Color Constancy Effects Measurement of the Retinex Theory

Daniele Marini [*] [a], Alessandro Rizzi [**] [b] and Caterina Carati [a]

[a] Dip. Scienze dell'Informazione - Università di Milano, Italy

[b] Dip. Elettronica e Automazione - Università di Brescia, Italy

ABSTRACT

Understanding chromatic adaptation is a necessary step to solve the color constancy problem for a variety of application purposes. Retinex theory justifies chromatic adaptation, as well as other color illusions, on visual perception principles. Based on the above theory, we have derived an algorithm to solve the color constancy problem and to simulate chromatic adaptation. The evaluation of the results depends on the kind of applications considered. Since our purpose is to contribute to the problem of color rendering on computer system display for photorealistic image synthesis, we have devised a specific test approach. A virtual "Mondrian" patchwork has been created by applying a rendering algorithm with a photorealistic light model to generate images under different light sources. Trichromatic values of the computer generated patches are the input data for the Retinex algorithm, which computes new color corrected patches. The Euclidean distance in CIELAB space, between the original and Retinex color corrected trichromatic values, has been calculated, showing that the Retinex computational model is very well suited to solve the color constancy problem without any information on the illuminant spectral distribution.

Keywords: Chromatic adaptation, color constancy, color perception, color appearance models, image synthesis, photorealism.

1. INTRODUCTION

Color adaptation is an aspect of human visual system of particular interest for a thorough understanding of color appearance and for an effective use of color in many computer based image analysis and synthesis applications. Color adaptation, or chromatic adaptation, is the ability to discount the spectral composition of the illuminant while observing a scene under different light conditions, so that, for instance, a white paper appears white to a human observer under daylight or under tungsten incandescent light. Color constancy is a field of research aiming at discovering models to estimate, from known trichromatic values, color constant representation of illuminated objects under different conditions. In principle this problem can be solved if the reflectivity of the objects and the color composition of the light source are known, and if hypothesis on linearity or uniformity of illumination are assumed. The major part of color constancy computational models are based on von Kries assumption of a linear response of chromatic sensors to stimulus; they have been tested by comparing chromaticity of colors measured under D65 and other illuminants, as pointed out by Fairchild [1], determining therefore the corresponding colors, i.e. colors that match in color appearance under different illumination conditions. Nayatani et al. [2] proposed an evolution to von Kries' linearity law, and hypothesize that color adaptation can be solved by a non linear model for each color stimulus with a power law which depends on the luminance of the visual field. Wandell [3] recalls that the estimation of the reflectance of a surface, necessary to recover its color, depends also on the unknown spectral composition of the light source. The two unknown can be estimated if one assumes a linear model of the light sources as well as of the surface reflectivity, in which case the problem can be reduced to the solution to a set of linear equations. Moreover this is a global approach and does not explain color illusions, like simultaneous contrast. Also D'Zmura and Lennie [4] assume a bilinear model, that still can be insufficient to derive the reflectivity of a surface, when the light source composition is unknown. To overcome this limit, they hypothesize that human vision takes advantage from multiple observation of the same scene under different conditions, viewpoints, or even from information taken by considering surface shininess. These global models of color adaptation assume that color adaptation is a retinal process, and their major limit is that they consider

[*] Correspondence: Via Comelico 39, I-20135 Milano – Italy, E-mail: marini@eidomatica.dsi.unimi.it, Phone +39 02 55006 358
[**] Correspondence: Via Branze 38, I-25123 Brescia - Italy, E-mail: rizzi@bsing.ing.unibs.it, Phone +39 030 3715 453

color stimuli isolated, not taking into account effects due to nearby colors in a complex scene, and they require some a priori knowledge on light sources or surfaces reflectivity to solve the color constancy problem.

Our approach is based on the Retinex theory, introduced by Edwin Land [5], which assumes that color perception depends strictly on the neural structure of the human vision system; being not clear if the retina or the cortex plays the central role, Land coined the term "Retinex", acrostic of the suffix of retina and cortex. Differently from all other models, Land and his colleagues assume that the stimulus is not the product of the light source and surface reflectivity only, but that the visual system processes the stimulus, integrating the spectral radiance and generating a ratio of integrated radiance of any region of the scene with that of the brightest region: this stimulus is called “lightness”. Three lightness channels produce the color appearance stimuli, further processed by cortical areas. Lightness can be computed from a given image by taking ratios of luminance from different areas of an image. The presence of an edge between two adjacent areas forces this ratio to approximate the ratio between the two reflectance’s. This model eliminates the effect of a non uniform illumination and is completely independent from any a-priori knowledge of the surfaces reflectance and light source composition. Moreover Retinex, in contrast to von Kries based global models, is a local model, which considers colored surfaces in the context of a complex scene. Recent progress in neurophisiology by S. Zeki [6] aims at identify at the cortical level the visual centers devoted to color processing. Zeki has observed that area V1 is active when subjects are stimulated with pure frequency (blind condition tests), while area V4 is active in contextual color stimuli. In this area, moreover, the spatial distribution of receptive fields of nearby neurons is randomly distributed, in contrast to V1 receptive field distribution, which is very regular, therefore suggesting that a comparison among different visual areas is performed during color cortical processing. Many scholars have investigated Retinex theory for color constancy application. In our opinion, particularly significant are the works by Z. Rahman et al. [7], who developed a multi scale Retinex filter, which simulates a center-surround process, and can solve color constancy as well as dynamic adaptation. Moore et al. [8], while proposing a neural implementation of Retinex model, discuss also the neural structure of human visual system, on the basis of Zeki’s experiments. Also their implementation is based on center-surround principle, while our approach grounds the computation of the Retinex filter on the Brownian–like distribution of the receptive fields of the area V4.

The solution to the color constancy problem in computer generated images is a critical step; synthetic images not only are subject to undesired effect in chromatic distribution, but also suffer from the limited dynamic range of typical computer displays. Originally addressed by Tumblin and Rushmeier [9], solutions to the problem, known as the “tone reproduction problem”, have been devised for gray scale images. Recently, besides the above mentioned works by Rahman et al., Pattanaik et al. [10] take into account also the color adaptation problem, by applying a method which derives from von Kries linear hypothesis, with good visual results. No measures, unfortunately, are known to the authors of the present paper, for testing the validity of the different proposed methods.

We have implemented an algorithm that simulates a Retinex filter; to test its validity we propose to work on computer generated images, computing a chromatic distance between a color and its Retinex filtered representation. This approach is very well suited to guarantee color constant image synthesis in varying light conditions, and can contribute to an effective solution to the problem of color reproduction and rendering on computer display systems. In previous papers [11,12] the authors have used the algorithm to simulate, with very encouraging results, simultaneous contrast color illusions.

The paper gives a short presentation in paragraph 2 of the algorithm implemented on the basis of the Retinex theory; in paragraph 3 we describe the test approach that we have adopted; in paragraph 4 we discuss the results, showing the ability of our approach to solve the color constancy problem for color appearance applications.

2. THE RETINEX ALGORITHM

We recall a mathematical treatment of the algorithm proposed by Land [13], from which our algorithm has been implemented. For each wavelength the relative reflectance of a colored patch is the mean value of relative reflectance computed along a number N of random paths to that patch. The average relative reflectance $R^{i}_{l,m,s}$ at the location i of the input image produced by the Retinex filter is the mean value of relative reflectance’s $r^{i,j}_{l,m,s}$ computed over a number N of random paths (see figure 1) ending at point *i* , separately for each wavelength:

$$R^{i}_{l,m,s} = \frac{\sum_{k=1}^{N} r^{i,j_k}_{l,m,s}}{N}$$

where:

$$r_{l,m,s}^{i,j} = \sum_{x \in path} d \log \frac{I_{x+1}}{I_x}$$

and:

$$d = \begin{cases} 1, & \text{if} \quad \left| \log \frac{I_{x+1}}{I_x} \right| > threshold \\ 0 & \text{else} \end{cases}$$

These computations are to be executed independently for the three fundamental wavelengths: long, medium and short. The above model depends on many parameters. The randomness and number of paths that are chosen for the computation of the relative reflectance's are critical for speed and accuracy of the result; the threshold plays the role of discounting non-uniform illumination, since it makes unessential low-reflectance ratios. The basic Land algorithm, in fact, during a path computation, adopts a reset mechanism so that if a brighter area is found, the cumulated relative reflectance is clamped to 0; this forces the computation to restart form the brightest areas. In other words, the effect of the reset mechanism is to consider the brightest area of an image as the reference value of the color white. Mimicking the receptive fields distribution of area V4, we have implemented a Brownian motion approximation to generate the random paths (see figure 2) along which the ratio computations are made. At this aim we have adopted the random mid point displacement technique [14]: the mid point of a segment is displaced randomly, originating two separate segments, and so on recursively.

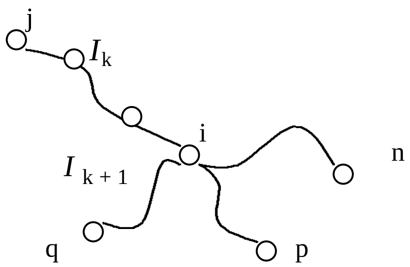

Fig. 1 Computation of the average relative reflectance

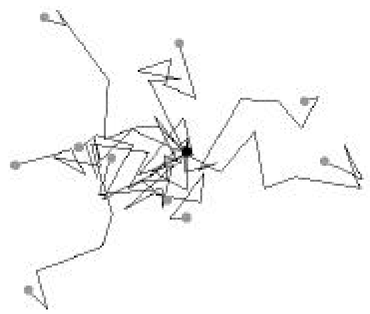

Fig. 2 Example of 10 Brownian paths

The Retinex algorithm can be effectively used to equalize colors or to simulate chromatic illusion. The only attempt to measure Retinex effectiveness, as far as we know, is due to Brainard and Wandell [15], their purpose was to verify the ability of Retinex to predict the color appearance on Mondrian patches (following Edwin Land's terminology, who found the patchwork's similarity to the Painter's works), and their conclusion was negative. In our opinion their work had the flaw of mixing colorimetric principles in a color appearance context. When evaluating the ability of a computational method to determine corresponding colors, the quantity to measure should be a chromatic distance. Therefore to verify the ability of the algorithm to solve the chromatic adaptation problem, and to reconstruct the corresponding color under standard illumination D65, we have devised a test, explained in the following paragraph.

3. THE TEST SETUP

The purpose of our test is to corroborate in a quantitative way the effectiveness of Retinex algorithm to discount the illuminant in computer generated images. It is frequent, in the field of photorealistic image synthesis, to define light sources whose spectral composition produces undesired chromatic effects, and the final image is not able to convey the wanted color appearance. We have generated some synthetic images of a colored patchwork in the following way. A patch is described as a simple geometric shape, a planar surface, with a known spectral reflectivity, and a surface treatment which guarantees Lambertian reflection. The geometric description and color appearance properties of the patchwork has been used as the input of a photorealistic image synthesis program, based on the ray tracing method. Using different standard light sources description, the program has generated different images of the same patchwork under the chosen illuminants, allowing us to measure a chromatic distance in the CIELAB space. A different approach would have been to measure the chromaticity of a real patchwork and compare the values with the filtered ones, but this approach would introduce many unwanted transformations on the data, that make the evaluation unreliable. In figure 3 we see the sketch of the test on real patchwork, while in figure 4 we see the sketch for synthetic imaging evaluation. Critical stages in figure 3 are: a) the scanning process, whose transfer function is very complex and the scanner parameters are not known in general, b) the comparison with filtered and real data, in particular it would be meaningless to measure the chromaticity of the patches from the computer display. The choice of a synthetic process allows us to keep under control and tune all the parameters.

To better understand the approach, it is worthwhile to recall how the light material interaction is simulated with the ray tracing based program that we have used. Most of the rendering programs used in synthetic image generation systems, adopt an approximate illumination model to compute colors following an implementation of the tristimulus theory. Reflected luminance is computed for spectral samples between 380 and 780 *nm* with 5 *nm* step intervals, and integrated to compute values in short, medium and long wavelengths.

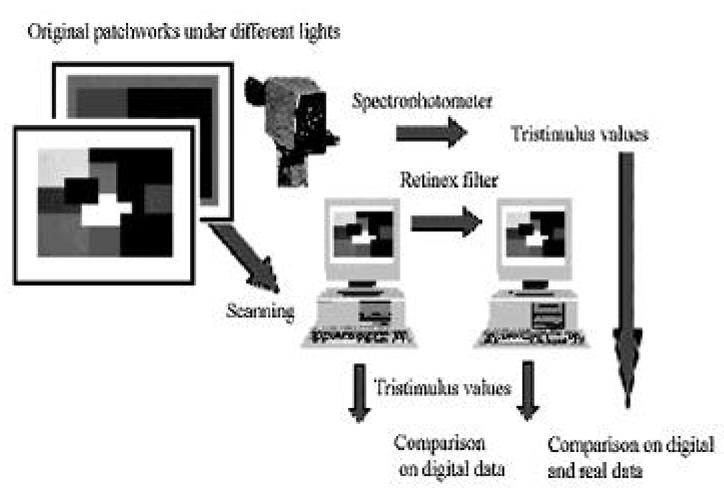

Fig. 3 Sketch of the test setup with real patchworks

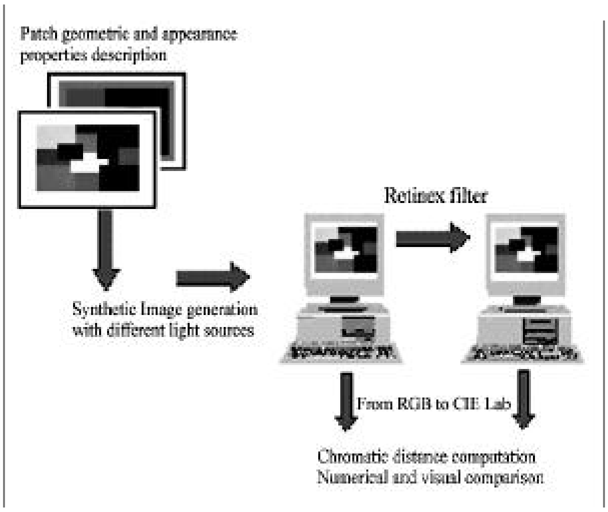

Fig.4 Our test setup

The program that we have used to generate the patchwork has been implemented at the Eidomatics Laboratory of our department; it is based on a physical model for the light – material interaction simulation based on the Cook and Torrance model [16] which allows us to approximate bi-directional reflectivity from known refraction indexes (in a dielectric material), with the following equation:

$$r_d(l) = \frac{\left(\frac{n_2(l)-1}{n_2(l)+1}\right)^2}{p}$$

where $r_d(\lambda)$ is the spectral bi-directional reflectivity of the material with refraction index $n_2(\lambda)$, under the hypothesis that the other medium is air, and the material is purely diffusive i.e. Lambertian. To compute the integrated bi-directional reflectivity the system accepts in input the spectral refraction index of the chosen material. Thus the luminance reflected from a diffusive object is therefore computed with the equation:

$$L_d(l) = r_d(l)E(l)$$

where E_λ is its the spectral illuminance from the light source. Given the reflected luminance, we can compute the tri-stimulus values:

$$X = \int_{380}^{780} L_d(l)x(l)dl\ ,$$

$$Y = \int_{380}^{780} L_d(l)y(l)dl \ ,$$

$$Z = \int_{380}^{780} L_d(l)z(l)dl$$

We have therefore generated the synthetic patchwork, giving the refraction indexes of each patch and the spectral composition of the following CIE standard illuminants: A, B, C, D50, D55, D65, D75, F2. The resulting images of the patchwork under different illuminants are shown in color figure 5.

The last step of the test process is the conversion of the tristimulus values describing each patch for each patchwork under different illuminant, into R,G,B triplets to display on the computer monitor, and into CIELAB for the computation of the chromatic distance from the Retinex filtered patchworks. The choice of CIELAB has been suggested by considering that this is the standard uniform color space, where chromatic differences can be specified.

Eventually the synthetic images of each differently illuminated patchwork have been processed with the Retinex algorithm, the Retinex Algorithms works on X,Y,Z tristimulus values, therefore also the resulting images have been converted to CIELAB.

4. RESULTS

The chromatic distance that we have chosen is the Euclidean distance in the CIELAB space ΔE [17]. In table 1 the chromatic distance of each patch under different illuminants from the corresponding patch illuminated with the standard D65 light source are compared, before and after the application of the Retinex filter.

ΔA: D65 versus	yellow	green	black	violet blue	light brown	blue	grey2	light yellow	red	grey1	White
A	54.98	49.25	0	48.79	42.34	44.85	44.67	59.04	33.55	47.40	60.16
Retinex A	31.09	13.92	22.46	11.40	8.95	7.42	7.92	32.87	19.88	7.91	0.59
F2	30.09	35.88	0	29.18	25.31	28.49	27.58	33.66	25.67	29.32	33.12
Retinex F2	10.21	16.06	10.90	9.05	11.12	8.40	7.28	13.12	21.21	7.76	0.39
D50	28.35	27.43	0	25.47	22.02	23.86	23.78	29.58	19.87	25.28	25.75
Retinex D50	10.56	8.89	6.39	5.85	7.94	6.23	7.26	10.45	9.64	7.89	0.97
D55	8.03	7.99	0	8.90	8.65	7.97	8.27	9.26	7.71	8.77	0
Retinex D55	8.03	7.71	3.54	8.45	8.65	7.58	8.13	9.25	7.53	8.51	0
D75	6	5.73	0	6.85	6.03	5.63	5.75	6.52	6.48	6.3	0
Retinex D75	6.02	5.66	3.54	7.06	5.82	5.78	5.94	6.23	6	6.31	0
B	10.58	13.03	0	12.71	15.04	11.51	14.2	13.38	14.1	14.73	5.21
Retinex B	8.55	11.40	3.54	10.48	13.91	9.31	12.57	11.1	13.36	13.18	1.78
C	5.36	6.80	0	7.63	5.12	6.57	5.92	4.41	3.39	6.92	0
Retinex C	5.36	6.71	3.54	7.85	4.66	6.87	6.23	4.11	3.38	7.31	0

Tab. 1 Chromatic distance of D65 illuminated patches from other illuminants before (I line) and after (II line) the Retinex computation.

We recall that the ΔE distance is considered negligible when its value is below 10 units, anyway up to 20 units ca. the colors still appear as corresponding. We note therefore that only colors yellow and light yellow have larger distance for illuminant A, while the white color has been perfectly corrected by the Retinex filter. In all other cases, all colors are well below the threshold of 20 units.

To better understand what are the critical colors and illuminants, in table 2, for each illuminant in comparison with D65, the patch colors have been displayed in order of increasing chromatic distance, showing the colors below the threshold of 10 distance units in bold, and over the threshold in italic. For illuminants D55, D75 and C all the colors are inside this limit and almost all the colors for the illuminant D50. The results prove that the Retinex filter behaves in the same way as the human visual system.

A qualitative analysis of the results should require psychophysics tests with some observers, that we have not yet make. Anyway, to give a better appreciation of our results we have adopted a method taken from Scientific Visualization techniques to show how Retinex change the relative position of color. A three dimensional representation of the CIELAB

Illuminant											
A	*Violet blue*	*Green*	*red*	*black*	*yellow*	*light yellow*	**white**	**blue**	**grey1**	**grey2**	**light brown**
F2	*yellow*	*black*	*light brown*	*light yellow*	*green*	*red*	**white**	**grey2**	**grey1**	**blue**	**violet blue**
D50	*light yellow*	*yellow*	**white**	**violet blue**	**blue**	**black**	**grey2**	**grey1**	**light brown**	**green**	**red**
D55	**white**	**black**	**red**	**blue**	**green**	**yellow**	**grey2**	**violet blue**	**grey1**	**light brown**	**light yellow**
D75	**white**	**black**	**green**	**blue**	**light brown**	**grey1**	**red**	**yellow**	**light yellow**	**grey2**	**violet blue**
B	*violet blue*	*light yellow*	*green*	*grey2*	*grey1*	*red*	*light brown*	**white**	**black**	**yellow**	**blue**
C	**white**	**red**	**black**	**light yellow**	**light brown**	**yellow**	**grey2**	**green**	**blue**	**grey1**	**violet blue**

Tab. 2 Colors in order of chromatic distance from D65 for each filtered image, *italic above 10 distance units,* **bold below**.

space has been implemented using the VRML language for virtual reality simulation. Each color patch illuminated under the different light sources has been displayed as a small colored cube, and an animation has been computed that shows how each colored patch moves from its original position to the corresponding color under D65 illuminant. A similar animation has also been computed on the CIE chromatic plane, where frequently the analysis of corresponding colors is shown. In color fig. 5 and 6 a snapshot of the animation is shown. The animation can be displayed using any WEB browser program which interprets VRML files, and will be soon published on the WEB. In figure 6 we have also represented the Mac Adam ellipses of the sample colors that are closest to Mac Adam samples: it can be seen that the corresponding colors move close or inside the ellipses, giving therefore a further confirmation of the effectiveness of Retinex to solve the chromatic adaptation problem and to discount of the illuminant.

5. CONCLUSIONS

We have implemented an algorithm that simulates a Retinex filter; to test its validity we have measured the Euclidean chromatic distance in the CIELAB space, between a color and its Retinex filtered representation of computer generated images. The image synthesis method used to create the test patchworks approximates light – material interaction following an illumination model due to Cook and Torrance, and samples the virtual visual space using a ray tracing method. The results show a significant chromatic adaptation: colors under different light sources are corrected and tend to correspond to colors under D65 illuminant, with a difference in chromatic distance frequently below 10 units, which is considered as below the JND threshold. A scientific visualization implementation of the migration of color samples to D65 corresponding colors has also been implemented using VRML language, to convey to the observer the effect of the Retinex filter.

The Retinex filter is very well suited to guarantee color constant image synthesis in varying light conditions, and can contribute to an effective solution to the problem of color reproduction and rendering on computer display systems, and we intend to integrate Retinex filter in a tone reproduction system for realistic image synthesis.

Future developments will apply the test methods to other algorithm proposed in the current literature, to compare Retinex algorithm effectiveness. Moreover we intend also to complete the Mac Adam ellipses analysis to improve the quantitative analysis of Retinex effects.

BIBLIOGRAPHY

1. M.D. Fairchild, *Color Appearance Models*, Addison Wesley, New York, 1998

2. Y. Nayatani, K. Takahama, and H. Sobagaki, "Formulation of a nonlinear model of chromatic adaptation," Color Res. App., **6**, pp. 161-171, 1981

3. B.A. Wandell, *Foundations of Vision,* Stanford University Press, Stanford, 1995

4. M. D'Zmura and P. Lennie, "Mechanisms of color constancy", Journal of Optical Society of America, **3**, 10, pp. 1662-1672, 1986

5. Land E. and McCann J., "Lightness and Retinex Theory", *Journal of Optical Society of America*, **61**,1, pp. 1-11, 1971

6. S. Zeki *A Vision of the Brain*, Blackwell Scientific Pub., Cambridge, 1993

7. Z. Rahman, D. Jobson and G.A. Woodell, "Multiscale retinex for color image enhancement", in *Proc. Of the IEEE Int. Conf. In Image Processing,* IEEE, 1996

8. A. Moore, J. Allman and R.M. Goodman, "A real-time neural system for color constancy", IEEE Trans. on Neural Networks, **2**,2, pp. 237-246, 1991

9. J. Tumblin and H. Rushmeier, "Tone reproduction for realistic images", IEEE Computer Graphics & Applications, **13** (6), pp. 42-48, 1993

10. S.N. Pattanaik, J.R. Ferwerda, M.D. Fairchild and D.P. Greenberg, "A Multiscale model of adaptation and spatial vision for realistic image display", Proc. Siggraph 98, in: Computer Graphics Proceedings Annual Conference Series, ACM SIGGRAPH, pp. 287-298, 1998

11. Marini D. Rizzi A. "Color Constancy and Optical Illusions: a computer simulation with Retinex Theory", in: S. Impedovo Ed. "*Progress in Image Analysis and Processing III*" Proceedings *7th ICIAP*, World Scientific, New Jersey , pp.657-660, 1993

12. Marini D. Rizzi A. "A computational approach to color illusions", in: A. Del Bimbo Ed., *Image Analysis and Processing,* Springer Verlag, Berlin, pp.62-69, 1997

13. E. Land, "Recent Advances in Retinex Theory and Some Implications for Cortical Computations: Color Vision and the Natural image", *Proc. Natl. Acad. Sc. USA*, Vol. 80, pp. 5163-5169, 1983

14. D. Saupe "Algorithms for random fractals" in: Barnsley et alt. *The Science of Fractal Images*, Springer Verlag, New York, 1988

15. D.H. Brainard and B.A.Wandell, "Analysis of the Retinex theory of color vision", J. Opt. Soc. Am., **3**, 1, pp. 1651-1661, 1986

16. A.S. Glassner, *Principles of Digital Image Synthesis*, Academic Press, London, 1991

17. G. Wyszecky and W.S. Stiles, *Color Science: Concepts and Methods, Quantitative Data and Formulas*, J. Wiley & Sons, New York, 1982

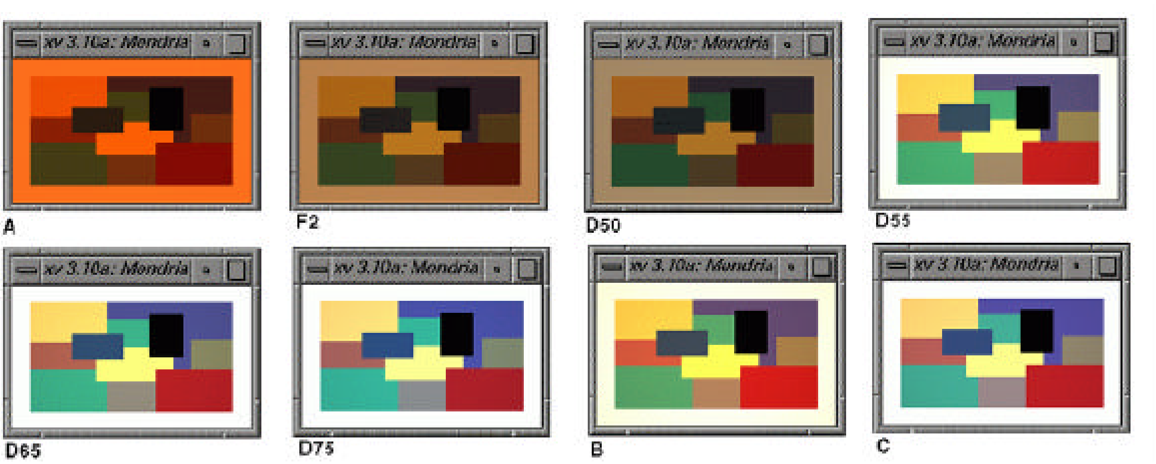

Fig. 5 Synthetic patchworks generated with different illuminants

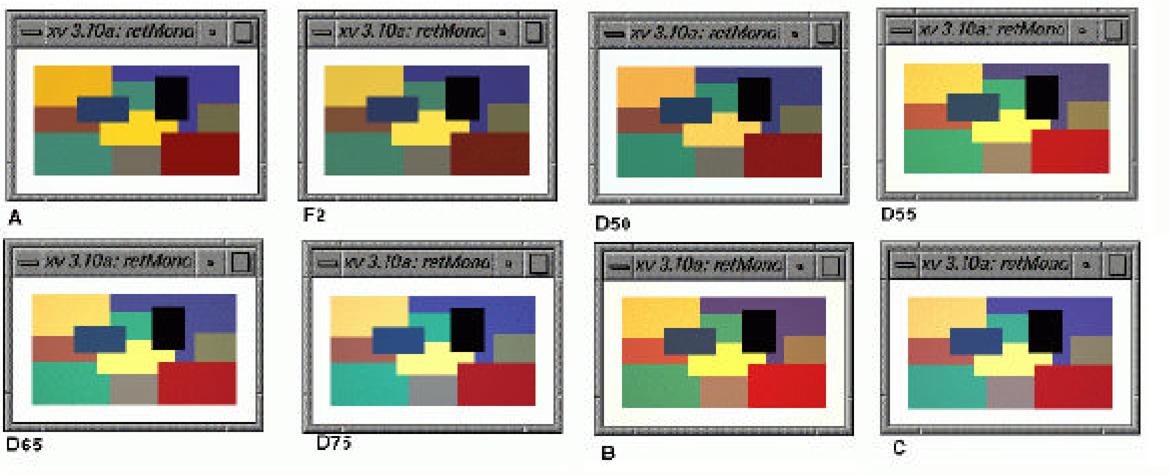

Fig. 6 The same patchworks after the Retinex filtering

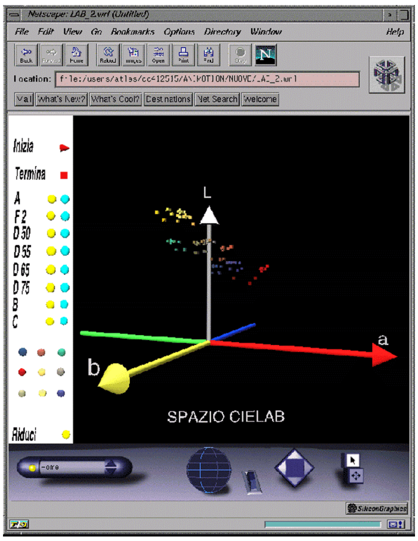

Fig. 7 3D display of corresponding color animation

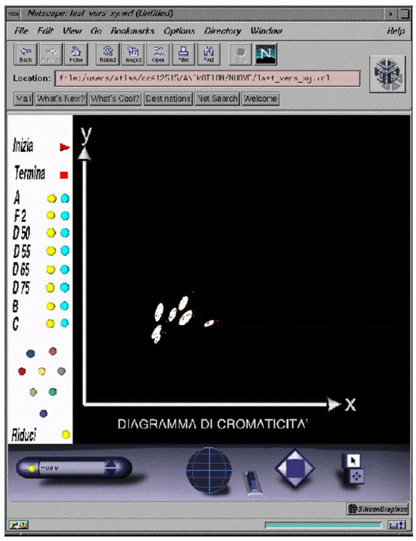

Fig. 8 Corresponding colors on CIE diagram