Perceived Quality of Printed Images on Fluorescing Substrates under Various Illuminations

Steven LE MOAN, Ludovic GUSTAFSSON COPPEL
Gjøvik University College, Norway

ABSTRACT

We design a quality assessment workflow to measure the perceived quality of prints across illuminants, while accounting for the fluorescence of the substrate as well as the ink UV absorption. Given an input multispectral image, we simulate the output of a CMYKRGB printer by means of a spectral gamut mapping and an extended cellular Yule-Nielsen modified Spectral Neugebaeur model allows us to account for both paper fluorescence and ink UV absorption. We demonstrate the relevance of considering these effects as they lead to substantial changes in the perceived image difference across illuminants. These findings are of particular interest for soft- and hard-proofing applications in spectral printing workflows.

1. INTRODUCTION

In printing, colorimetric workflows ensure that the print looks as good as possible under one specific illuminant (typically daylight), but without accounting for the fact that colours, and therefore colour differences, may change drastically from one illuminant to another (Le Moan, 2014). This effect is referred to as metamerism: two objects may seem to have the same colour under one light, but not under another. There are several applications that require having some control over the quality of a print under various viewing conditions, and for which colorimetric workflows are therefore not appropriate. Furniture catalogues or paint swatch books are among these applications as it is important that customers have a good idea of the colour of a piece of furniture or a particular pigment under the light of their living room for example. Only in a spectral workflow is one able to have such control, by using the pixels' spectral reflectance factor, rather than e.g. RGB or CIELAB values. Controlling quality in such workflows is however challenging due to the potentially large number of viewing conditions that need to be considered (e.g. all kinds of domestic lights) and because distances between pixels (such as the Euclidean distance) carry very little meaning in terms of perception, when computed in the "reflectance domain" (as opposed to the "colour domain").

There is a variety of so-called image-difference metrics in the literature, that aim at predicting the perceived difference between an original image and its reproduction (e.g. a simulated print), using features such as structure, contrast, detail visibility, etc… However, most of these metrics work with three-dimensional colour spaces optimised for one illuminant only. Recently, Le Moan and Urban (2014) proposed a scheme to extend one of these metrics, called CID, for spectral workflows by using a set of representative illuminants and combining the CID scores between the renderings obtained for each of them. The resulting multi-illuminant metric is referred to as Spectral Image Difference (SID) and it has been reported to significantly outperform traditional spectral difference metrics such as the root-mean square error (RMSE) when compared to subjective data. Although SID can be applied to control quality within a spectral printing workflow, it fails to consider paper fluorescence and its impact on the perceived quality of the print. It is well known however that fluorescing whitening agents (FWA) are used to make papers appear whiter (Coppel, 2012). These dyes absorb UV radiation and re-emit light in the blue region of the electromagnetic spectrum. In this study, we design a quality assessment workflow to investigate the influence of paper fluorescence on perceived image quality. Given an input multispectral image, we simulate the output of a CMYKRGB printer by means of a spectral gamut mapping (Urban, 2011) and an extended cellular Yule-Nielsen modified Spectral Neugebaeur model allows us to account for both paper fluorescence and ink UV absorption. We demonstrate the relevance of considering these effects as they lead to substantial changes in the perceived image difference across illuminants. These findings are of particular interest for soft- and hard-proofing applications in spectral printing workflows.

2. QUALITY ASSESSMENT WORKFLOW

2.1 Spectral separation and gamut mapping

Urban and Berns (2011) introduced a spectral gamut mapping strategy, based on a sequence of colorimetric mappings within paramer-mismatch gamuts. For example, given two illuminants γ_1 and γ_2 and given that γ_1 should be prioritized over γ_2, the spectral mapping aims at minimizing the colour difference under γ_2 while keeping the difference under γ_1 unnoticeable (i.e. lower than JND – Just Noticeable Difference). We used this approach and considered a cellular Neugebauer spectral model calibrated for an HP-Z3200 printer in the 7-channel CMYKRGB mode with an almost non-fluorescing EFI offset proof 9200 semimatt 200 g/m^2 paper. Note that, as in Urban and Berns' study, only 4-ink combinations including K were considered (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 and are therefore of limited interest in the present study (in other words, most of the spectral gamut can be described with 4-ink combinations only).

2.2 Fluorescing substrate

When fluorescence is present, the reflectance factor is no longer independent of the illumination and must be estimated for each illuminant. For a halftone print on a fluorescing substrate, the incident light is first partly absorbed by the ink dots before it changes wavelength due to the fluorescence process, and is finally partly absorbed at that longer wavelength by the ink dots. Assuming opacity in the excitation wavelength band and introducing an equivalent scalar transmittance t'_j of the Neugebaur Primaries (NP) in the excitation band, Hersch (2014) proposed an extension of the spectral Yule-Nielsen modified Neugebauer model (Wyble, 2000) expressing the total reflectance factor R^{tot} from measurement of the substrate and NPs in one illumination without excitation radiation and in one illumination with excitation radiation:

$$R^{\mathrm{tot}}(\lambda) = \left[R_{\mathrm{p}}^{\mathrm{tot}}(\lambda) - R_{\mathrm{p}}^{*}(\lambda)\right]\left[\sum_{j=1}^{N} a_j t'_j\right]\left[\sum_{j=1}^{N} a_j t_{\mathrm{j}}(\lambda)^{\frac{1}{n}}\right]^{n} + R^{*}(\lambda)\,, \quad (1)$$

where $R_{\mathrm{p}}^{\mathrm{tot}}$ is the reflectance factor of the substrate in an illumination including the excitation wavelengths, R_{p}^{*} is the reflectance factor of the substrate in an illumination without fluorescence excitation, $t_{\mathrm{j}}(\lambda)$ is the transmittance of NP *j* at emission wavelength λ, R^{*} is the reflectance factor of the printed substrate without fluorescence excitation, and $N = 2^4$ (four inks) is the number of NPs. The Yule-Nielsen model is applied with factor *n* to account for the lateral light propagation within the substrate (optical dot gain).

Equation (1) states that the reflectance factor of a halftone is the sum of the reflectance of the halftone without excitation radiation (R^*) and of the paper substrate's fluorescent component attenuated by the weighted t'_j in the excitation band and the weighted t_j in the emission band of the FWA. The apparent transmittances in the excitation band t'_j are obtained by spectrally fitting Eq. (1) with *N*=1 to the measured reflectance of fulltone individual NP ($a_j = 1$) with (R_j^{tot}) and without (R_j^*) fluorescence excitation. Two i1 spectrophotometers (X-rite Inc.), with and without UV cut-off filter were used to determine t'_j and $t_\mathrm{j} = \left(R_j^*/R_\mathrm{s}^*\right)^{1/2}$ of the inks when printed on a fluorescing substrate whose fluorescent component was measured in the same way. We propose here to determine the paper's fluorescent component in different illuminations from the Donaldson matrix $D(\lambda_1, \lambda_2)$, which gives the bispectral reflectance from all excitation wavelengths λ_1 to all emission wavelength λ_2. From this matrix we computed the fluorescent component of the reflectance factor of the paper according to (Zwinkels, 1999),

$$R_\mathrm{p}^{\mathrm{tot}}(\lambda_2|E) - R_\mathrm{p}^*(\lambda_2) = \frac{1}{E(\lambda_2)} \sum_{\lambda_1<\lambda_2} D(\lambda_1, \lambda_2) E(\lambda_1), \quad (2)$$

where *E* is the spectral power distribution (SPD) of the illuminant. Note that, in practice, FWA tend to decrease $R_\mathrm{p}^*(\lambda_2)$ in the 400-420nm band (Coppel, 2011) but this effect is neglected in this study. It is also worth noting that the fluorescent component depends on this SPD in the emission band of the FWA. This means that two illuminants that have the same SPD in the excitation band do not necesseraly lead to the same fluorescent component (Coppel, 2013). The Donaldson matrix of a typical paper sample with 18 kg/T FWA measured with a bi-spectrophotometer (Coppel, 2011) was used here.

Once the ink surface coverages are determined by the spectral separation and gamut mapping for the non-fluorescence case, Eq. (1) is used to simulate the printed spectral images with fluorescence under illuminants CIED65 and CIEA. Figure 1 shows the relectance factor of the unprinted and fulltone patches in the different illuminants.

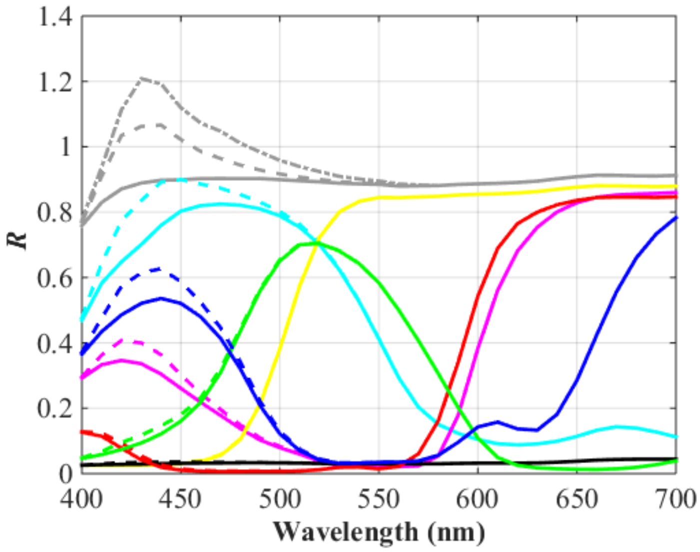

Figure 1. Measured reflectance factors R of the process inks and paper without fluorescence (solid) and simulated R with fluorescence in illuminant CIEA (dash) and CIED65 (dash-dot, only bare paper). The inks are represented by their respective colours. Note that light tones and ink combinations with only cyan, blue and magenta are the most subject to colour shifts due to fluorescence.

3. SPECTRAL IMAGE DIFFERENCE

In order to evaluate the perceived quality of the simulated prints, we used the Spectral Image Difference metric (Le Moan, 2014), with only the two illuminants under consideration. This metric evaluates the perceived image difference under each illuminant and computes the weighted mean value as the final score. Note that it uses a chromatic adaptation transform in order to account for the ability of our visual system to adjust to various viewing conditions. The resulting score was shown to correlate with human judgement to a great extent. For this particular study, we used the most recent implementation of the CID metric - on which SID is based - referred to as MSiCID (*Multi-Scale improved* CID) (Le Moan, 2015). Incidentally, we renamed the SID metric as iSID (*improved* SID). We define it as follows:

$$\mathrm{iSID}(\mathbf{I}_1;\mathbf{I}_2) = \alpha \mathrm{MSiCID}\left(\mathbf{i}_{1,D65};\mathbf{i}_{2,D65}\right) + \beta \mathrm{MSiCID}\left(\mathbf{i}_{1,A};\mathbf{i}_{2,A}\right), \quad (3)$$

where $\mathbf{I}_1$ and $\mathbf{I}_2$ are two spectral images, $\mathbf{i}_{x,\gamma}$ is the rendering of $\mathbf{I}_x$ for illuminant γ and α and β are weighting coefficients. We considered that CIED65 should be prioritized over CIEA as daylight is still the most used reference illuminant in many printing applications. Consequently, we used the following coefficients: $\alpha = 0.75$ and $\beta = 0.25$.

3. RESULTS

We used the 16 natural scenes from the two Foster hyperspectral image databases (Nascimento, 2002). They depict natural scenes (vegetation, urban areas…) and contain between 30 and 32 spectral channels, sampling the visible range of wavelength from 400 to 720nm. However, in order to fit the characteristics of our printer model (see Section 2.2), all images were modified to be in the range 400-700nm. For images whose spectral ranges starts at 410nm, the band at 400nm was assumed to be equal to the one at 410nm.

Table 1 gives the mean, standard deviation and maximum iSID scores obtained when comparing the simulated prints with and without fluorescence. Note that iSID scores range from 0 (no difference) to 1 (largest measurable difference). Figure 2 shows an example of images rendered for CIED65, with and without considering the fluorescence phenomenon. Figure 3 shows the DE2000 pixel-wise colour-difference maps for CIED65 and CIEA for one of the 16 spectral images considered in this study, for illustrative purposes. What we believe is particularly noteworthy here is that not considering fluorescence will likely result in a perceivable difference in the final print, up to 0.122 iSID units on the data tested, which is considerably high.

Table 1. Obtained iSID scores on each scene of the Foster database, between simulated prints with and without fluorescence and ink UV absorption (respectively $\mathbf{I}_{\mathrm{fluo}}$ *and* $\mathbf{I}_{\mathrm{no\_fluo}}$*).*

	$\mathrm{iSID}\left(\mathbf{I}_{\mathrm{fluo}};\mathbf{I}_{\mathrm{no\_fluo}}\right)$
Average	**0.057**
Standard deviation	**0.034**
Maximum	**0.122**

Figure 2. Simulated prints, without (left) and with (right) considering fluorescence and ink UV absorption, for CIED65. Note how these phenomena change particularly the colour of the flower petals, which consist mainly of magenta ink.

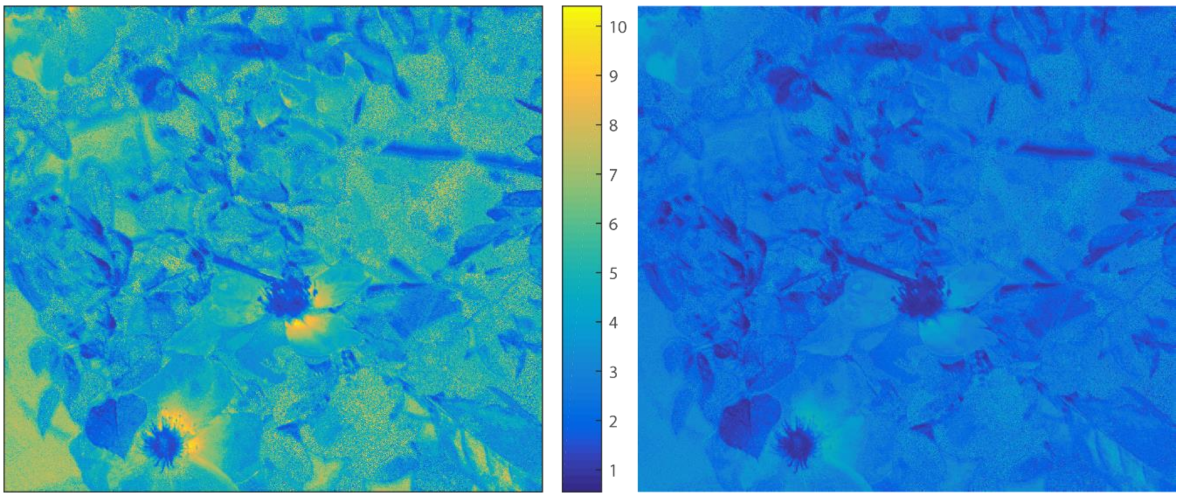

Figure 3. DE2000 colour-difference maps for CIED65 (left) and CIEA (right). Note that daylight, which contains more energy in the UV wavelengths and therefore engenders more fluorescence, yields colorimetric errors larger than 10 DE2000 for this particular image

4. CONCLUSIONS

We designed a quality assessment workflow to measure the perceived quality of prints across illuminants, while accounting for the fluorescence of the substrate as well as the ink UV absorption. Given an input multispectral image, we simulated the output of a CMYKRGB printer by means of a spectral gamut mapping and an extended cellular Yule-Nielsen modified Spectral Neugebaeur model allowed us to account for both paper fluorescence and ink UV absorption. We demonstrated the relevance of considering these effects as they lead to substantial changes in the perceived image difference across illuminants.

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REFERENCES

Coppel, L.G, Anderson A, Edström P. and Kinnunen J. 2011. *Limitations in the Efficiency of Fluorescent Whitening Agents in Uncoated Paper*. Nordic Pulp Paper Research Journal, 26(3), 319–328.

Coppel, L.G., 2012. *Whiteness and Fluorescence in Layered Paper and Board*. Doctoral Thesis No. 138, Mid Sweden University.

Coppel, L.G., Andersson M., Norberg O. and Lindberg S. 2013. *Impact of Illumination Spectral Power Distribution on Radiance Factor of Fluorescing Materials*, IEEE Proc. Colour and Visual Computing Symposium (CVCS).

Hersch, R.D. 2014. *Spectral Neugebauer-based Color Halftone Prediction Model Accounting for Paper Fluorescence*, Applied Optics 53(24), 5380–90.

Le Moan, S. and Urban, P., 2014. *Image-Difference Prediction: From Color to Spectral*, IEEE Transactions on Image Processing 23(5) 2058-2068.

Le Moan, S. and Urban, P. 2015. *Evaluating the Multi-scale iCID Metric*, IS&T/SPIE Image Quality and System Performance XII, 9396, 38.

Nascimento, S.M.C., Ferreira, F.P., and Foster, D.H. 2002. *Statistics of Spatial Cone-excitation Ratios in Natural Scenes*, Journal of the Optical Society of America A, 19(8), 1484–1490.

Urban, P. and Berns, R.S. 2011. *Paramer Mismatch-based Spectral Gamut Mapping*, IEEE Transactions on Image Processing 20(6), 1599-1610.

Wyble, D.R. and Berns, R.S. 2000. *A Critical Review of Spectral Models Applied to Binary Color Printing*, Color Research and Application, 25(1), 4-19.

Zwinkels, J.C. and Gauthier, F. 1999. *Instrumentation, standards, and procedures used at the National Research Council of Canada for high-accuracy fluorescence measurements*, Anal. Chim. Acta, 380, 193–209.

Address: The Norwegian Colour and Visual Computing Laboratory,
Gjøvik University College, Teknologivegen 22, 2815 Gjøvik, NORWAY
E-mails: steven.lemoan@gmail.com, ludovic.coppel@hig.no