Sensor Transforms to Improve Metamerism-Based Watermarking

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Abstract

It was suggested [Bala_CIC17] that metamerism could be exploited for watermarking applications by utilizing narrowband LED illuminant spectra for breaking apart metamer colors. It was noticed that, for metameric ink reflectances differing only by the K ink contribution, absolute differences between metamer pairs peaked around a few wavelengths: LEDs with those spectra were then used for displaying the watermarks.

Here we investigate the idea of interposing a camera and a display system to make the effects produced more pronounced. We develop an optimization to produce a matrix that best transforms the camera sensors such that color differences between erstwhile metamer pairs are maximized, under the new lights. As well, we consider the problem of optimizing on the lighting itself in addition, leading to even more emphatic breaking apart of metamer pairs and thus more visible watermarks.

Introduction

In [1], Bala et al. examine whether radically changing the illuminant can successfully break metamerism sufficiently to be used in watermarking. There, printed inks metameric under illuminant D50 were used, with spectra for metameric pairs corresponding to the widest difference in K values. It was observed that subtracting these pairs of surface spectral reflectance functions always produced difference spectra that peaked in absolute value at roughly the same two spectral locations, about 518nm and 621nm. Therefore it was considered that illuminating with LED illumination near those spectral values would most increase RGB discriminability. That is, the idea would be to print a document using such metamer pairs for a hidden background and foreground that would be revealed under narrowband LED illumination. This would therefore complement the idea of using substrate fluorescent properties for hidden watermarks [2] by moving into the domain of visible light.

The results in that work, while promising, are not as emphatic as desired, in that the separation between background color and foreground color was not convincingly large. Therefore, in this work we follow the same basic idea but interpose a camera, to allow for greater flexibility than simply the human visual system. As well, we subsequently apply what amounts to a sensor matrix transform (reminiscent of spectral sharpening [3]) specifically with the objective of maximizing the difference, under a new illuminant, of the difference between formerly metameric pairs.

That is, suppose we decide to interpose a camera and a display, instead of simply using the eye and XYZ tristimulus values. Then is there a matrix transform, applied to the camera RGBs, which will best emphasize the difference between foreground and background ink? To answer this question, we develop an optimization generating a 3×3 matrix M for linearly transforming the color space such that the difference between background and foreground colors is maximized, for metamer pairs observed under the new, LED lighting.

As well, since the availability of LED light chromaticity is very broad [4], we also examine whether a different choice of LED lighting or combination of LEDs provides the most effective discriminability. It turns out that, indeed, a more general combination of LEDs is more effective than using the original two lights suggested in [1]. To do so, we include a vector of binary weights w in our optimization, where w selects whether or not to include narrowband LED spectral colors in the new illumination – i.e., we optimize on color space transform matrix M and simultaneously on the LED illumination to be used so as best to provide discriminability of watermarks visible only under LED lighting.

In general, we would also like to optimize on designing ink reflectance spectra as well as illumination spectra, for this application, as in the optimization set out in [5] in another context. Nevertheless, even without further optimization on the inks themselves, one finds that it is already possible do better with a camera than using the eye. Note that in the following we simply use RGB differences to drive an optimization, but certainly one could use perceptual color. As well, here we use only a small set of metamer pairs, in that the paper provides a proof in principle rather than an exhaustive solution to this general problem.

Xerox metamers

Here, we consider a set of 6 ink patches, divided into 3 sets of metamer pairs. These 3 pairs have close to matching XYZ values under illuminant D50. Reflectance spectra are plotted in Fig. 1, along with the spectral differences between pair members (cf. [1]). These curves are indeed basically metamer pairs under D50: transforming to XYZ and then to CIELAB with normalizing illuminant D50, we obtain ΔE values between color signal pairs, given by metamer reflectances times D50, as follows:

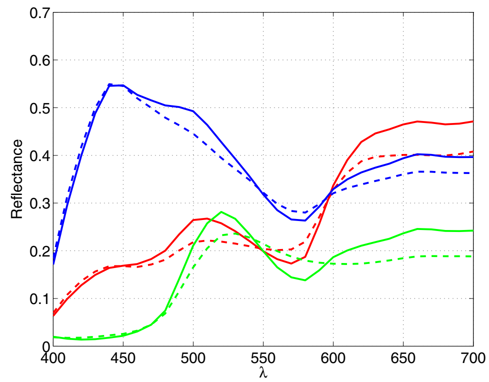
Pair	ΔE
1–2	0.82
3–4	0.59
5–6	1.05

(And, with flat, equi-energy illumination applied, the reflectance pairs themselves have ΔE nearly zero.)

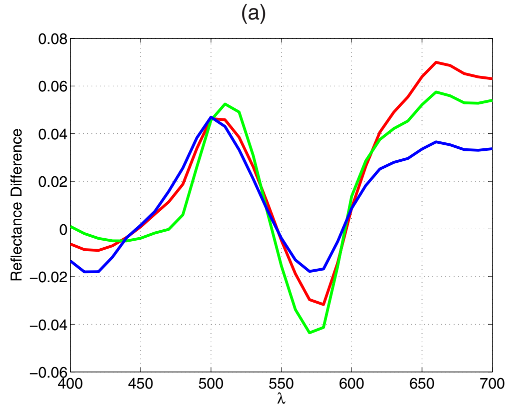
Color space transform

Fixed Lights

In [1], difference curves were examined for metamer pairs (differing by maximum K value range), and it was pointed out that



(a)



(b)

Figure 1. *(a): Xerox ink metamers (widest K values); (b): Metamer-pair differences*

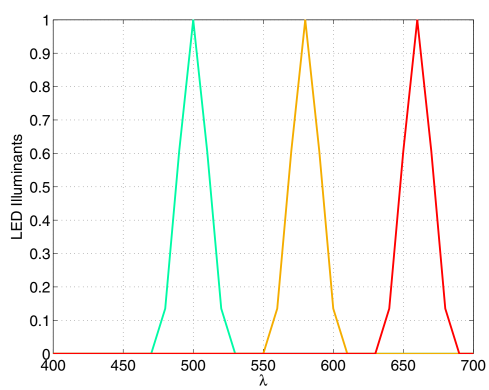


Figure 2. *LED illumination*

two maxima and a minimum occurred at about the same wavelengths for each pair. In Fig. 1(b), we note that, for the present three metamer pairs, indeed three extrema occur at wavelengths of about 500, 580, and 660nm. Now suppose, as in [1], we use equi-strength LED lighting, with lights at each of these special wavelengths. Here we simply use Gaussians for a simple model of LED reflectances. Then the LED lighting appears as in Fig. 2. To be entirely specific, let's use a particular camera as well: here we use the Kodak DCS420 digital still camera, with sensors as in Fig. 3. But note that for the method set out here we do not

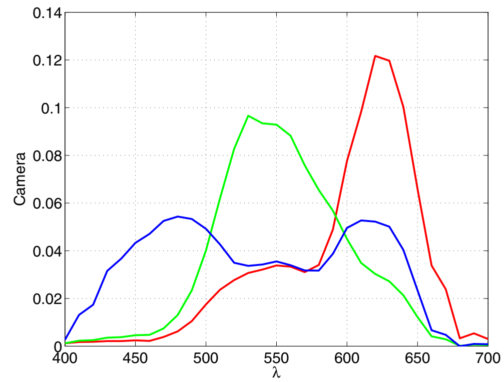


Figure 3. *Kodak DCS420 camera*

need to actually know sensors, just measured colors — here we use camera sensor data simply to form realistic RGB values.

XYZ for metamer pairs

First let us examine XYZ values for this small set of metamer pairs: Fig. 4(a) displays XYZ tristimulus values moved into non-linear sRGB space [6] and scaled to maximum=1.0. The figure serves to show that, indeed, each of the 3 pairs of metamers do match within pairs under D50: top to bottom, the figure shows patches 1 and 2, 3 and 4, and 5 and 6. And in fact they almost match under D65, as well, as shown in Fig. 4(b). Once we switch, in Fig. 4(c), to the LED lighting in Fig. 2, there is some breaking of metamerism, but not much.

Camera RGB

Now consider the same pairs as they are seen **via the camera**. First, consider RGB values for the patches, imaged by the camera under D50, under D65, and under LED lighting: Fig. 5 shows that changing the observer to a camera does indeed split apart the metamers, slightly.

In Fig. 6, we show in a different fashion how the six color patches appear to the camera under LED lighting. On the top row, we show the erstwhile metameric pairs, under the LED illuminant, imaged by the camera. Each pair is displayed as a background color, for the first pair member, and a foreground color for the other pair member. Unsurprisingly, the illuminant change plus different observer have broken apart the colors. But only very slightly! (and best observed on a screen rather than the target print application).

On the bottom row is shown the effect of a color space transform (given in the next Section): numerically, the sum of the squared differences between the transformed color-pairs is substantially greater than before a color space transform. In the next section, we consider an optimization formulation for a camera-sensor transform to emphasize metamer color splitting under this given, fixed LED lighting.

Optimized Sensor Transform for Fixed Lights

To generate a color-space transform to emphasize the breaking of metamerism under the LED illumination, we wish to maximize the sum of squared differences between the pairs of metameric inks, in the new color space. But to be able to display the resulting colors, they must be constrained to be nonnegative.

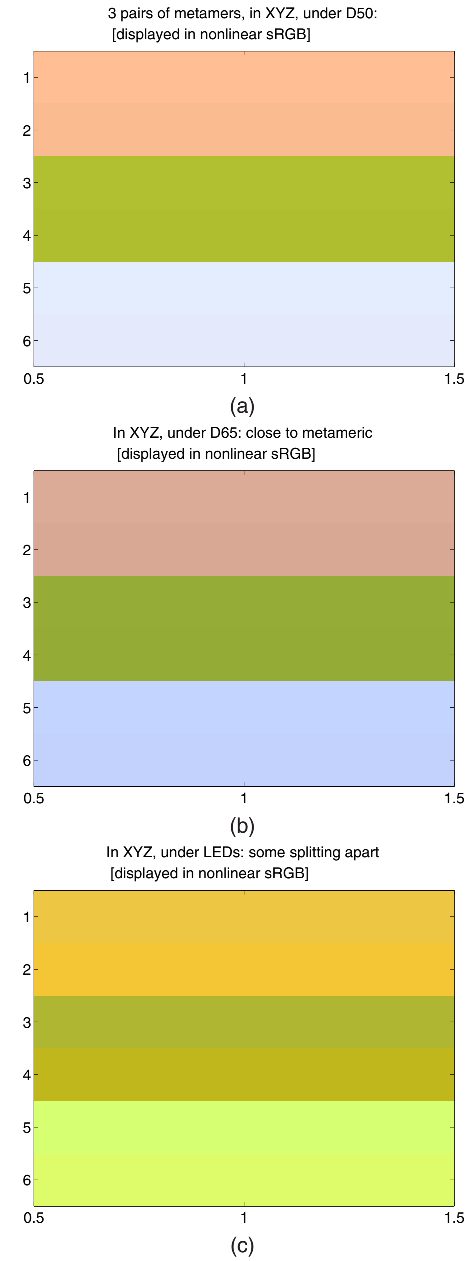


Figure 4. *(a): XYZ for 3 pairs of colors, metameric under D50; (b): almost metameric under D65 as well; (c): under LED lights, there is some splitting, but not much.*

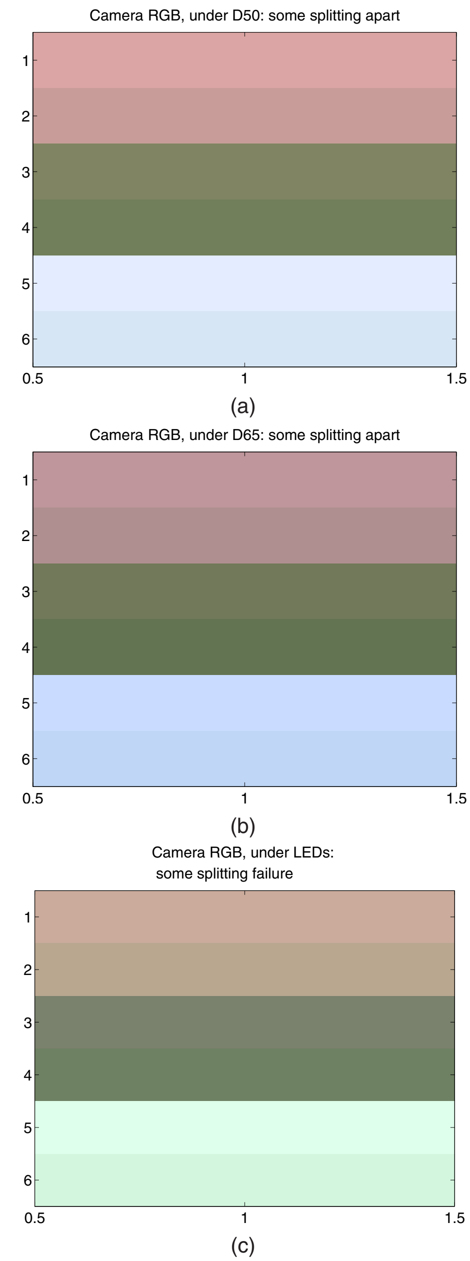


Figure 5. *(a): Camera RGB under D50 – some splitting apart; (b): again some splitting apart under D65 as well; (c): under LED lights: the expected metamer splitting we wished to see under LED lights is not very evident.*

Moreover, for any candidate 3×3 color-space transform matrix M, to make a fair comparison between different matrices M we must normalize the image, consisting of colors for all pairs together, to maximum brightness.

Let colors for the first half of the 3 pairs be ρ_1 (i.e., 3 RGB colors under the given LED lighting in Fig. 2) and let the other half be ρ_2: i.e., ρ_1 and ρ_2 are each 3×3 — three column vectors of RGB colors. Thus altogether we thus seek a matrix M such that the squared difference is maximized, subject to our positivity and normalization constraints:

$$\max_{M} \; Tr\left\{ (M(\rho_1 - \rho_2))^T (M(\rho_1 - \rho_2)) \right\}$$
$$\text{such that} \begin{cases} M\rho_1 \geq 0, \, M\rho_2 \geq 0 \\ \max(M\rho_1, M\rho_2) = 1 \end{cases} \tag{1}$$

where Tr is the trace. The bottom half of Fig. 6 shows the effect of utilizing the generated sensor transform matrix M. For all pairs discriminability is numerically improved (although this

Figure 6. *Top: Camera RGB for pairs under LED illumination; Bottom: after color space transform: foreground-background difference is much more discernible.*

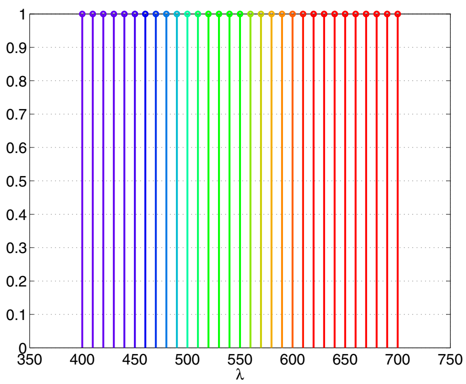


Figure 7. *31 narrowband LED illuminants*

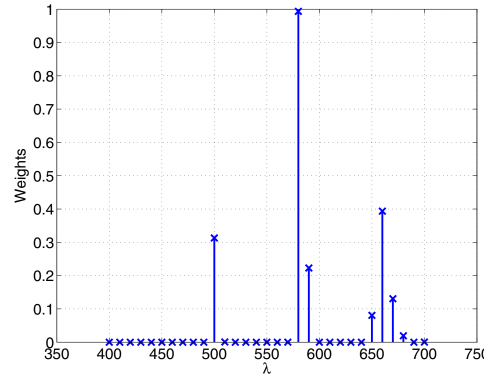


Figure 8. *Optimized weights w.*

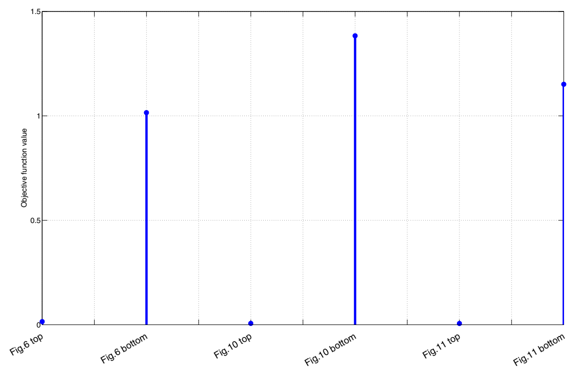


Figure 9. *Objective function values: 3 LEDs, no M; 3 LEDs, matrix M; Weighted LEDs, no M; Weighted LEDs, matrix M; 4 LEDs, no M; 4 LEDs, matrix M.*

is not easy to see for the third pair).

Optimization of Lights As Well

The question arises: Can we do better if we include the choice of LED lights in the optimization? Suppose we wish to derive a best combination of all possible visible narrowband LEDs, shown in Fig. 7 with peaks at 10nm intervals. Let w be a 31-vector of weights, for selecting amounts of these LED lights. Let R be the $31 \times 6 \times 3$ set of RGB values of our 6 inks, measured separately under each of these lights, divided into sets R_1 and R_2 for the three metamer pairs. Regroup each of R_1 and R_2 into a 3×93 matrix.

Now defining a 93×93 diagonal weight matrix W consisting of replicated weights w via $W = [w_1, w_1, w_1, \; w_2, w_2, w_2, \; w_3, w_3, w_3, \ldots, w_{31}, w_{31}, w_{31}]$, our optimization now reads:

$$\max_{M,w} \; Tr\left\{ (M(R_1 - R_2)W)^T (M(R_1 - R_2)W) \right\}$$

$$\text{such that} \begin{cases} MR_1W \geq 0, \; MR_2W \geq 0 \\ \max(MR_1W, MR_2W) = 1 \\ 0 \leq w \leq 1 \end{cases} \tag{2}$$

This is a convergent nonlinear program, which we intialize with weights $w = 1$ for the 3 lights in Fig. 2 and the M from Fig. 6. The results for w are shown in Fig. 8: there are now more non-zero lights than our original three and weights are not equal. For this illumination, Fig. 9 shows that the values of the optimization objective function is indeed increased, using optimized M and w (shown as the fourth value).

The result of not using matrix M, for LED illuminants weighted according to w, is shown in the top half of Fig. 10, whereas making use of an optimized M for this illumination is shown in the bottom half of Fig. 10 — clearly the best result so far. Therefore, optimization over lights does indeed make a positive difference.

Optimize with Binarized Weights

Finally, one can ask what is the effect of maximizing over M for *fixed* lights with weights given by Fig. 8, but binarized: i.e., using the LEDs determined by light-optimization, but with fixed strengths. Suppose we focus on the 4 nonzero contributions with values $w > 0.2$ — then a fourth light has been added at 590nm. The result is shown in Fig. 11 and has objective function value (from Fig. 9, sixth value) almost as good as the best possible (Fig. 10, bottom). But in fact, in terms of our perception, newly optimized matrix M generating the final arrangement,

Figure 10. *Ink pairs under the LED illumination according to the weights w in Fig. 8: top – no matrixing; bottom – optimized matrix M.*

Figure 11. *Using 4 LEDs at full strength (binarized weights w): top – no matrixing; bottom – re-optimized matrix M for these LED lights.*

Fig. 11 bottom, has about the same appearance, notwithstanding that numerically and for a normalized image the sum of all the RGB squared differences are not as good as the optimum. This points out the failing of using non-perceptual difference values.

Conclusion

One issue not addressed here is the job of choosing the metameric reflectances in the first place: one would certainly not like the watermark to be observable under D65, say, if the patches were metameric under D50. This extra objective could in fact become part of a more complicated optimization.

One approach would be to consider using ink combinations that are still metameric, but are themselves optimized blends along the iso-color locus so that we are not necessarily using the extreme cases of min-K and max-K. The set of objectives would be to

- reduce visibility under D65 as much as possible
- and, again, increase discriminability under LED illumination as much as possible.

Also, for moving into perceptual coordinates, we could make use of the Jacobian of the CIELAB transform [7].

Another problem, as seen here, is that some metamer pairs do not separate as much as others — this could be addressed by weighting some pairs more than others in the optimization.

Alternatively, designing more general lights and reflectances, specifically for the task addressed here, is also a possibility (cf. [5]).

The Gaussian model for LED lights is useful but nonphysical. Also, clearly, the use of perceptual color rather than RGB would be an improvement. And of course we would like to consider more than just 3 metamer pairs.

Nevertheless the present investigation demonstrates a promising start to an intriguing problem.

Finally we remark that the concepts here are related to a paper presented at last year's conference on the effect of observer metamerism on anti-piracy algorithms for digital cinema [8]. In that work, the authors tackle the problem of inserting a watermark into a video stream so as to appear invisible to all normal observers, while being revealed when captured by a camcorder. Broadly speaking, both papers deal with the issue of obtaining metameric pairs with respect to a set of viewing parameters, including viewer, stimulus, and capture device. However the applications are different: ours focuses on printed materials and Ref. [8] deals with video display.

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