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Analysis of tristimulus interdifference and contextual color correction

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Abstract. *We explore how an RGB representation can be computed from a spectral description of real images, with many different colors. To pass from spectral distribution to tristimulus values, several color-matching functions (CMFs) were proposed, derived from experimental setups with simplified visual conditions, considering the colors pointwise and independently from any visual context. A high interdifference is observed in cone spatial distribution between human subjects, without any corresponding significant difference in final color sensation. It is likely that a spatial compensation is performed by human observers that strongly decreases the subjectivity in color perception, and we ask if a similar principle should be considered in digital imaging. We investigate the interdifference among some CMFs when used to compute color information in complex visual conditions, where multiple, spatially distributed different colors are present. This is relevant in synthetic image generation of scenes under different illuminants, computed at the spectral energy distribution at* 5-nm *intervals, to be converted into RGB for monitor display. The analysis of the interdifference among tristimulus colors obtained using different CMFs shows a significant decrease of the interdifference when a contextual color correction is applied, based on Von Kries or Retinex methods.*
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1 Introduction

From a physical point of view, a color signal comes from the interaction between spectral light distributions and surface reflectances. To form the final color sensation a set of color-matching functions (CMFs), or alternative integration curves, convert continuous or stepwise spectral information into a limited number of chromatic values (usually a triplet). Much research has been performed in the colorimetry field. In 1931 the experiments of Wright and Guild led to the 2-deg CIE 1931 Standard Observer.[1,2] In 1964, averaging the data from the experiments of Stiles and Burch[3] with those from the slightly different tests of Speranskaya,[4] the 10-deg CIE 1964 Standard Observer[1,5] was defined. A large amount of research on CMFs has been performed by scholars to deeper investigate the conversion from spectral information to triplets.[1] More recently, in 1992 Thornton proposed new experiments and alternative curves.[6] In this paper we do not discuss or compare different CMFs, rather we investigate their effect when color transformations are considered in the context of complex scenes. CMFs have been proposed considering color as an isolated stimulus, in comparison with a control. Given that the spatial distribution of cones in the human retina has high variance among different subjects,[7] we would expect a corresponding difference in subjective color perception, but that has not been observed. This suggests that some perception mechanisms compensate this variability, as suggested by many studies on visual perception.[8–12] We therefore ask what the relationship is between contextual models of color perception and different CMFs.

A second element that reinforces the existence of a compensation mechanism for spatial color perception is the evidence that human cone spectral sensitivities are highly overlapped and uneven.[1] Moreover, the cones' spectral curves are very different from proposed CMFs.

An image digitalization process mimics the first stage of human vision, substituting for the retina with a tricromatic sensor with specific sensitivities. Similarly, synthetic image generation in computer graphics mimics this approach by computing a spectral color distribution and converting it to tricromatic information, assuming a virtual observer with standard CMFs. This process cannot avoid undesired differences between the digital image and the expected result, based on human experience. To solve this problem some computational models of human vision have been proposed.[11–15] In this paper we investigate how spatial color computation can decrease the effect of CMFs variation in color rendition in synthetic image generation. To this aim we devise an experimental setup to test the inter-

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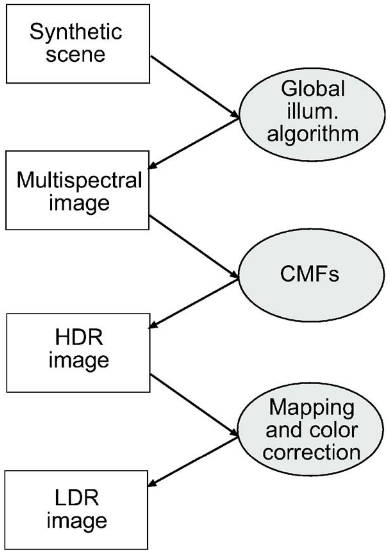

Fig. 1 Pipe line.

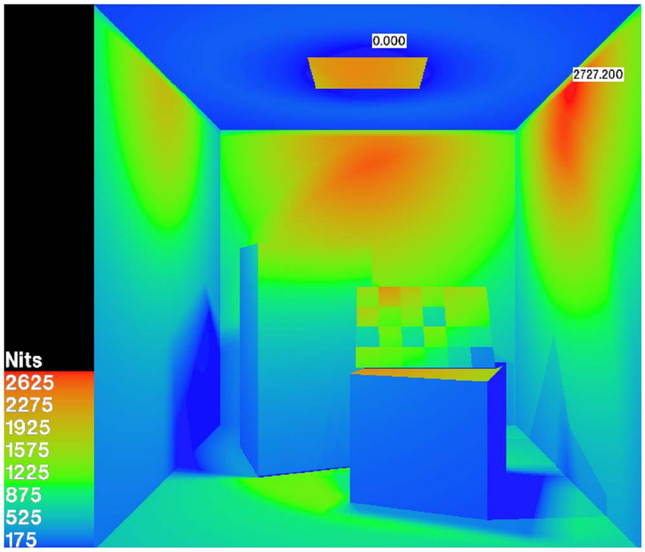

Fig. 2 False color image of the synthetic test scene. Luminance values range from about 0 to 2700 cd/m^2 for D65.

difference among tristimulus colors obtained using different CMFs and the change of this interdifference when a spatial color correction is applied.

Section 2 describes how we compute the synthetic image, applying a photometric and spectral computational method. Section 3 describes the test setup. Section 4 presents the experimental results, and Sec. 5, a discussion and conclusion.

2 Multispectral Image Generation

Multispectral image generation can give rise to images that have a dynamic that can or cannot exceed the available dynamic of the chosen device. In the first case, it is necessary to transform the luminance distribution into the available range, but in both cases, we investigate how colors are modified when going from multispectral to tristimulus representations. Our approach to color rendition is therefore organized in a pipe line (see Fig. 1).

A global illumination algorithm (such as, e.g., ray tracing or radiosity) computes the interaction between spectral light distributions from light sources and surface reflectances. Normally these methods generate a high-dynamic-range spectral luminance distribution, due to an accurate photometric characterization of light sources.

The multispectral image computed by the rendering method is converted into a high-dynamic-range RGB image, applying different sets of CMFs. In Fig. 2, false colors provide the reader with a hint concerning the luminance values of the scene. The last stage in the pipe line is the application of a tone-mapping operator to convert the high dynamic range (HDR) to the available dynamic range of the output device (a monitor).

We built a synthetic scene, similar to the Cornell box,[16,17] containing a simplified Macbeth-like color checker. The Macbeth-like color checker was characterized by the same reflectances as the original one, without the patch gray separation, to simplify its geometrical description.

We chose two sets of illuminants: the first has two D65 light sources, while the second has one A and one C illuminant. In both cases, the positions of the sources are the same: the first in the center of the ceiling, the second in the top left corner, pointing to the opposite corner. To render the scene we used a photometric ray tracer by Rossi *et al.*[18] that samples, for each pixel, spectral luminance values in 80 frequency values ranging from 380 to 775 nm at increments of 5 nm.

The result of these computations is a multispectral image. Two subsequent steps are necessary: the first to transform the multispectral values into a triplet, and the second to map the triplet values into a displayable range.

3 Test Setup

To test the interdifference among tristimulus colors obtained using different CMFs we tested CIE RGB 1931 curves,[1,2] the set of CMFs proposed by Stiles and Burch,[3] and a set of curves defined by Thornton.[6,19] We chose CIE RGB 1931 curves[1,2] because they are the most used standard for RGB conversion; Stiles and Burch's curves[3] because they contribute to the standard 10-deg CIE 1964. Thornton's[6,19] CMFs were chosen because they are a recent example in the direction of CMF improvement. An advantage of the chosen CMFs is that they produce RGB-like tristimulus values without the necessity for any other transformation. Figure 3 shows the shape of the three sets of CMFs.

CMFs are applied to two spectral images, computed under illuminant D65 and under illuminants A and C. The results are HDR images that require a mapping to fit the

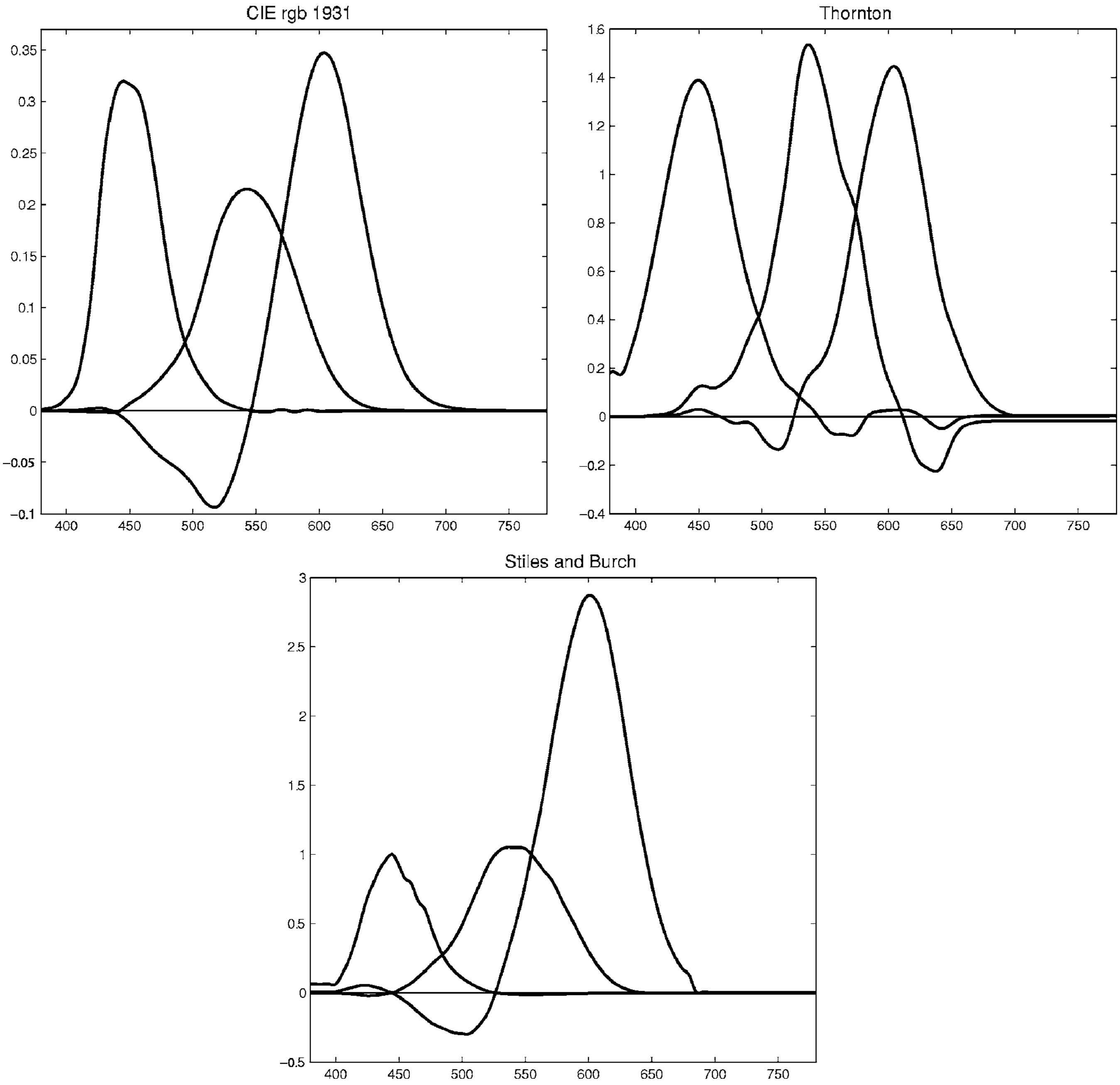

Fig. 3 Graphics of chosen CMFs.

available display dynamics.

To analyze the CMFs' interdifference to color rendering, we separate the mapping from the color correction. The chosen methods are Von Kries,[12] which implements a global spatial color correction, and Retinex,[10] which implements a local and global color correction. Both methods are applied to absolute actual values, then the final mapping is performed with a simple scaling.

We also analyze the CMFs' interdifference without any color correction, applying only a simple logarithmic mapping, that, like a generic gamma correction, does not perform any color adjustment.

There are many variants of the Retinex color model and multiple implementations. We used a Brownian path approximation with saccadic-like steps, to compute chain ratios.[20] In the resulting images, separately for illuminants D65 and A/C, we measured the interdifferences among the resulting low-dynamic-range (LDR) images. Figure 4 presents the test setup.

Recall that interdifference represents how much the choice of CMFs affects the color rendition in the image synthesis pipe line. As a measure of interdifference we use the Euclidean ΔE in perceptually uniform *CIELab* space. We computed ΔE as the average distance of each pixels between a couple of images, considering first the whole image and second each single color patch of the virtual Macbeth color checker:

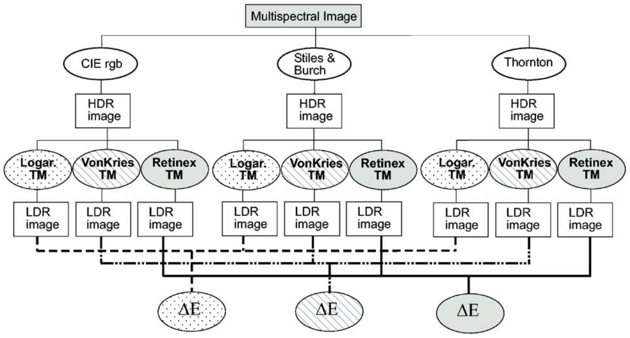

Fig. 4 Scheme of the experiment for each illuminants configuration.

$$\Delta E_{\text{mean}}(I_1,I_2)=\frac{\sum_{p\in \text{Imm or patch}} \Delta E[I_1(p),I_2(p)]}{\#\ \text{pixels}}.$$

4 Test Results

Figure 5 presents a comparison diagram showing the distance, averaged on a whole image, between the three CMFs pairs. Per pixel transformations, like the logarithmic mapping, exhibit a considerably higher interdifference with respect to the two color in context correction methods. Let us analyze how single patch colors are effected. To this aim we measured the distance among the colors of each patch (see Fig. 6), averaging around a neighbourhood excluding patch edges. Figure 7 shows the results for D65 illuminant, and Fig. 8 shows the results for the A/C illuminants. In Fig. 7, for patch 2, for CIE RGB versus Stiles-Burch CMFs, there is the only case where no color correction results in a lower interdifference than Von Kries global color correction method, but still Retinex shows a lower interdifference.

We also drive the attention on gray patches and some low-saturation colors, where ΔE values for the Retinex color correction method are very low, even 0 for black patch 24 in Fig. 8 for the Stiles-Burch versus Thornton CMFs.

Figures 9–14 display the computed images under different conditions. Recall that the purpose of this research is not about absolute color correction, but rather to compare the difference between various results. It is evident from a visual comparison that a higher degree of color normalization is the result of a contextual color correction. In fact Fig. 9 clearly shows a high interdifference, which is much less noticeable in Figs. 10 and 11. When A/C illuminants are used, we observe the same behavior.

5 Discussion and Conclusion

First note that ΔE values cannot be interpreted as a classic chromatic distance, since they represent an interdifference of the CMFs effect. Moreover we do not intend to make any comparison of the effectiveness of the methods or of the CMFs to recover a corresponding color. On the other hand, it is strongly evident that a spatial color correction decreases interdifference among the tristimulus colors obtained using different CMFs. It is also evident that CMFs still play a role since the interdifference never goes to zero.

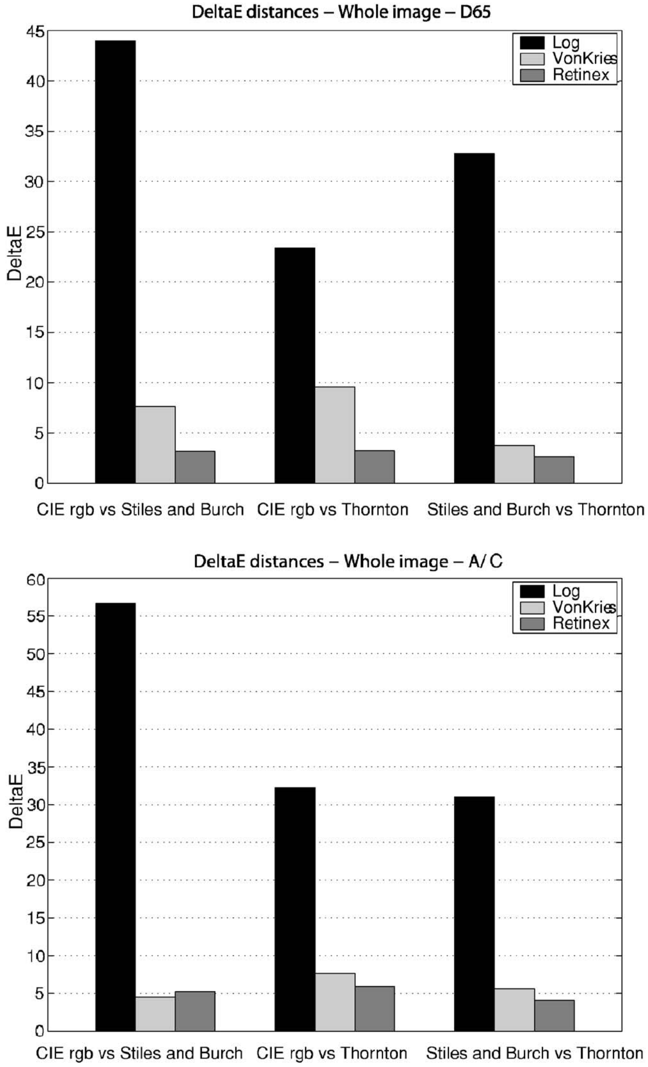

Fig. 5 Average ΔE computed on the whole image.

The fact that some patches have larger interdifference suggests the necessity to better investigate the role of wavelength peaks and overlaps in CMFs. Spatial color correction compensates the different energy of the CMFs, as we proved in previous papers.[21,22]

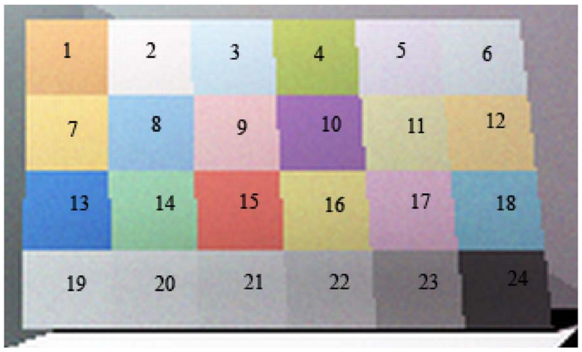

Fig. 6 Patches.

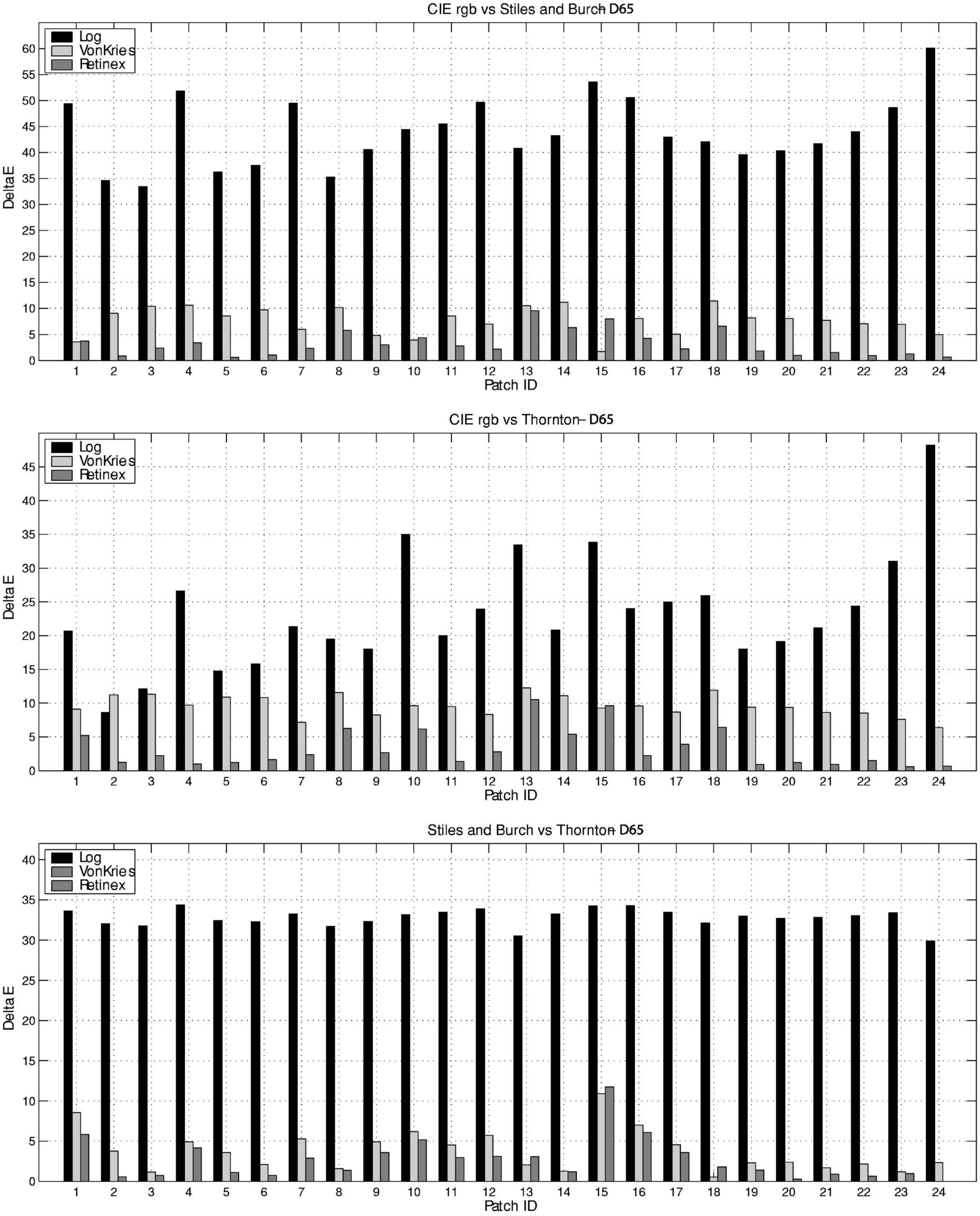

Fig. 7 Average ΔE on each patch. Numbers on the x axis correspond to patches, as in Fig. 6. Three diagrams are for the D65 illuminant.

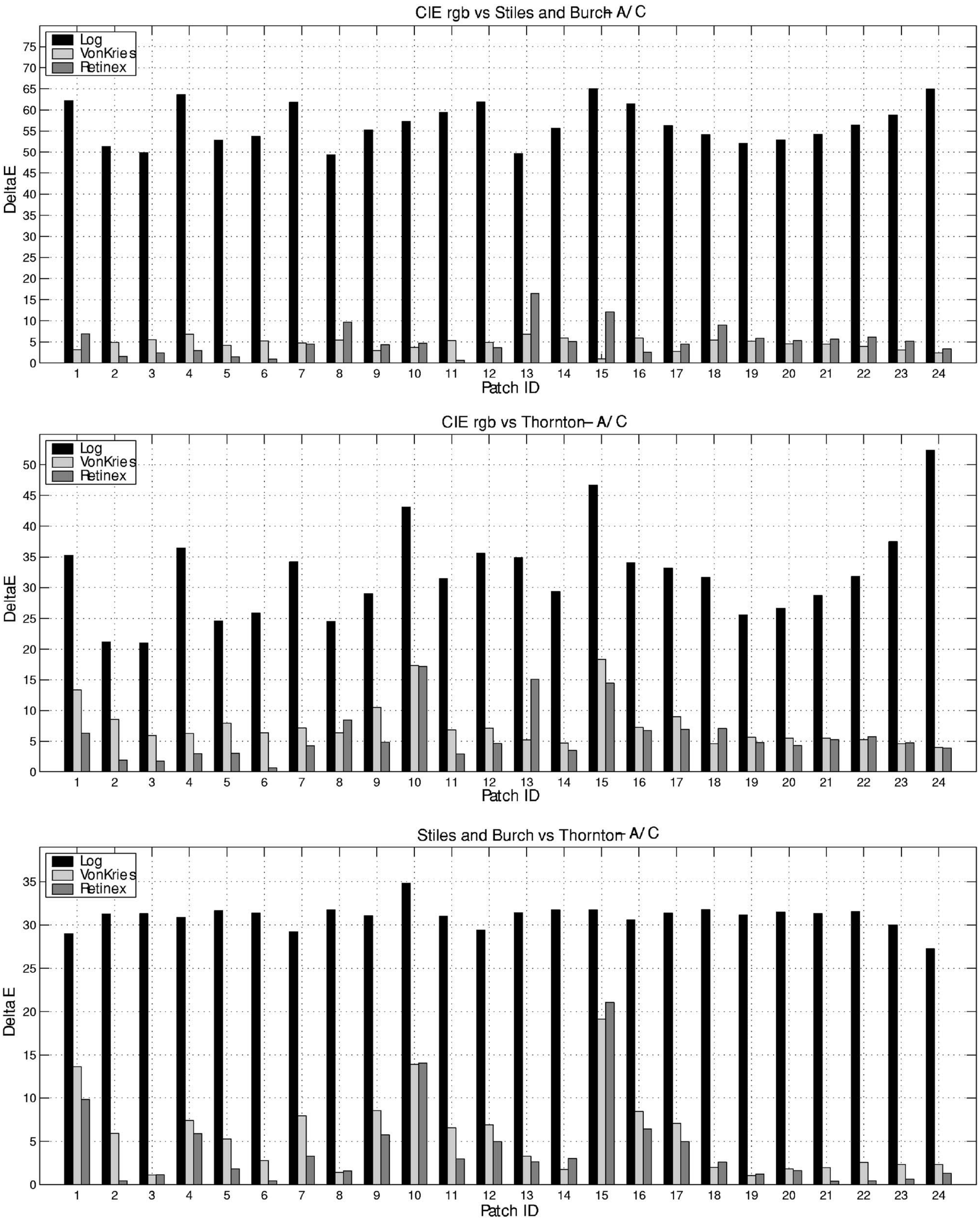

Fig. 8 Average ΔE on each patch. Numbers on the *x* axis correspond to patches, as in Fig. 6. Three diagrams are for the A/C illuminants.

Fig. 9 Logarithmic mapping for the D65 illuminant: CIE RGB (left), Stiles and Burch (center), and Thornton (right) CMFs.

Fig. 10 Von Kries color correction for the D65 illuminant: CIE RGB (left), Stiles and Burch (center), and Thornton (right) CMFs.

Fig. 11 Retinex color correction for the D65 illuminant: CIE RGB (left), Stiles and Burch (center), and Thornton (right) CMFs.

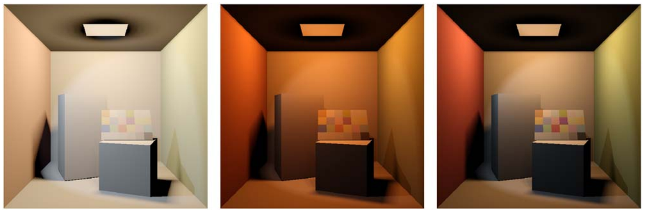

Fig. 12 Logarithmic mapping for the A/C illuminants: CIE RGB (left), Stiles and Burch (center), and Thornton (right) CMFs.

Fig. 13 Von Kries color correction for the A/C illuminants: CIE RGB (left), Stiles and Burch (center), and Thornton (right) CMFs.

Fig. 14 Retinex color correction for the A/C illuminants: CIE RGB (left), Stiles and Burch (center), and Thornton (right) CMFs.

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