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A computational approach to color adaptation effects

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Abstract

The human vision system has adaptation mechanisms that cannot be managed with the classic tri-stimulus color theory. The effects of these mechanisms are clearly visible in some well-known perception phenomena as color illusions, but they are always present in human observation. The discrepancy between the observation of a real scene and the observation of a picture taken from the same scene, derives from the fact that the camera does not have such mechanisms. In this paper, we propose a biologically inspired implementation of the Retinex algorithm, introduced by Land and McCann, that simulates these adaptation mechanisms, in order to reproduce some effects like dynamic adjustment, color constancy, etc. typical of the human vision system. The algorithm has been tested not only on a Mondrian-like patchwork to measure its effect, but also on different pictures, photographs and typical color illusions to test its adaptation effects. The examples demonstrate the ability of the model to emulate some characteristics of human color perception and to obtain better equalized and color-corrected images. © 2000 Elsevier Science B.V. All rights reserved.

Keywords: Color appearance; Color constancy; Color illusions; Color perception; Retinex

1. Introduction

Some common visual experiences show that human color perception cannot be completely explained by the classic tri-stimulus theory. Consider a picture taken with a camera in a room illuminated by tungsten lamps: a red-orange chromatic dominant modifies the original colors. On the contrary, no chromatic dominant is perceived if we directly observe the scene. In fact, if we observe an indoor scene in different light conditions, illuminated for instance by a tungsten lamp or by the sunlight through a window, we do not perceive any color difference. This phenomenon is known as *color constancy*. This human ability to compensate for varying light conditions cannot be explained by a color theory based on a physical model of light–matter interaction. These theories can only explain how the spectral composition of light reflected by a known surface changes, as the spectral composition of the illumination changes.

Several models have been developed to cope with color constancy [2,6,7]. Most of them try either to extract the reflectance characteristics of the objects in the scene or to estimate the color triplets after an illuminant change, making some assumptions about the scene itself or looking for global chromatic invariants. Typical of these approaches, complex transformations have been developed to map the colors perceived under various illuminants to a reference illuminant (i.e. D65) or to eliminate known and unknown color dominants.

The approach of Retinex, proposed by Land and McCann [9–11,16], is different. It justifies the color constancy phenomenon by simulating some mechanisms of the human color perception [24]. Other recent research on image color filtering reconsiders this approach [20].

Our work proposes a new implementation of the Retinex algorithm, used not to predict a precise color triplet according to the changing of the illuminant, but to compute a qualitative color in terms of relative appearance. Therefore, no attempts are made to fix or measure the levels of the image brightness. The proposed algorithm has been devised as an unsupervised color equalization, but can be used to predict the perceptive result of complex color configuration as well.

We start from the color constancy adaptation effect in computer vision (Section 2) to introduce the Retinex model (Section 3) and our implementation (Sections 4 and 5). In the presented tests, we first measure the Retinex color shifts under different illuminants (Section 6), then the algorithm is used to equalize photographic images (Section 7) and finally is applied on color illusions (Section 8).

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2. Color constancy in computer vision

Color constancy is an important global adaptation mechanism of the human vision system, it has been studied with different approaches by various researchers [3,5,12] and can be described in the following way.

Consider a target characterized by its reflectance $R(\lambda)$ and an observer who is looking at the target. The spectral distribution of the illuminant light is $E(\lambda)$ and $R^x(\lambda)$ is the reflectance of the surface at a point x. Therefore, the reflected light spectral distribution that hits the observer's eyes is given by:

$$C^x(\lambda) = E(\lambda)R^x(\lambda).$$

The observer has three arrays of photoreceptors that sample the reflected light spectral distribution. Their response $S^x_{\mathrm{R,G,B}}$ is computed from the reflected light spectral distribution $C^x(\lambda)$ and the spectral sensitivity of the photoreceptor's (retinal cones) pigment $\rho_{\mathrm{R,G,B}}(\lambda)$ in the following way:

$$S^x_{\mathrm{R,G,B}} = \int C^x(\lambda)\cdot\rho_{\mathrm{R,G,B}}(\lambda)\,\mathrm{d}\lambda$$

or equivalently

$$S^x_{\mathrm{R,G,B}} = \int E(\lambda)\cdot R^x(\lambda)\cdot\rho_{\mathrm{R,G,B}}(\lambda)\,\mathrm{d}\lambda.$$

The color constancy problem arises when the ambient light spectral power distribution $E(\lambda)$ is not known and $R^x(\lambda)$, which determines the color, has to be estimated from the three receptor responses $S^x_{\mathrm{R,G,B}}$. Such information is not sufficient for this purpose.

To compute $R^x(\lambda)$ several solutions have been proposed. Some methods restrict the color space in terms of where to look for the illuminant or for the object reflectance estimate. The idea of this approach derives from the fact that a surface can reflect no more light than is cast on it [7]. Other methods approximate reflectance as the solution of a linear system composed of various samples of the same color under different illuminants [6]. Some other methods work with nonlinear transformations in color spaces like CIELUV or CIELAB, that also take into account the illuminance level which significantly affects the human color-matching capability [22].

Most of these methods disregard the role of the human color perception mechanism. In contrast, the Retinex theory tries to explain how the human visual system can reconstruct the missing information of light source spectral composition. Retinex assumes that the color perception is the result of complex comparisons among different visual areas [9]. The input to this processing is the cones stimulus in the retina, and the processing is completed in the higher cortical visual area of the brain.

So far, different software [1,8,18] and hardware [19] implementations of the Retinex theory have been developed; however, our approach differs from the previous ones in the way the image is "explored" by the algorithm. More attention has been paid to keep the computation as close as possible to some recent biological models of color perception [25].

3. The Retinex color theory

The Retinex theory assumes that the color perception depends strictly on the neural structure of the human vision system. Land coined the term "Retinex" mixing the words *retina* and *cortex*, since both play an important role in the vision process. The fundamental observation that drove Edwin Land in the Retinex theory development is: "… the eye, in determining color, never perceives the extra red [produced by a tungsten lamp] because it does not depend on the flux of radiant energy reaching it." [10].

The first Land experiment was based on the projection of two black and white slides, one projected through a red filter and the second without any filter at all. The result was, counter-intuitively, an image with all the original colors, not only ones ranging from white to red. Following other experiments, Land verified that a quantity exists, named "lightness", which is associated to every object of a scene, and changes neither with illumination conditions nor object location. Lightness is perceived by the human visual system independently from the light flux that impinges the eye. Through a second experiment, Land verified that a full color sensation of color gamut can be obtained producing a light stimulus to rods and long wavelength (red) sensitive cones; color sensation is again not dependent on spectral fluxes reflected by each object, but on a comparison of lightness. A third experiment demonstrated that color sensation, produced by the so-called *Mondrian scene* is still independent of the reflected spectral flux, rather it depends on the spectral reflectivity which is the property of color constancy.

The Retinex theory assumes that human vision is based on three retinal–cortical systems, each processing the low, middle and high frequency of the visible spectrum independently. Each system forms a separate image of the world; the images are not mixed but compared, and each system on its own discovers the reflectance of the various regions of the image, independently of the variations of the light source spectrum. Land and McCann discussed how the relative reflectance computation can be simulated. They came to the conclusion that a couple of excitatory and inhibitory neurons in a chain can account for the reset mechanism required by the search for the lightest area (i.e. the white).

4. A computational implementation of the Retinex theory

According to the Retinex theory described above, every color sensation derives from three independent stimuli in the three wavebands RGB. For each waveband, the relative reflectance of a colored point is computed as the mean

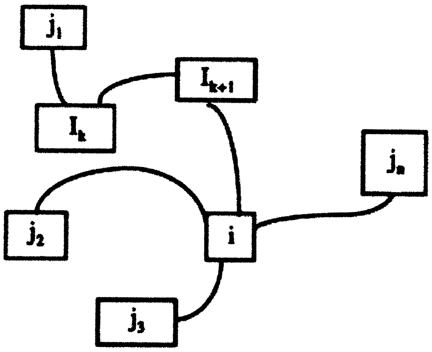

Fig. 1. Random paths to pixel *i*.

value of relative reflectance along a number N of random paths across the image, ending at that point (Fig. 1).

Hence, using Retinex as a model of the cortical computation, the "perceived" RGB intensity values for each point i is the mean value of relative reflectances $r^{i,j}_{\mathrm{R,G,B}}$ computed over a N number of random paths (Fig. 1) ending at point i, separately for each RGB channel:

$$R^{i}_{\mathrm{R,G,B}} = \frac{\sum_{k=1}^{N} r^{i,j_k}_{\mathrm{R,G,B}}}{N}$$

with

$$r^{i,j}_{\mathrm{R,G,B}} = \sum_{x \in \mathrm{path}} \delta \log \frac{I^{x+1}}{I^{x}}$$

where, for each chromatic channel RGB, I^x is the pixel brightness at the location x and I^{x+1} the brightness at the following location $x+1$ along the random path (Fig. 1) and δ a threshold value computed in the following way:

$$\delta = \begin{cases} 1 & \text{if } \left|\log \dfrac{I^{x+1}}{I^{x}}\right| > \text{threshold} \\ 0 & \text{else} \end{cases}$$

For the three channels RGB, these computations are executed independently.

As seen in the formula above, Retinex has a reset mechanism; if, during a path computation a lighter area is found, the cumulated relative reflectance is forced to zero, making the average computation restart from this area. The effect of the reset mechanism is to consider the lightest area of an image as the reference value of the color white.

A critical problem in the algorithm is the choice of the random path. The results depend on the randomness and on the number of the paths that are chosen for the computation of the relative reflectance. Moreover, the relative reflectance depends on the value of the threshold, making low reflectance ratios, which correspond to a smooth color shading, less relevant.

The solution proposed in this paper is based on an approximation to Brownian motion. The idea is that the receptive field's centroid distribution of cortical area V4, responsible for color vision in complex scenes [25], can be approximated by a Brownian path. The application of an approximated Brownian path generation to the Retinex algorithm greatly improves the effectiveness of the algorithm and its speed.

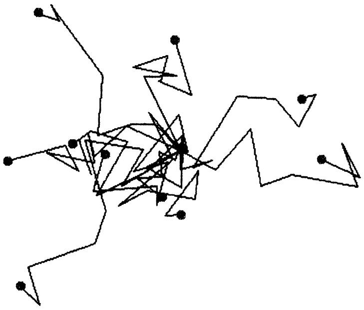

Fig. 2. Example of 10 mid-point displacement random paths.

5. The Brownian-path algorithm

A random mid-point displacement technique [21] has been adopted to implement the Brownian motion to approximate a path in the Retinex algorithm. The number of recursions to generate the Brownian path is a power of two. An example with 10 paths can be seen in Fig. 2. They strongly resemble the centroids distribution in the area V4 [25].

Along the path, the algorithm scan converts the pixels, computing the relative reflectance for each pixel along the edge:

```
foreach chromatic channel do compute sequentially each pixel as follows:
  generate N random points in the image and
  foreach random point do
    generate a path by $2^M$ random mid-point displacement;
    follow the generated path and
    foreach pixel do
      calculate the new chain function value (Knew);
      if Knew > threshold then Kold = Knew;
      if Knew > 1 then Kold = 1;
        (a pixel with an higher lightness value has been visited)
      newChromaticPixelValue = average of all N final values Kold;
        (1 foreach random path)
```

Comparing the results of this algorithm with a traditional straight paths random generation approach, a significant reduction of the number of paths necessary to approximate the lightness value of each pixel has been observed. While the straight-path algorithm requires about 200 paths, the Brownian-path algorithm gives the same result with less than 20 paths per pixel. Therefore, the drastic reduction of

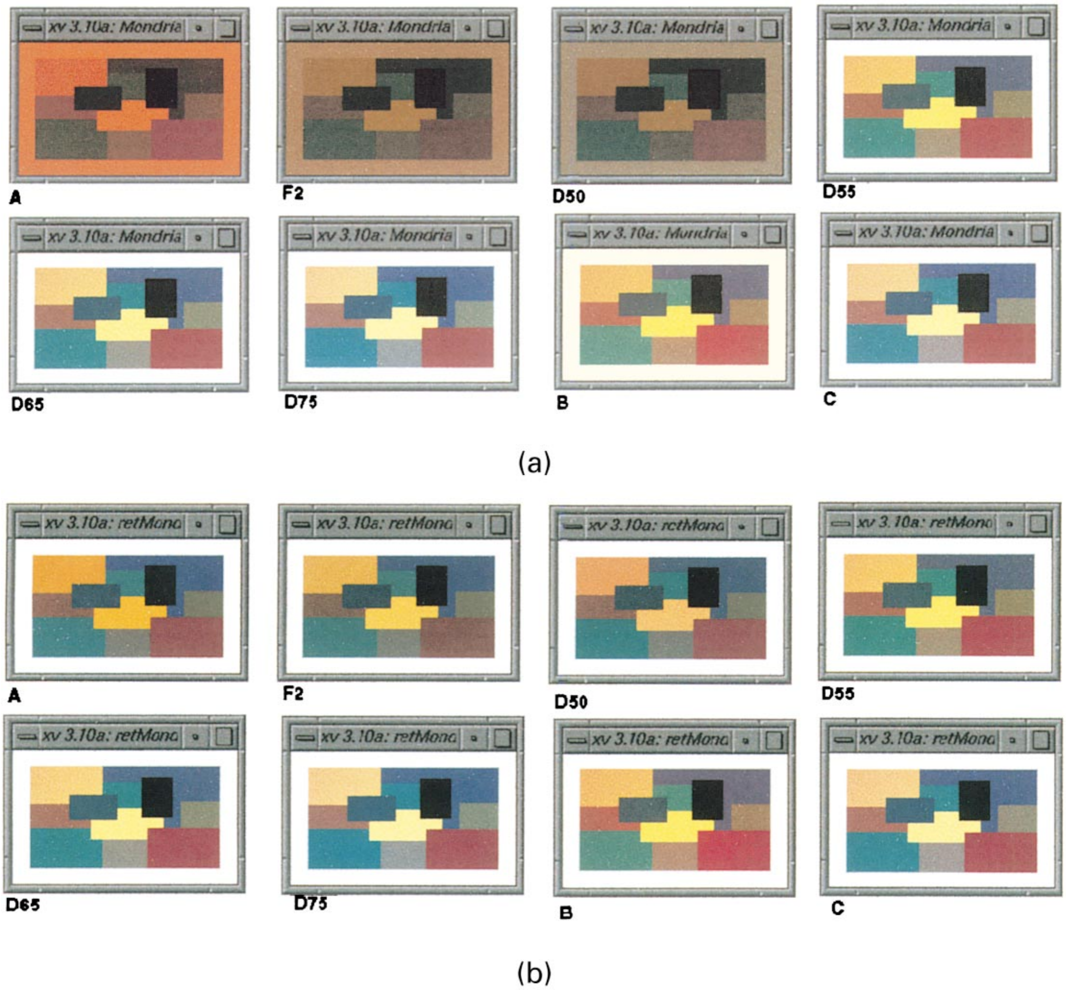

Fig. 3. (a) Synthetic patchworks generated with different illuminants. (b) The same patchworks after the Retinex filtering.

the total number of paths required justifies the computational overhead of generating the Brownian path approximation.

The computational space complexity of the algorithm is not heavy, it requires only the memory to keep the original image and the filtered one. On the contrary the computational time complexity is heavy: with *k* paths crossing *x* of the *n* pixels of the image for each pixel computation, the number of floating point pixel ratios is $k \cdot \chi \cdot n$. The value of *x* can be controlled by tuning the Brownian paths generation parameters (max distance, max displacement, number of displacement, etc.) and *k* can be set as a parameter, affecting the quality of the result (see Section 4). A 640 × 480 image is processed with 60 Brownian paths, by a Pentium II at 333 MHz with Linux in about 10 min. A multi-scale algorithm is under development in order to reduce the processing time.

6. Retinex recovery of the corresponding color

From a colorimetric point of view, the algorithm has proven its ability to solve the chromatic adaptation problem, and reconstruct the corresponding color under standard illumination (D65). In order to measure its precision, we have devised a test on synthetic images [15]; we recall here the main results of our test.

The purpose of this test is to quantitatively corroborate the effectiveness of the Retinex algorithm to discount the illuminant in computer generated images. 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 have been used as the input of a photorealistic image synthesis program, based on the ray tracing method. Using various standard-light source descriptions, the program has generated different images of the same patchwork under these chosen illuminants, allowing us to measure a chromatic distance in the CIELAB space. 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. The synthetic images are visible in Fig. 3a and the Retinex results in Fig. 3b.

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

ΔE: 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

The chosen chromatic distance is the Euclidean distance ΔE in the CIELAB space [5]. 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.

As can be seen from Table 1, all the distances for each colored patch, between each illuminant and the reference illuminant D65 decrease after the Retinex filtering, except for the black patch. The fact that Retinex does not perform well over very dark regions derives from its "normalization to the white" that mimics the human visual system behavior. Such behavior has been tested in the following test section.

7. Image enhancement and chromatic equalization

If the Retinex algorithm is used to enhance an image without any information about the acquisition phase (e.g.

Fig. 4. Retinex equalization comparison.

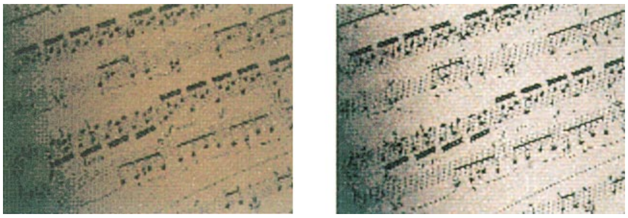

Fig. 5. Color constancy effect of the Retinex filter.

an image from internet), measuring the color shift appears to be useless. In this case the equalization properties of the algorithm are crucial to obtain a better image in terms of readability, color dynamics and overall preference.

Recent topics in digital image research address the problem of the tone reproduction from the "user's preference" perspective, decreasing the attention on the image fidelity and increasing the attention on all the characteristics (saturation, contrast, etc.) that make an image more visually appealing [4,23].

Following this approach, we have tested the Retinex filter on various photographic images, comparing its equalization

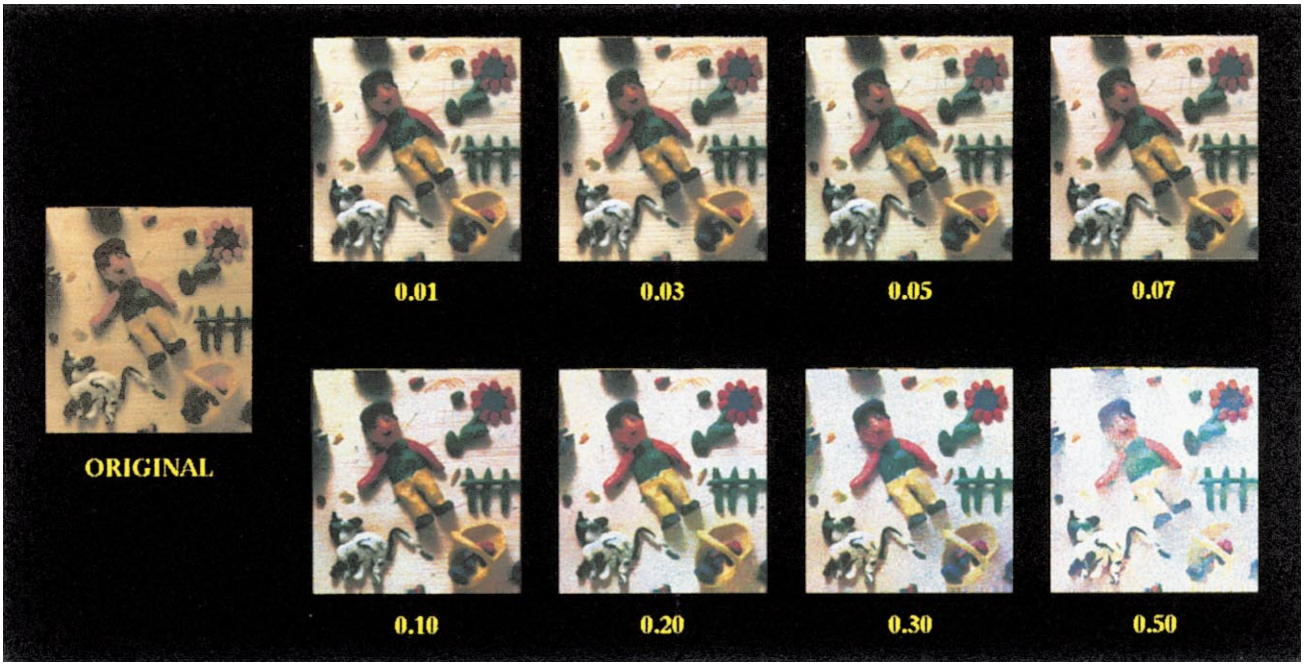

Fig. 6. Retinex effects with different threshold values.

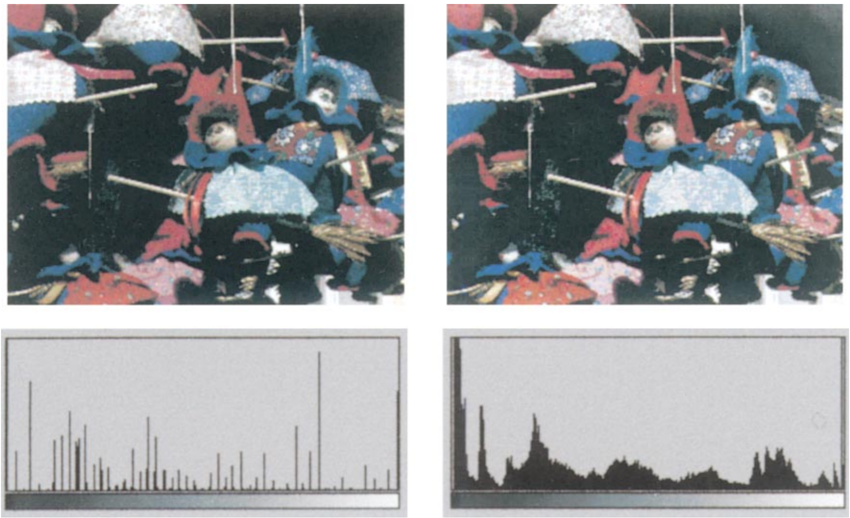

Fig. 7. Retinex dequantization effect.

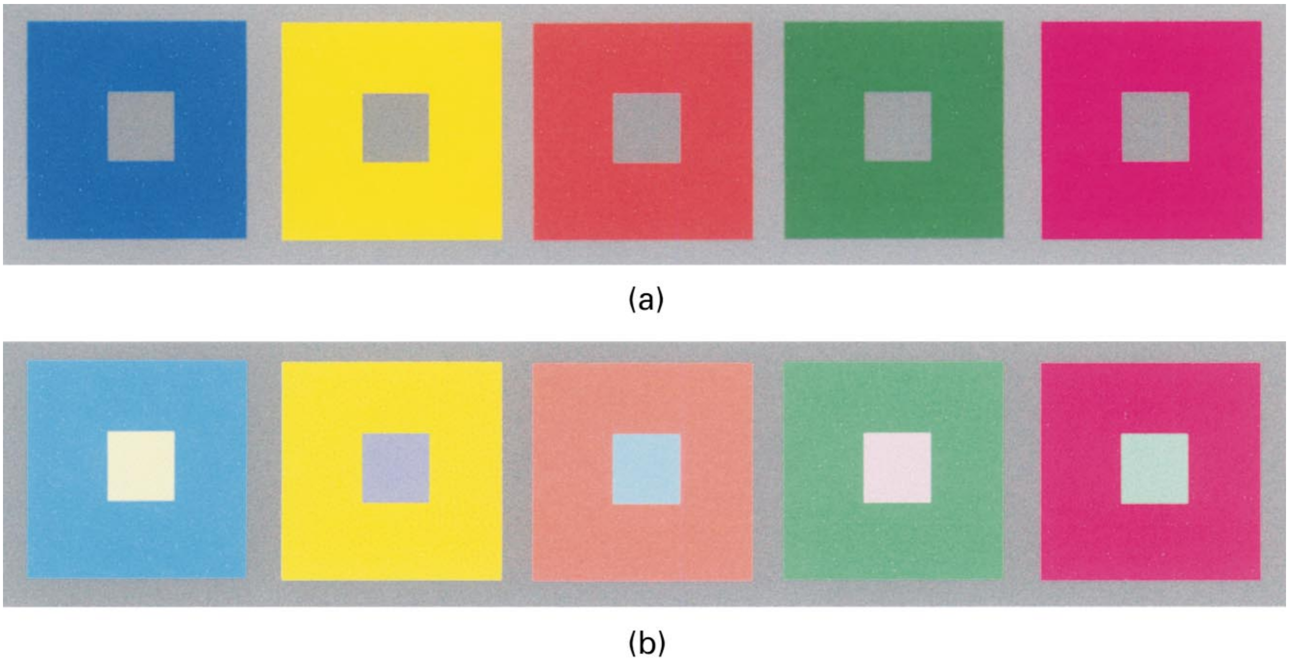

Fig. 8. (a) Simultaneous contrast illusion. (b) Simultaneous contrast after the Retinex filtering.

results with the classic histogram equalization. Fig. 4 shows a comparison of the Retinex equalization properties versus the histogram equalization. The original image (Fig. 4, top) is underexposed, white color is missing. In the Retinex filtered image (Fig. 4, bottom left) the snow returns white and all the other tones are equalized in a natural way; in this case the histogram equalization exaggerates the image contrast and false the colors, e.g. the sky blue is oversaturated (Fig. 4, bottom right).

As seen in Section 6, Retinex discounts any chromatic dominant. In Fig. 5 an example is presented, showing the color constancy phenomenon. In the image processed with Retinex (Fig. 5, right) the light brown color dominant of the original image (Fig. 5, left) has been eliminated.

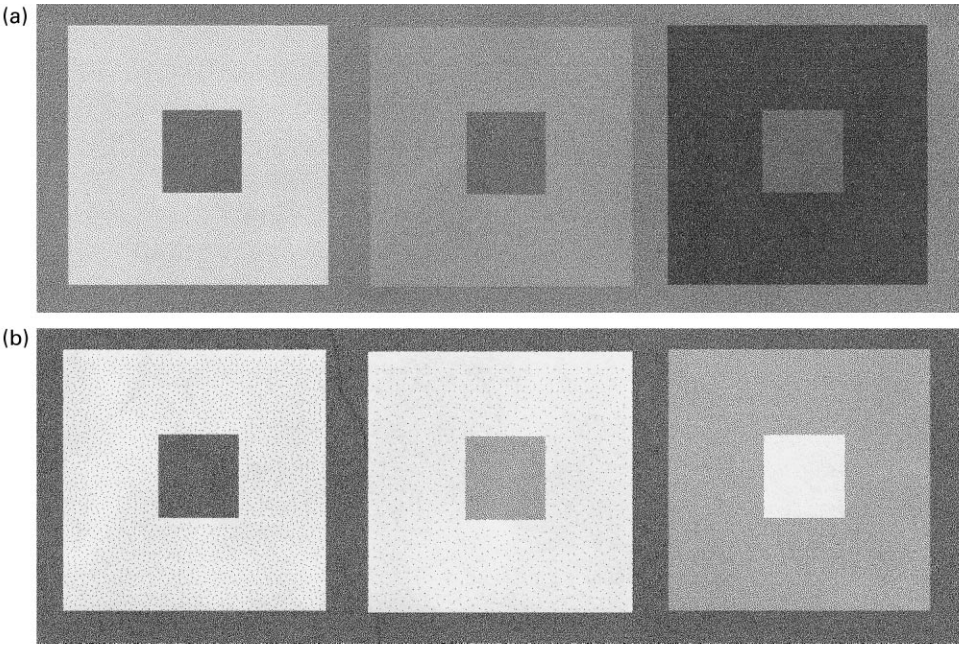

Fig. 9. (a) Simultaneous contrast with gray patches. (b) Simultaneous contrast with gray patches after the Retinex filtering.

Table 2
Patch RGB values in the simultaneous contrast illusion

Surround color	RGB surround	RGB center
Light blue	39–171–254	179–179–179
Yellow	255–255–0	179–179–179
Red	252–69–69	179–179–179
Green	53–209–41	179–179–179
Purple	248–3–250	179–179–179

Moreover, the smooth varying illumination effect in the original image (Fig. 5, right) has been reduced by the threshold comparison.

Regarding the threshold effect, Fig. 6 shows some Retinex output from the same image, using different threshold values. As the threshold increases there is less saturation on the final image; we have discovered through experimentation that it is not a critical parameter and a value around 0.5 gives a natural effect on every type of image. It must be noticed that the color constancy property of the algorithm is not affected by the threshold value, in all the cases, the orange dominant of the original image is wiped out.

Retinex has a global and a local effect [17]. The global effect discounts the illuminant of the scene while the local one computes the new pixel value according to the neighborhood pixels explored by the Brownian paths. In this way Retinex performs a data driven local dequantization. In Fig. 7 an eight bit color image and the same image after the Retinex filtering with their corresponding histograms are shown. The original image is quite balanced, thus the application of Retinex does not change very much the overall appearance of the image, but from the histogram it can be noticed that the image tones increased and their distribution appears more uniform.

8. Color illusions experiments

The color illusion phenomena (as well as color constancy), are difficult to explain with the classical color models. In these cases, a local chromatic adaptation mechanism occurs, producing a color sensation modified by local effects such as lateral inhibition, background effect, contrast enhancement, etc.

We have tested the algorithm on some classic color illusions in order to verify that the Retinex model behaves like the human vision system [13,14].

Table 3
Patch RGB values in the simultaneous contrast illusion after the Retinex filtering

Surround color	RGB surround	RGB center
Light blue	91–247–253	252–250–180
Yellow	253–253–5	180–180–251
Red	251–127–126	180–252–252
Green	112–253–90	252–217–252
Purple	251–18–251	182–252–181

Table 4
Patch gray values in the simultaneous contrast illusion

Surround color	Gray value surround	Gray value center
Gray1	235	179
Gray2	204	179
Gray3	153	179

Table 5
Patch gray values in the simultaneous contrast illusion after the Retinex filtering

Surround color	Gray value surround	Gray value center
Gray1	251	192
Gray2	253	224
Gray3	226	254

A well-known color illusion derives from what Itten, Albers and others call *simultaneous contrast*. It arises, e.g. when a small gray square lays on a larger and saturated background color (Fig. 8a). In this case, what the observer perceives is not the gray color but a hue, which tends to complement the color of the background. The Retinex results show that the algorithm computes a color triplet, which is very similar to the perceived color in natural conditions (Fig. 8b). The numerical values of this experiment can be seen in Tables 2 and 3.

If gray patches instead of the colored ones are used, the results of the Retinex filter still goes in the direction of the human vision system behavior, as can be noticed from Fig. 9a,b and the relative Tables 4 and 5. The gray patches in the center have the same value, but they are perceived differently according to the background lightness. The more light the background is, the more dark appear the patch in the center and the Retinex output follows this illusion.

In Fig. 10, a color illusion by Joseph Albers is simulated. In the original image (Fig. 10, left) the two brown squares are of the same color; due to the background, our visual

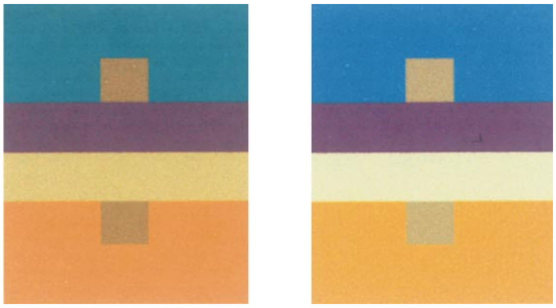

Fig. 10. Albers color illusion.

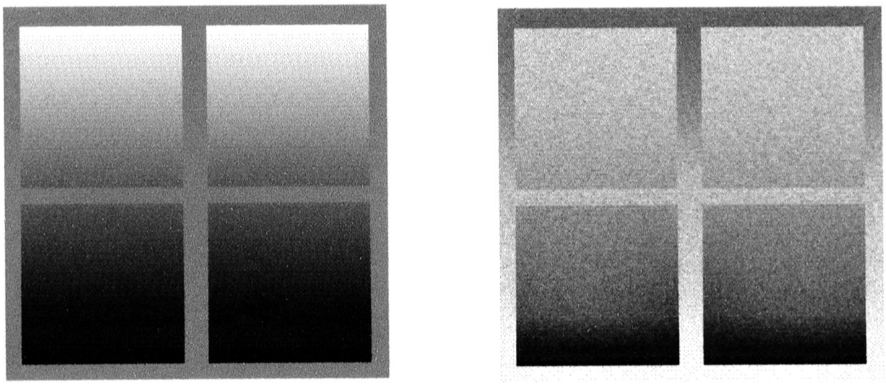

Fig. 11. Itten gray window illusion.

system perceives them as different. Retinex output (Fig. 10, right) also reflects this difference.

Finally, in Fig. 11 another illusion by Joseph Albers is computed with the Retinex algorithm: in the original (Fig. 11, left), the gray background is perceived as non-uniform and smoothly changing, in the opposite way of the internal squares smooth changing. In this case, the Retinex output (Fig. 11, right) emphasizes this effect as well.

9. Conclusion and perspectives

In this paper an algorithm that computes the Retinex model of color vision is proposed. Our approach adopts an approximation of a Brownian path using a mid-point displacement technique. This idea is inspired by the results of some neuro-physiological researches about human cortical vision areas, where the distribution of receptive fields centroids mimics a Brownian path, as demonstrated in many experiments by Zeki [25] on macaque monkeys.

The proposed algorithm has demonstrated the capability to account for color constancy, discounting the illuminant of the scene. Moreover it exhibits useful color equalization properties and can be used to solve tone reproduction problems or simply to obtain better balanced and more pleasant images. It expands the image dynamic according to the spatial distribution of the color information achieving a natural equalization and a data driven dequantization.

Finally, we have tested the algorithm on color illusions and have discovered that it is devised in the same way as the human vision system.

Retinex does not have problems only on critical color configurations, it also does not perform a good color balance in dark local areas with very low pixel values and limited dynamics. This problem can be solved by computing a negative input image, applying Retinex, complementing the result and then balancing it with the regular Retinex filtering. This idea must be further investigated and a correct way to fuse the two outputs should be found.

The algorithm, in this presented version, is computationally heavy, but we are developing a multi-scale version to solve this problem.

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