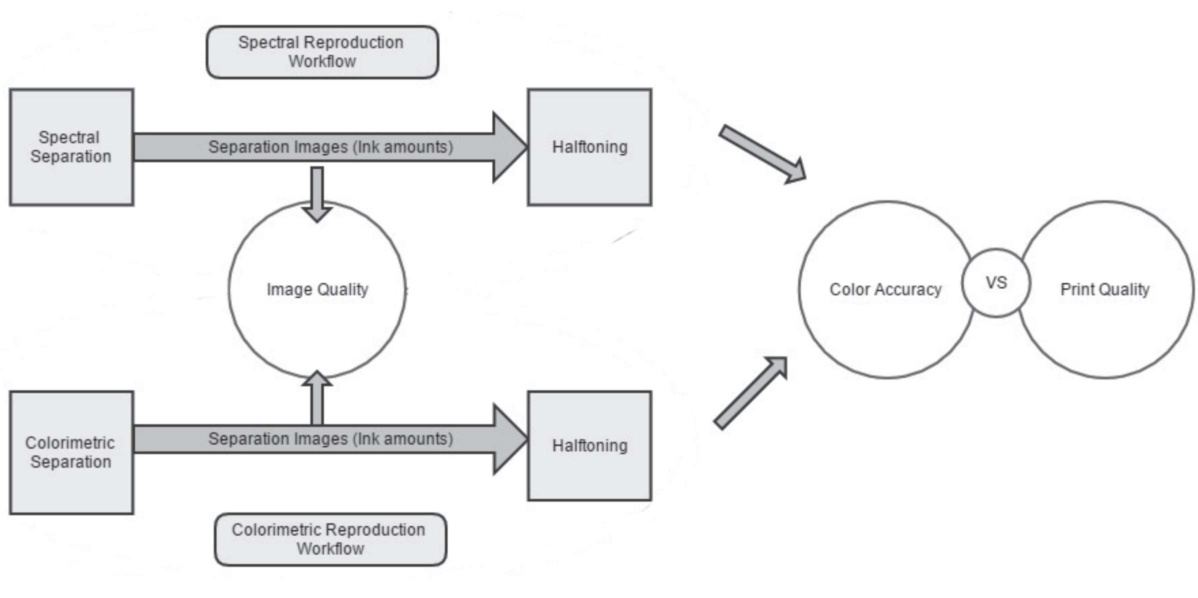

Figure 1: Overview of the analyses done in the paper; spectral and colorimetric workflows are compared in terms of color accuracy and image quality of the final print (print quality)

Figure 2: Spectral images used in experiment: (1) Wool, (2) Painting – section, (3) Flower, (4) Building, (5) Print ramps, (6) Painting – full, (7) Cork, (8) Skin1, (9) Skin2, (10) Orange; (3 and 4) are from Foster database and the others except the painting in (6) are from SIDQ

Figure 3: Textiles sample set used for color accuracy assessment

reflection spectra as the inks used on prints where printability of these reflectances using colorimetric and spectral reproduction is proven to be satisfactory.

The print reproductions were made with a 12 ink Z3200 PS multichannel printer (Hewlett-Packard) using seven Vivera inks (CMYKRGB) that are made for high endurance and large color gamut. For substrate we used HP Artist Matte Canvas which has shown to have optimal absorption balance, large color gamut and pleasing reproductions. The printer was directly controlled by supplying a pre-halftoned 1200 dpi, 7 channel, TIFF binary image, through a Caldera (Caldera, Strasbourg, France) Raster Image Processor (RIP) with all color management features off.

Both the textile samples and their print reproductions were measured with an i1 spectrophotometer (X-Rite, Inc.). The printed images were scanned with an Epson Expression 10 000XL scanner using a custom built ICC profile from a Kodak Q61 IT 8.7/2 target printed on our substrate. All prints were made with a 300 dpi resolution while the scanner resolution was double that of the prints (600 dpi). The scanned images were then converted to CIE $L^*a^*b^*$ space with previously created scanner profile. The scanning method is illustrated in Figure 4 and described in detail by Pedersen et al. (2010).

2.2 Multi-illuminant separation

We used an implementation of a spectral gamut mapping and separation algorithm (Coppel, 2015; Tzeng and Berns, 2000) that follows the work from Urban and Berns (2011). It is based on a sequence of colorimetric mappings within paramer mismatch gamuts. Given a set of illuminants in a prioritized order, the spectral gamut mapping aims at minimizing the color difference between the printer model estimate and the target under other illuminants (second or third in line),

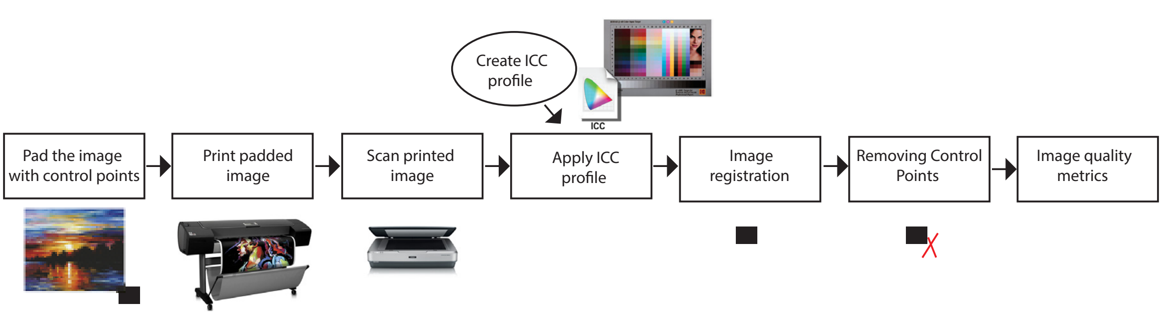

Figure 4: Framework for scanning of the print reproduction

while keeping the difference under the first illuminant below 1 ΔE^*_{ab}. We used ΔE_{94} as a measure of color difference since it is accurate enough for our purpose and less computationally expensive than ΔE_{00}. The printer was modelled with the cellular Yule Nielsen modified Neugebauer (cYNSN) model, described by Wyble and Berns (1999), using four cells. The calibration set included all 4 ink combinations at 5 apparent ink coverages (0–100 % with 25 % step). We considered only 4 ink combinations including K (e.g. CMYK, CKRG or MYKB) since it was observed that 5, 6 or 7 ink combinations do not contribute much to the spectral variability of the printouts (Coppel et al., 2014). In this work, we applied the separation algorithm with D50 as the first illuminant and A as the second illuminant. This means that for each pixel in the images the search was performed for the CMYKRGB combination that leads to $\Delta E_{94} < 1$ under D50 and minimal color difference under A. Note that a gamut mapping was performed under D50 prior to the separation.

2.3 Colorimetric separation

The colorimetric workflow was based on the v4 ICC architecture (ICC, 2010). The ICC profile was made with X-Rite i1Profiler software. We used custom generated chart with 3 000 patches to build a profile which would guarantee high accuracy with acceptable computation time. The profile had a Grey Component Replacement algorithm (GCR) applied but to a lower extent (black starts at 50 % and ends at 100 % with medium GCR level).

2.4 Halftonings

In order to establish a relation between color accuracy (usually associated with color management) and print quality (usually associated with halftoning) of the reproduction, selection of halftoning was restricted to halftoning methods that give the least visible textures and thus high image quality. Therefore the list of selected halftoning methods starts with widely used Floyd Steinberg Error Diffusion (ED) method described by Ulichney (1987), CI DBS developed by Lieberman and Allebach (2000), and channel dependent DBS developed for modern inkjet multichannel printing environment, proposed by Slavuj and Pedersen (2015). The DBS is one of the model based algorithms for halftoning where a printer dot placement model is combined with a model of spatial frequency detection when performing search for optimal solution. Optimization process yields optimal dot distribution in the area of processing (e.g. block of neighboring pixels in the image). The MC DBS uses a hierarchical scale constructed of various dot luminances (Figure 5), starting from a dot of lowest luminance (e.g. of black ink) to the highest luminance dot (yellow ink). Therefore, dots with the lowest luminance are the most visible in contrast to the white paper and their optimal distribution is of highest priority. Each separated channel was firstly halftoned, independently. The four binary images were then summed for identification of the overlaps of CM, CY and MY combinations. These overlaps were replaced with some of RGB inks and the CMY overlaps were changed to one of the BY, RC, or GM complementary color combinations.

2.5 Image and print quality evaluation

As shown in Figure 2, the multi-illuminant (spectral) and the ICC based colorimetric workflows differ only in the separation step. We wanted to evaluate the impact of this separation on perceived image and print quality and of its interaction with subsequent halftoning steps. Noise has many sources but in this work we limited our evaluation to the noise of separation error (e.g. error of interpolation or rounding), pixel-wise processing (in contrast to neighborhood based operations), and halftoning induced noise.

To quantify noise of a reproduction workflow, we used the Noise Quality Measure (NQM) which corresponds to a perceived noise (Damera-Venkata et al., 2000). The NQM was taken from luminance channel only because most of the changes in relation with halftoning are evident there. The metric was computed on the *Y* channel in CIE *XYZ* space, and both original image and scanned print were filtered with HVS model to account for the viewing conditions. The assumed viewing distance was set to 50 cm. For evaluation of the separations we used images number 1–5 and 10 shown in Figure 2. For the image quality of the separation and halftoning, all images from Figure 2 were used. The procedure of the printing, scanning and the metrics application is shown in Figure 4.

To add a halftoning contribution to the noise of a reproduction system, the graininess metric was added (Hains, Wang and Knox, 2003). Graininess is defined as

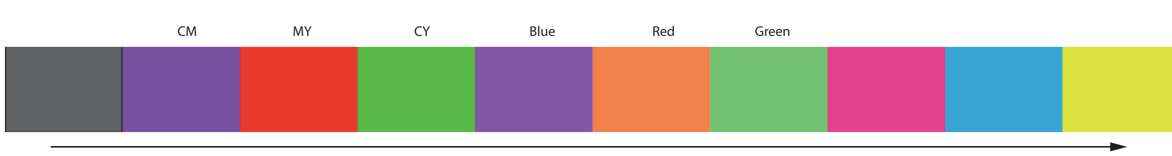

Figure 5: Primary colorants and their overlaps by visibility with decreasing luminance from right to left

aperiodic fluctuations of the optical density at a spatial frequency greater than 0.4 cycles per millimeter in all directions. However, this applies only to monochrome reproductions. For color reproduction, we instead quantify graininess as the standard deviation of the ΔE_{00} differences as proposed by Ortiz Segovia, Bonnier and Allebach (2012b).

3. Results and discussion

3.1 Color accuracy

The CIE $L^*a^*b^*$ values of the textile patches are compared to the gamut of the printer in Figure 6. The sample set had around 30 % samples out of the gamut of the used printer and substrate. The color differences between the textile patches and their reproductions, both spectral and colorimetric are given in Table 1 for both D50 and A illuminants. Color differences in Table 1 point to rather different performance of spectral and colorimetric workflow, where the spectral one was more color accurate. This is true under both illuminations.

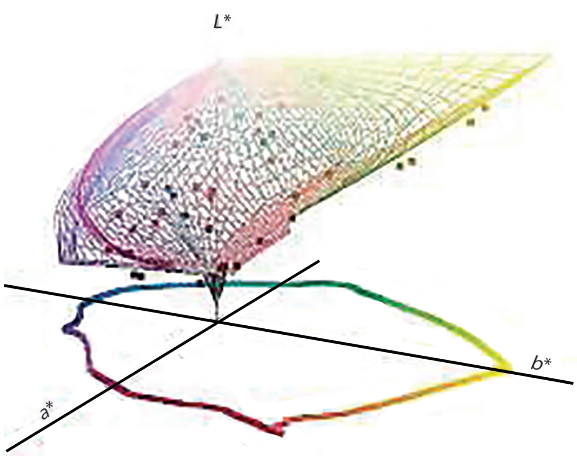

*Figure 6: Gamut plot in D50/2°, CIE L*a*b* space of the HP Z3200 multichannel printer (wireframe) and measurements of textile patches*

3.2 Separation noise analysis

The NQM scores for spectral and colorimetric separations are shown in Figure 7. For the total 5 images used, the ICC separation gave better NQM scores than the spectral separation except for the orange image, which on the other hand had very low score for both separations. Overall, NQM scores were very different for different images, and the difference between different images was larger than the difference between spectral and color separation.

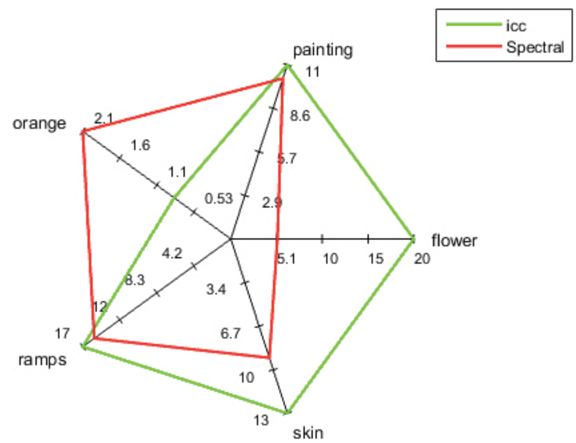

Figure 7: NQM score of spectral and colorimetric separations for five images used

Mean NQM score computed for all images is shown in Table 2. Noise generated in the spectral separation was clearly higher than in the colorimetric separation. From Tables 1 and 2 it is clear that spectral separation had better color accuracy but, because of the choices made in separation process, significantly higher noise, and therefore lower image quality. The source of this noise came mostly as the result of additional gamut mapping (from D50 to A illuminant) but also from constraints imposed to separation.

Table 2: Mean NQM scores of spectral and colorimetric (ICC) separations

Workflow	Mean NQM score
Spectral	6.43
ICC	9.62

Table 1: Color difference between measurements of the textile samples and print reproductions for the spectral and colorimetric (ICC) workflows

	ΔE_{00} at D50				ΔE_{00} at A			
Workflow	Mean	Median	Max	95th %	Mean	Median	Max	95th %
Spectral	4.04	4.32	6.21	5.61	3.89	4.35	6.66	6.14
ICC	8.73	8.00	23.62	18.05	8.29	7.59	23.89	17.84

3.3 Effect of halftoning on print quality

In this part we evaluate image quality performance of different halftoning methods. In fact, it is also a trial to extract a contribution of the halftoning to the overall system's noise. We tried to achieve this by applying different halftoning on noisy spectral separation. First we have compared widely used CI ED with Floyd Steinberg filter with channel dependent MC DBS.

To emphasize the differences, prints were made with 150 dpi resolution. Channel independent ED in combination with spectral separation produced banding artefacts while CI DBS have optimized spatial distribution which reduced banding artefacts. For MC DBS, the same as for CI DBS applies, but it also improved texture uniformity in shadow and dark areas and increased level of detail in these areas as well.

Due to its neighborhood filtering, CI ED created artefacts on already noisy separation images (Figure 8). It showed significant artefacts in light areas of the image passing through the area of subtle gradient (a shadow on the wall). Similar behavior was reported by Gerhardt and Hardeberg (2006) where due to error filter passing through the area of rapid light to dark transitions (noise area), error is accumulated and released toward the end of scan line (assuming raster scanning direction). Other halftoning methods also struggle with noisy spectral separation but it seems that MC DBS gives the least artefacts due to its post processing method. Same is true on more smooth images such as image of the painting (Figure 9), but this comes on the expense of slightly reduced image contrast.

Overall, the results confirmed that halftoning plays a significant role in print quality and that the impact of halftoning is higher for colorimetric workflow, which has smoother or less noisy separation. Although colorimetric separation exhibits significantly less noise as a result of separation, after halftoning step, spectral and colorimetric workflow showed similar noise level. Table 3 provides the mean of the print quality score used to compare spectral and colorimetric workflows with different halftoning applied.

As expected, NQM score is lower than that after separation only, for both spectral and colorimetric workflow.

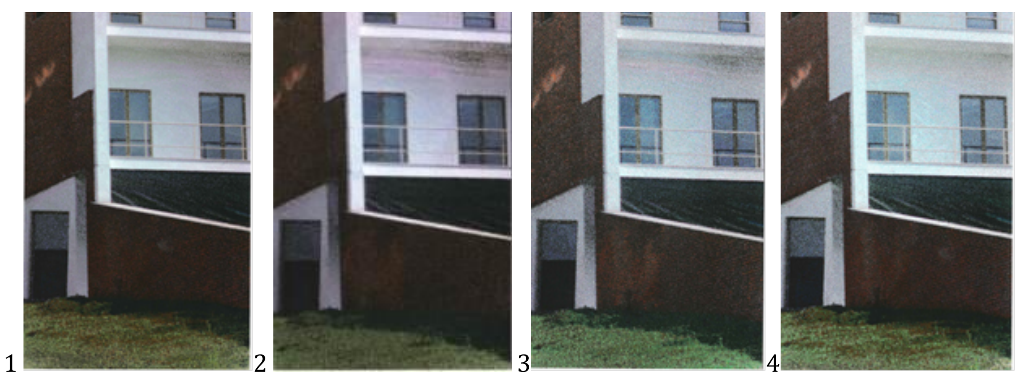

Figure 8: Spectral separation with simulated image (1), channel independent error diffusion (2), channel independent direct binary search (3), multichannel direct binary search (4)

Figure 9: Spectral reproduction of painting using error diffusion halftoning (1) and multichannel direct binary search (2) as multichannel direct binary search replaces overlaps, image on the right looks slightly washed out and with less contrast but it gives smoothness and reduces halftoning noise

The halftoning adds significant perceptual noise which lowers the NQM score, and this is true for all halftoning methods that are evaluated. However, NQM score can be increased by using MC DBS over CI DBS or CI ED.

Table 3: NQM and graininess mean score for all tested images; both colorimetric and spectral separation are combined with all evaluated halftoning methods

Print quality score	NQM	Graininess (halftoning)
Colorimetric + CI ED	5.3	2.8
Colorimetric + CI DBS	6.2	2.5
Colorimetric + MC DBS	7.3	1.6
Spectral + CI ED	4.4	2.9
Spectral + CI DBS	5.8	2.3
Spectral + MC DBS	7.1	1.7

The overall conclusion is that the halftoning has more influence to the NQM score than the separation process (Table 2 and 3). Truly, it is possible to increase the score of the perceptual noise by selection of appropriate halftoning method. The DBS algorithm in all cases shows better performance than ED, both in NQM and graininess score, especially in case of MC DBS.

4. Conclusions

We evaluated image and print quality of a colorimetric and a spectral separation combined with halftoning and their color accuracy. Although spectral separation and halftoning has shown higher color accuracy, the colorimetric separation via commonly used ICC profile combined with halftoning yielded less noise and therefore shown better image quality. Print quality depends mostly on used halftoning but this is even more the case if spectral separation is applied prior to the halftoning. For both colorimetric and spectral workflow, the MC DBS halftoning showed signs of improvement in final print quality. When combined with appropriate halftoning, spectral separation could yield print quality similar to colorimetric separation. As expected, halftoning has much more impact on final print quality, but proper selection of the halftoning algorithm could give an optimal and satisfying reproduction no matter what color management workflow is used.

Acknowledgements

This work was supported by the Marie Curie Initial Training Networks (ITN) CP7.0 N-290154 funding. Special thanks to Caldera who provided the RIP.

References

Agar, A.U. and Allebach, J.P., 2005. Model-based color halftoning using direct binary search. *IEEE Transactions on Image Processing*, 14(12), pp. 1945–1959.

Alsam, A. and Hardeberg, J.Y., 2004. Optimal colorant design for spectral colour reproduction, In: *Color and Imaging Conference, 12th Color and Imaging Conference Final Program and Proceedings*. Scottsdale, Arizona, November 2004. Springfield: Society for Imaging Science and Technology. pp. 157–162.

Coppel, L.G., Le Moan, S., Žitinski Elias, P., Slavuj, R. and Hardeberg J.Y., 2014. Next generation printing – towards spectral proofing. In: N. Enlund and M. Lovreček, eds. *Advances in Printing and Media Technology: Proceedings of the 41st International Research Conference of iarigai*. Swansea, September 2014. Darmstadt: International Association of Research Organizations for the Information, Media and Graphic Arts Industries. pp. 19–24.

Coppel, L.G., 2015, Spectral gamut mapping and ink separation with fluorescing substrates. In: *2015 Colour and Visual Computing Symposium (CVCS 2015)*. Gjøvik, Norway, 25–26 August 2015. Piscataway, NJ, USA: IEEE. pp. 17–20.

Damera-Venkata, N., Kite, T.D., Geisler, W.S., Evans, B.L., and Bovik, A.C., 2000. Image quality assessment based on a degradation model. *IEEE Transactions on Image Processing*, 9(4), pp. 636–650.

Derhak, M.W.; Green, P. and Lianza, T., 2015. Introducing iccMAX: new frontiers in color management. In: *Color Imaging XX: Displaying, Processing, Hardcopy, and Applications: Proceedings of SPIE/IS&T 2015 Electronic Imaging Science and Technology*. San Francisco, CA, USA, 8–12 February 2015. Springfield, VA, USA: IS&T and Bellingham, WA, USA: SPIE. p. 9395–20.

Foster, D.H., Amano, K., Nascimento, S.M.C. and Foster, M.J., 2006. Frequency of metamerism in natural scenes. *Journal of the Optical Society of America A*, 23(10), pp. 2359–2372.

Gerhardt, J. and Hardeberg, J.Y., 2006. Spectral colour reproduction by vector error diffusion. In: *Conference on Colour in Graphics, Imaging, and Vision: CGIV 2006 Final Program and Proceedings*. Leeds, UK, June 2006. Springfield: Society for Imaging Science and Technology. pp. 469–473.

Hains, C., Wang, S.-G. and Knox, K., 2003. Digital color halftones. In: G. Sharma, ed. 2003. *Digital Color Imaging Handbook*. Boca Raton: CRC Press. Ch. 6, pp. 385–490.

ICC, 2010. *Specification ICC.1:2010 (Profile version 4.3.0.0): Image technology colour management – Architecture, profile format, and data structure*. [pdf] International Color Consortium. Available at: <http://www.color.org/specification/ICC1v43_2010-12.pdf> [Accessed April 2017].

Lee, J.H., and Allebach, J.P., 2001. CMYK halftoning algorithm based on direct binary search. In: *9th IS&T/SID Color Imaging Conference: Color Science and Engineering: Systems, Technologies, Applications.* Scottsdale, Arizona, USA, 6–9 November 2001. Springfield, USA: Society for Imaging Science and Technology.

Le Moan, S., George, S., Pedersen, M., Blahová, J., and Hardeberg, J.Y., 2015. A database for spectral image quality. In: M.-C. Larabi and S. Trianttaphillidou, eds. *Proc. SPIE 9396, Image Quality and System Performance XII*. San Francisco, CA, USA, 08 February 2015. Bellingham, WA, USA: SPIE. p. 25.

Lieberman, D.J. and Allebach, J.P., 2000. A dual interpretation for direct binary search and its implications for tone reproduction and texture quality. *IEEE Transactions on Image Processing*, 9(11), pp. 1950–1963.

Morovič, P., Morovič, J., Arnabat, J. and Garcia-Reyero, J.M., 2012. Revisiting spectral printing: a data driven approach. In: *20th Color and Imaging Conference Final Program and Proceedings*. Los Angeles, CA, 12–16 November 2012. Springfield, USA: Society for Imaging Science and Technology. pp. 335–340.

Ortiz Segovia, M.V., Bonnier, N. and Allebach, J.P., 2012a. Ink saving strategy based on document content characterization and halftone textures. In: R. Eschbach, G.G. Marcu and A. Rizzi, eds. *Proceedings SPIE 8292, Color Imaging XVII: Displaying, Processing, Hardcopy, and Applications*. Burlingame, CA, USA, 25 January 2012. Bellingham, WA, USA: SPIE.

Ortiz Segovia, M.V., Bonnier, N. and Allebach, J.P., 2012b. Print quality analysis for ink-saving algorithms. In: F. Gaykema and P.D. Burns, eds. *Proceedings SPIE 8293, Image Quality and System Performance IX*. Burlingame, CA, USA, 24 January 2012. Bellingham, WA, USA: SPIE.

Pedersen, M., Bonnier, N., Harderberg, J.Y., and Albregtsen, F., 2010. Attributes of image quality for color prints. *Journal of Electronic Imaging*, 19(1), pp. 11–16.

Samadzadegan, S. and Urban, P., 2013. Spatially resolved joint spectral gamut mapping and separation. In: *21st Color and Imaging Conference Final Program and Proceedings*. Albuquerque, New Mexico, USA, 4–8 November 2013. Springfield, USA: Society for Imaging Science and Technology. pp. 2–7.

Shaked, D., Arad, N., Fitzhugh, A. and Sobel, I., 1999. *Ink Relocation for Color Halftones, HPL-96-127(R.1)*. [pdf] Hewlett Packard. Available at: <http://www.hpl.hp.com/techreports/96/HPL-96-127R1.pdf> [Accessed April 2017].

Slavuj, R., Marijanovic, K. and Hardeberg, J.Y., 2014. Colour and spectral simulation of textile samples onto paper: a feasibility study. *Journal of the International Colour Association*, 12, pp. 36–43.

Slavuj, R. and Pedersen, M., 2015. Multichannel DBS halftoning for improved texture quality. In: R. Eschbach, G.G. Marcu and A. Rizzi, eds. *Proceedings SPIE 9395, Color Imaging XX: Displaying, Processing, Hardcopy, and Applications*. San Francisco, CA, USA, 8 January 2015. Bellingham, WA, USA: SPIE.

Taplin, L.A., 2001. *Spectral Modeling of a Six-Color Inkjet Printer*. MSc Thesis. Rochester Institute of Technology.

Trager, B., Wu, C.W., Stanich, M. and Chandu, K., 2011. GPU-enabled parallel processing for image halftoning applications. In: *2011 IEEE International Symposium on Circuits and Systems (ISCAS)*, Rio de Janeiro, Brazil, 15–18 May 2011. Bellingham, WA, USA: SPIE. pp. 1528–1531.

Tzeng, D.-Y. and Berns, R.S., 1998. Spectral-based ink selection for multiple-ink printing I. colorant estimation of original objects. In: *Color and Imaging Conference, 6th Color and Imaging Conference Final Program and Proceedings*. Springfield, USA: Society for Imaging Science and Technology. The Sun Burst Resort Scottsdale, Arizona, 17–20 November 1998. Springfield, USA: Society for Imaging Science and Technology. pp. 106–111.

Tzeng, D.-Y. and Berns, R.S., 2000. Spectral-based six-color separation minimizing metamerism. In: *IS&T/SID Eighth Color and Imaging Conference*. The Sun Burst Resort Scottsdale, 7–10 November 2000, Springfield, USA: Society for Imaging Science and Technology. pp. 342–347.

Ulichney, R., 1987. *Digital Halftoning*. Cambridge, MA: MIT Press.

Urban, P. and Berns, R.S., 2011. Paramer mismatch-based spectral gamut mapping. *IEEE Transactions on Image Processing*, 20(6), pp. 1599–1610.

Wang, Z., Aristova, A. and Hardeberg, J.Y., 2010. Quantifying smoothness of the LUTs-based color transformations. In: *ICIS 2010, 31st International Congress on Imaging Science (ICIS): Imaging Science and Technology in the Digital Era*. Beijing, China, 13–15 May 2010. [online] Available at: <www.colorlab.no/content/download/28373/325564/version/1/file/Wang2010a.pdf> [Accessed April 2017].

Wyble, D.R. and Berns, R.S., 1999. A critical review of spectral models applied to binary color printing. *Color Research & Application*, 25(1), pp. 4–19.