Substrate Fluorescence: Bane or Boon?

Raja Bala, Reiner Eschbach, Xerox Research Center Webster; Yonghui Zhao, Rochester Institute of Technology, Rochester, New York

Abstract

Substrates found in standard digital color printing applications frequently contain optical brightening agents. These agents fluoresce under UV light, thus increasing substrate reflectance in the short wavelength regime. The fluorescence phenomenon poses a considerable challenge in standard color management applications. This research presents a method of beneficially exploiting this phenomenon for a different application, namely watermarking. Information can be embedded in a printed color image that is perceptually invisible under normal illumination, and revealed via substrate fluorescence under UV illumination. The watermarking problem is formulated as an optimization problem that seeks pairs of colors exhibiting a close match under normal light, while producing visible luminance contrast under UV light. Models for predicting color under normal and UV light are described, and several successful watermarking examples are shown. From a practical standpoint, the approach requires no special colorants or media, and therefore can be offered at no extra cost to the user. Decoding of the watermark is easily accomplished with a common portable UV lamp.

Introduction

It is well known that a large fraction of substrates used in digital color printing contains optical brightening agents (OBAs). These agents increase the perceived paper brightness via fluorescence, whereby incident light in the ultraviolet (UV) regime is converted into light reflected in the short-wavelength (blue) regime of the spectrum. This in turn increases the "blueness", and subsequently the perceived "whiteness" of the substrate. Fig. 1 shows the spectral reflectance of typical substrates used in digital printing, with and without OBAs. Daylight (D50) illumination was used to generate these curves. It is evident that the light source has a UV component, and the resulting increase in reflectance in the short wavelength regime brought about by fluorescence is also immediately apparent.

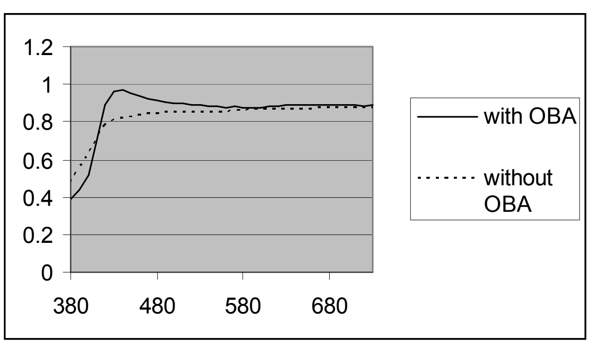
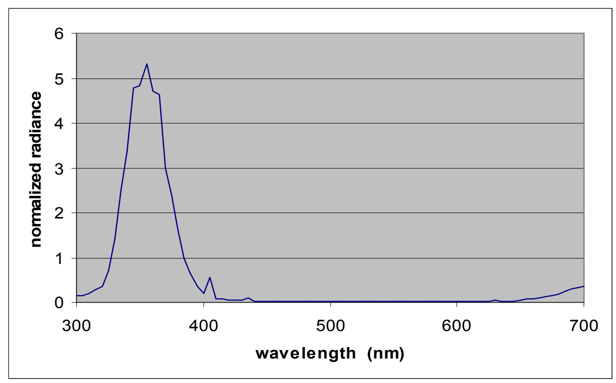


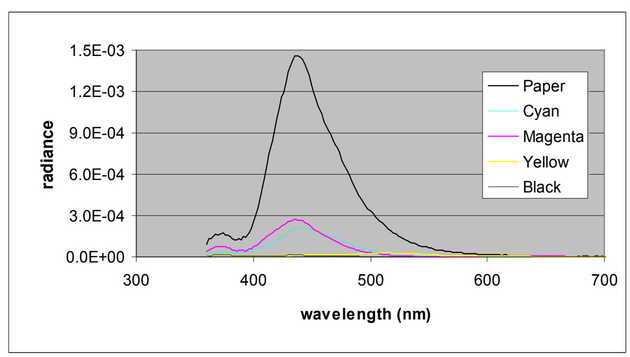
Figure 1: Spectral reflectance of standard digital printing substrate with (solid) and without (dashed) OBAs.

Substrate fluorescence can pose a significant challenge for color reproduction, and is currently a source of considerable debate in the color management community [1]. The basic challenge is that the UV excitation in common light sources can vary noticeably, thus making it impossible to predict the extent of paper fluorescence and the colorimetry of the resulting print in a given viewing environment. A common approach to address this problem is to use a UV cut-off filter when making spectrophotometric measurements for device characterization [1].

When we commenced our study of this problem, however, serendipity took us down a different path. If we consider the extreme, albeit contrived scenario where the illuminant contains solely UV excitation, some interesting effects come to play. Fig. 2(a) shows the spectral power distribution of pure UV illumination found in a GretagMacBeth Spectralight III lightbooth (the data was obtained from GretagMacBeth Product Support).



(a)



(b)

Figure 2 (a) UV light spectral power distribution (b) radiance of UV light reflected from colorants printed on optically brightened paper.

The UV excitation band exhibits a broad peak at 360 nm. An optically brightened substrate was selected, and patches of solid C, M, Y, K were printed using a Xerox DocuColor 8000 laser printer. The substrate was placed in the lightbooth under the UV illumination, and the reflected spectral radiance was measured with a PhotoResearch 705 spectroradiometer. The radiance plots are shown in Fig. 2(b). We note first the strong substrate fluorescence, with a broad UV emission peak at 438 nm. The black colorant absorbs strongly at all wavelengths, as expected. Cyan and magenta are ideally supposed to be transparent at short wavelengths, but as is well known, these colorants exhibit strong unwanted absorptions in both the short visible and UV regimes. Yellow exhibits strong absorption at short wavelengths, and thus reflects very little light in a substantial portion of the fluorescence emission band. Finally observe that while the shapes of the spectral radiances of C, M and Y are vastly different under normal light (after all this is what yields a rich color gamut in subtractive color mixing), the corresponding spectral shapes under UV light are very similar. Essentially they are attenuated versions of the bare substrate reflectance. This would lead us to believe that for colors viewed under UV light, the visual system perceives primarily lightness-darkness variations, and exhibits little acuity in the hue and chroma dimensions. This is illustrated in Fig. 3 for a wide range of mixed colorant patches. An interesting observation from Fig. 3 is that yellow (marked by the green circles) is a bright color under normal light, since it is highly transparent in the middle and long wavelengths. However it becomes considerably darker than the substrate under UV light.

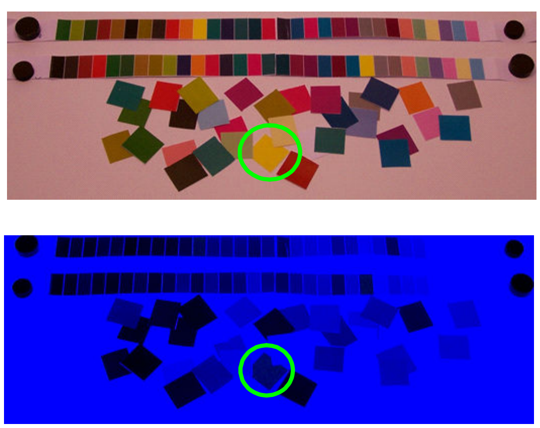


Figure 3 CMYK patches printed on fluorescent substrate and viewed under D50 illuminant (top) and UV light (bottom). Yellow patch is marked by the green circle. Images were captured with a Kodak DX6340 digital camera.[1]

The above scenario demonstrates how a fluorescent substrate viewed under UV light presents a rather extreme case of illuminant metamerism. This leads us to the question: Could substrate fluorescence, which has been a bane of color management, actually be exploited beneficially in a data hiding application such as watermarking? The idea would be to create certain patterns within an image which would be hidden when viewed under normal illumination, but revealed when viewed under pure UV light. Note that the use of metamerism to create special effects in prints has been shown by others [2]. The aspect that distinguishes our work is the fact that we explicitly incorporate a critical property of the substrate, namely fluorescence.

Substrate Fluorescence for Data Encryption

The general notion of using fluorescence in image and document watermarking is not new. Security features found on e.g. banknotes and passports employ fluorescence to reveal special signatures when viewed under UV light. However, what is common to these applications is that the fluorescing agents are added to the inks, rather than the substrate. These specialty inks are costly, and are only economically viable for long runs or for documents of very high value. Our proposal is to accomplish the optical inverse of the standard approach. Namely, instead of adding special fluorescing agents into the colorants, we will selectively subtract the fluorescence already found in standard digital media by printing standard C, M, Y, K colorants. This allows us to offer a fluorescence based security feature while incurring *no* additional cost by way of special printing materials.

Figure 4 shows digital camera images of a simple watermarking example created with optically brightened substrate and standard electrophotographic colorants. The lower half of the image has a text string embedded within a noisy background. The latter comprises a mosaic of two colors: 50% cyan and 50% magenta, arranged as a white noise pattern. The text string is encoded purely within the yellow separation of the image. The modulation in yellow is difficult to discern under normal light, due to the low luminance contrast, and also from the fact that the white noise cyan-magenta background serves as a distraction pattern. Under UV light, the yellow text exhibits strong contrast with respect to the background, thus becoming visible. In this example, the watermark is an identification number on a concert ticket (shown also as visible text in the upper portion).

Figure 4. Fluorescence watermark example seen under normal light (left) and UV light (right). The alpha-numeric sequence seen in the upper portion has been duplicated as a watermark in the lower portion, and should be revealed in the right-hand image.

Figure 5 is another example wherein the text and background are simply created with two different levels of yellow colorant. This example nicely illustrates how the contrast of the yellow with respect to paper increases dramatically under UV light. It also demonstrates how chrominance modulation under normal light is converted into luminance modulation under UV light. Thus the UV viewing condition invokes a different human contrast

[1] No camera characterization or appearance modeling was applied to the digital camera pictures, since the raw images show the intended effects on a nominal display.

sensitivity mechanism, and we are able to see finer detail (i.e. smaller text).

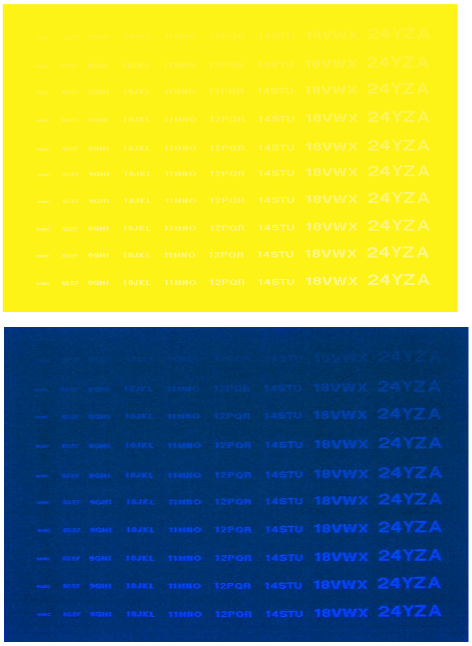


Figure 5 Text and background created with two different levels of yellow, viewed under normal light (top) and UV light (bottom).

To quantify the contrast induced by the yellow colorant, several luminance measurements were made of solid yellow vs. plain substrate used in the DocuColor12 printer. Two substrates were selected: Substrate 1 contains a large amount of optical brightener, and Substrate2 contains very little optical brightener. Luminance measurements were made under three illuminants: i) D50 ii) UV, iii) D50 with a standard blue Wratten filter. The latter was intended to represent a known practice of using the blue channel to identify the presence of yellow dots on paper. The luminance ratio Y_{paper}/Y_{yellow} was used as a simple measure of contrast exhibited by the yellow colorant. The data is summarized in Table 1. Clearly the case of yellow on brightened paper under UV illumination yields the greatest contrast.

Table 1: Luminance contrast of yellow as a function of illuminant and substrate fluorescence

	Y_{paper}/Y_{yellow}	
	Substrate 1 (high OBA)	**Substrate 2** (low OBA)
D50 (Daylight)	1.23	1.15
UV	12.7	1.61
D50 with blue filter	6.89	5.09

A general framework for fluorescence-based watermarking

While the examples in Fig. 4 and 5 were derived from simple intuition on colorant absorption characteristics, we seek a more general and rigorous formulation of the fluorescence watermarking problem. In the simplest case, we have a two-level watermark, where one color serves as a flat background, and the other color is used to render the watermark as e.g. an alphanumeric text string. The goal is to derive two CMYK colorant combinations, C_1 and C_2, which have the property that the resulting printed colors are similar when viewed under normal light, but of sufficient contrast when viewed under UV illumination.

More formally, let $f_n(C)$ be the printer model function that relates CMYK to perceived CIELAB color under normal illumination. Let $f_{uv}(C)$ be the corresponding printer model that relates CMYK to perceived color under UV light. Further, let $D_n(f_n(C_1), f_n(C_2))$ denote a color difference metric between the two colors as perceived under normal viewing conditions. $D_{uv}(f_{uv}(C_1), f_{uv}(C_2))$ is the corresponding color difference under UV light. Given an initial C_1, the corresponding C_2 can be solved by the following optimization problem:

$$C_2 = \arg\min \{ D_n(C_1, C_2) \}, \text{ subject to } D_{uv}(C_1, C_2) > T_1 \quad (1)$$

where T_1 is an empiricially determined threshold for sufficient contrast under UV light. Here we drop the terms f_n and f_{uv} for brevity, with the understanding that the functional relationship is implied. An alternative formulation would be to maximize luminance contrast under UV subject a color match within tolerance under normal light:

$$C_2 = \arg\max \{ D_{uv}(C_1, C_2) \}, \text{ subject to } D_n(C_1, C_2) < T_2 \quad (2)$$

The problem can also be viewed as a pareto-optimization problem, that attempts to achieve two competing goals:

$$C_2 = \arg\min \{ \alpha_1 D_n(C_1, C_2) - \alpha_2 D_{uv}(C_1, C_2) \} \quad (3)$$

where α_1 and α_2 are weights that trade off the relative importance of matching colors under normal light vs. achieving sufficient contrast under UV light. The various components of this framework are now discussed in greater detail.

Printer model for normal lighting

This function is essentially the printer characterization that relates CMYK to CIELAB, measured under normal viewing conditions. Any of the well known techniques can be applied, such as the spectral Neugebauer model [3] or empirical data fitting methods [4].

Printer model for UV lighting

The more interesting case is the printer characterization for UV illumination. In principal, any of the techniques used for the normal viewing condition can be applied here, the only practical difference being the measurement of the characterization targets, which must be done for pure UV illumination. Recall that simple spectral reflective measurements made by a spectrophotometer will not properly account for substrate fluorescence. The most straightforward approach is to place a characterization target of known CMYK values under UV light and measure the spectral radiance emanating from each patch with a spectroradiometer. The radiance is then readily converted to CIEXYZ and CIELAB coordinates. While this approach is accurate, it suffers from the drawback that radiometric measurement can be extremely tedious and time-consuming. A simpler alternative would be measure only the 16 solid CMYK overprints, and ramps of pure C, M, Y, K and derive a Neugebauer model from this data. However even this approach can be time consuming, thus motivating the need for even simpler models.

Recall from our earlier discussion that the primary dimension of interest under UV illumination is luminance. Furthermore, for the watermarking application, it is not the absolute luminance, but the luminance differential or contrast that is of interest. If we make the simplifying assumption that C, M, Y and K all absorb 100% of the light in the fluorescence emission regime, then the luminance of a printed color under UV light is related simply to the fractional area exposed by the bare substrate. Another interpretation is that the difference in luminance between any pair of colorants is assumed to be negligible compared to the difference between any colorant and paper. The paper area coverage can be estimated from the C, M, Y, K colorant amounts and knowledge of the halftone configuration. For example, for a rotated dot configuration, an estimate of paper area coverage is given by $P = (1-C)(1-M)(1-Y)(1-K)$, where C, M, Y, K are fractional colorant area coverages. For a dot-on-dot configuration, $P = 1 - \max(C, M, Y, K)$. For a dot-off-dot scheme, $P = \max(0, 1-(C+M+Y+K))$. The practical advantage with this approach is that no radiometric measurements are required. (For simplicity, dot area coverages are assumed to be linearly related to digital count, with the realization that improved accuracy can be obtained by accounting for nonlinear dot gain via additional measurements of single-colorant ramps [3]).

Color difference metrics

Given the preceding discussion, we will select difference in lightness as the distortion metric under UV light. For perceived color difference under normal light, we choose the simple Euclidean ΔE^*_{ab} metric, although it can be replaced with other metrics such as ΔE_{94}, or CIEDE2000 [5]. One issue to consider is the spatial frequency content of the watermark. If for example we wish to embed a high frequency watermark (e.g. small point text) into an image or document, we may wish to exploit properties of the human contrast sensitivity functions, and relax the constraint on chrominance error, while applying greater emphasis on luminance errors. The examples in Fig. 4 and 5 may be viewed as a simplistic solution to the optimization problem (1), whereby the color difference metric completely ignores color differences along the yellow-blue opponent dimension. Such an approach would work well for watermarks comprising fine scale modulations in yellow that are hard to perceive under normal light. In the most general case, we wish to derive a strict metameric match. Fortunately feasible solutions are theoretically possible due to the colorimetric redundancy inherent in a CMYK printing process. That is, for many regions within the printer gamut, multiple CMYK combinations can produce the same or similar CIELAB color. The optimization problem (1-3) will attempt to find two such combinations that produce sufficient UV contrast. We can relax the constraint of strict color matching by introducing tolerances, thus posing the classic tradeoff between how well the watermark is hidden under normal viewing conditions, versus how clearly it is revealed under UV illumination.

Experiment and results

Experiments were conducted on a Docucolor 8000 electrophotographic CMYK printer. A Xerox Color Expressions substrate with a Brilliance Index of 98[2] was chosen. This is a standard substrate used with many digital color devices, and exhibits substantial fluorescence.

Several halftoning methods were tried, and the one that was chosen finally was a dot-off-dot halftone employing a successive screening technique [6]. To simplify the model derivation, we imposed the constraint that $C+M+Y+K \le 1$ (i.e. no dot overlap is permitted).

For the case of normal viewing illumination, several printer characterization models were investigated, and finally, an empirical approach employing distance-weighted locally linear regression [4, 7] was chosen as it provided the best accuracy. For an independent test set of 200 colors distributed throughout the printer gamut, the characterization achieved an average prediction error of $\Delta E_{ab} = 0.98$ and 95^{th} percentile error of 2.54.

Several models were also evaluated for the case of UV illumination. Since the model based on paper area coverage is particularly appealing for its practical simplicity, we examine the efficacy of this model. Recall that for the dot-off-dot halftone, paper coverage $P = 1 - (C+M+Y+K)$ for the case where $C+M+Y+K \le 1$. Fig. 6(a) is a plot of measured lightness vs. paper area coverage for single colorant ramps under UV illumination. Reasonable linearity is achieved for the cases of larger paper area coverage (i.e. $P \ge 0.5$). Fig. 6(b) is a corresponding plot for mixed colorant combinations. Again, for lighter colors, paper coverage is a reasonable indicator of lightness, and more importantly, lightness contrast. For darker colors, the differences in absorption levels and interactions among colorants begin to dominate. We will thus use paper area coverage to estimate UV luminance, while restricting the selection of colors (C_1 and C_2) to colorant combinations with paper area coverage greater than 50%.

The optimization problem described by Eqn (1)-(3) is a constrained nonlinear optimization problem. Many standard approaches exist, the one that was chosen for this research is sequential quadratic programming [8].This is a robust iterative technique that locally approximates the objective function as a quadratic function, and the constraints as linear functions. A set of initial colors C_1 were selected that exhibited a variety of hues under normal light, while satisfying $P > 0.5$. For a given C_1, the two optimization problems (1) and (2) were solved in parallel, and the C_2 that resulted in the largest D_{uv} and smallest D_n was chosen. A UV contrast threshold of $\Delta L^* = 10$ was chosen for T_1 in Eqn (1),

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[2] The brilliance index is proportional to the OBA amount and thus the substrate fluorescence

and a color matching tolerance of $\Delta E^*_{ab} = 2.0$ was chosen for T_2 in Eqn (2). These values were determined heuristically from pilot experiments.

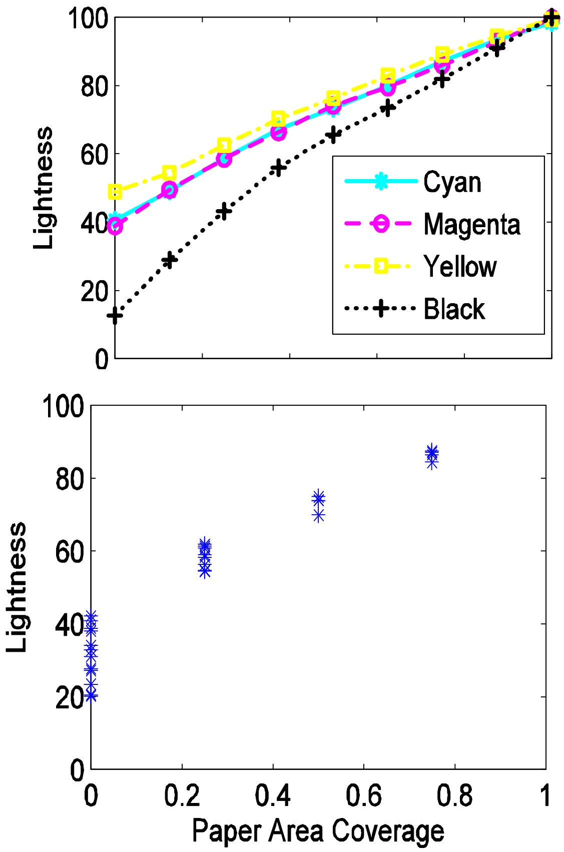

Figure 6 UV Lightness vs. paper area coverage for single-colorant ramps (top) and color mixtures (bottom).

Figures 7 and 8 are two examples of watermarks created with the aforementioned optimization algorithm. The optimization produces satisfactory results despite the use of a simplistic model for predicting UV luminance. (Note: the discernability of the watermark may vary depending on the display or printer with which the images are rendered.)

Figure 7. Image with embedded fluorescent watermark seen under daylight (top) and UV illumination (bottom). The text string: "3rd Jaguar Show and Swop Meet" should be visible in the lower image.

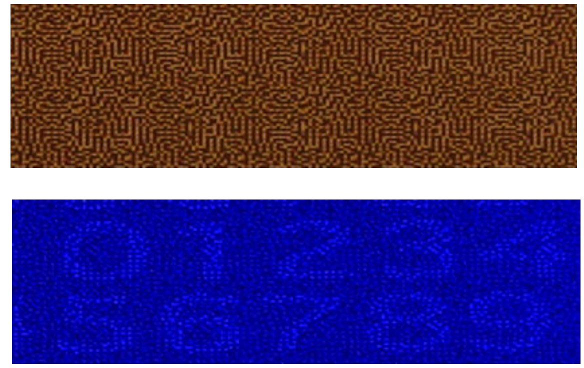

Figure 8 Image with embedded fluorescent watermark seen under daylight (top) and UV illumination (bottom). A series of numerals should be visible in the lower image.

One question that arises is the sensitivity of the watermark as a function of different (normal) viewing illuminants. For example, if the watermark is designed for minimum visibility under tungsten illumination (which has little UV excitation), would it be more strongly visible when viewed under a source with greater UV excitation, such as fluorescent or daylight illumination? In our informal experimentation, we have found that the watermark is quite robust to normal viewing illuminants. Our reasoning is that since the watermark is designed to be visible only under *pure* UV light, it is plausible that any significant power in the visible regime would greatly diminish its visibility.

Conclusions and future work

Substrate fluorescence and illuminant metamerism are often considered hurdles towards achieving predictable color management. This research presents a novel way to beneficially exploiting these phenomena for a watermarking application. Interestingly the problem calls for some of the same color modeling principles and methodologies used in conventional color management, but now formulated in a different context. From a practical standpoint, the approach requires no special colorants or media, and therefore can be offered at no extra cost to the user. Furthermore, decoding is also made practical thanks to the availability of portable consumer UV lamps. The strength of the watermark can be designed to be either fragile or robust to common operations such as scan-print, and photocopying.

Several future directions can be pursued. Extensions of the UV prediction model can be explored with appropriate trade-offs between accuracy and effort. For example, it was alluded to earlier that capturing the nonlinear dot-gain characteristics would increase model accuracy. Preliminary experiments reveal that the shapes of the dot gain curves of C, M, Y, K are very similar under normal vs. UV light. One could derive the shapes of these curves with normal colorimetric measurement, and then scale them by the luminance measurements of solid colorants under UV light. One can also envision the use of a digital camera for estimating the color of prints under UV illumination. Another aspect being investigated is the selective introduction of textures to mask watermark visibility under normal light. This would alleviate the demand for strict color matching under normal light, which is made difficult due to various sources of imperfections in the printing system, including inevitable errors in the color models. Finally, an exploration of how luminance contrast translates to text legibility under UV light would be an interesting study.

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Author Biography

Raja Bala received the Ph.D. degree from Purdue University in Electrical Engineering. Since then, he has been employed at the Xerox Innovation Group, where he is a Principal Scientist conducting research in color science and color management. His research interests include device characterization, gamut-mapping, optimal color transformations, and novel imaging techniques utilizing spatial and spectral context. Raja has over 85 patents and publications in the field of color imaging, and is a member of IS&T.