Color Contrast: A Biological Model and its Application for Real Images

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Abstract

A novel biological model for color contrast is presented. An additional goal of the model was to achieve automatic color correction of still and video images. The model predicts human visual performance according to the physiology of the first and second order of the color-coded cells in visual system. It is based on the properties of retinal ganglion cells (opponent cells) and cortical cells (double opponent cells) as well as on chromatic adaptation mechanisms in these double opponent color-coded cells: remote chromatic adaptation. The simulations calculated the perceived image for still images, and were performed in order to correct image colors. The results indicate that the contribution of adaptation mechanisms to color contrast is significant, robust, and enables color correction of still images.

Introduction

There is widespread agreement in the literature that the perception of color is affected by adjacent chromatic stimuli. Studies have shown that color perception is influenced not only by adjacent contrasting regions but also by more remote noncontiguous regions within a visual scene.[1-7]

We suggest that adjacent and remote effects on perceived color are regarded as being of the first order. What about the second order effect, which is the influence of the contrast of peripheral areas on the contrast of a central area? Psychophysical and electrophysiological findings show the existence of second order adaptation at the cortical level, i.e., contrast-contrast adaptation, with spatio-temporal basic properties somewhat similar to the first order effects.[8-10] The biological rationale for this is also derived from the findings that contrast induction has been shown to have interocular transfer which suggests that it has a cortical locus, whereas color induction has been found to have a pre-cortical locus.[6,7] More direct evidence on the locus of the contrast-contrast effect was found by recording from single cells in the V4 area.[10] These authors found a large spectrally sensitive surround outside the "classical receptive field" of most V4 cells.

The model suggested here presents a possible mechanism for the second order cortical level, which shares many common properties of gain control, i.e., a "curve-shifting mechanism", as suggested for first order color adaptation.[11,12] A curve-shifting effect is the transition from one response curve to another, due to a change in light intensity (or color), in order to obtain a higher gain of the new light intensity.[11-14] In the current model the "curve-shifting" mechanism relates to an increase in the color contrast domain and not to the color or intensity as in our previous models.[11,14]

Model

The model is presented in three main stages. The first stage (I) describes the transformation of visual stimuli into retinal ganglion cells' responses of three types of color-coded On-center cells. The second stage (II) describes the cortical color coded cells, double opponent cells and the remote adaptation mechanism which acts on their responses. The third stage (III) calculates a transformation of these cells' activity levels to a perceived image, in a standard CIE notation (XYZ) or RGB scale. This is performed through an inverse function.

I. The Responses of Three Color Coded Types of On-Center Cells

During the first stage of the model an image was processed in the three most common color-coded channels of the retina (L^+M^-, M^+L^- and $S^+(L+M)^-$), producing three activation-level maps of On-center color coded cells, with L, M and S standing for long, medium and short wavelength sensitivity, respectively. For example, an $S^+(L+M)^-$ cell has an excitatory S ('blue') response in its receptive field center and an inhibitory (L+M) ('yellow') response in its surround area. These three cell types belong to the On type cells.

The input to the cones level is the spectral composition of the light reaching the retina, when the illumination falls on surfaces of objects and is reflected from them. The field of view is mapped by the three types of cones, L, M and S. The quantum catch of each of the three cone-types, L_{cone}, M_{cone} and S_{cone}, is expressed by an inner product of the cone pigment sensitivities, the spectral composition of the illumination and the reflectance properties of the surface.[15]

The spatial response profile of the two sub-regions of the opponent RF (receptive fields), 'center' and 'surround' is expressed by the commonly used Difference-of-Gaussians (DOG). The 'Center' signals for the three spectral regions L_{cen}, M_{cen} and S_{cen}, that feed the retinal level are defined as an integral of the cones' quantum catches over the center sub-region, with a Gaussian decaying spatial weight function.

$$L_{cen} = \iint_{cen-area} L_{cone}(x,y) f_c(x,y)\,dxdy \quad (1)$$
$$M_{cen} = \iint_{cen-area} M_{cone}(x,y) f_c(x,y)\,dxdy$$
$$S_{cen} = \iint_{cen-area} S_{cone}(x,y) f_c(x,y)\,dxdy$$

where f_c is defined by:

$$f_c(x,y) = \frac{exp[-(x^2+y^2)/\rho^2_{cen}]}{\pi\rho^2_{cen}};\ x,y \in center \quad (2)$$

The 'center' can be stimulated by as little as a single cone, as frequently occurs in the fovea (the center of the gaze). The 'Surround' signals L_{srnd}, M_{srnd} and $(L+M)_{srnd}$ are similarly defined, with a spatial weight function three times larger in diameter than that of the 'center'.[13]

The color-coded 'center' and 'surround' sub-regions adapt separately, before the subtraction operation between their responses, as shown physiologically.[13,14] However, as mentioned above this operation is skipped here, since the color constancy is not performed for this application. The response, R, of each of the On-center color coded cells was therefore expressed by:

$$R(G,t) = \frac{G_{cen}(t)}{G_{cen}(t)+\sigma_{cen}(G_{cen},t)} - \frac{G_{srnd}(t)}{G_{srnd}(t)+\sigma_{srnd}(G_{srnd},t)} \quad (3)$$

where G is the signal (of each of the color coded cells) feeding the 'center' (Eq. 1) or the 'surround' sub-regions and σ is used here as the 'saturation constant' of the Naka-Rushton equation and not as the adaptation factor.[6,11,14]

Opponent Cell Responses: A color opponent cell's response R_{op} (R_{op} = R(G,t)), (Eq. 4), is the subtraction between the responses of the center and the surround of each retinal ganglion cell type: for On-center cells the response is expressed as L^+M^-, M^+L^- and $S^+(L+M)^-$, and for Off-center cells as L^-M^+, M^-L^+ and $S^-(L+M)^+$:

$$R_{op(l+)} = L_{cen} - M_{srnd} \quad (4)$$
$$R_{op(m+)} = M_{cen} - L_{srnd}$$
$$R_{op(s+)} = S_{cen} - (L+M)_{srnd}$$

II. Double-Opponent Cells

The "double-opponent" (do) cells of the visual cortex, in V1 and V2 areas (which their receptive fields are spatially larger than those of the opponent cells), combine the responses of the On-center and Off-center retinal ganglion (opponent) cells. A double-opponent cell is fed by an On cell type receptive field, for example, to long-wave light and an Off cell type to middle-wave light in the center receptive field region of the double opponent cell and by an opponent cell type of the receptive field in the surround region.[16] Thus, the structure of the double opponent cell is composed of a center receptive field, for example $L_{do\text{-}c}$ ("do-center" (do-c) signal) from the first group of On-center ganglion cells (for example, L^+M^-, the group that subtracts green surround responses from L center responses) located in a do-center area, and receives its own surround response $L_{do\text{-}s}$ ("do-surround" (do-s) signal) from a corresponding group of Off-center (e.g., L^-M^+) cells located in a do-surround area**.** The mathematical formulation for the three-color do-center expressions that serve as both responses and filters is given by:

$$L_{(do-c)} = \iint_{center\_area} R^*_{op(l+)} f_{(do-c)}(x,y)\,dxdy \quad (5)$$
$$M_{(do-c)} = \iint_{center\_area} R^*_{op(m+)} f_{(do-c)}(x,y)\,dxdy$$
$$S_{(do-c)} = \iint_{center\_area} R^*_{op(s+)} f_{(do-c)}(x,y)\,dxdy$$

where $R^*_{op\ (l+)}$, $R^*_{op\ (m+)}$, $R^*_{op\ (s+)}$ are each a spatial as well as a spectral filter convolved with $f_{(do\text{-}c)}$, the weight function of the center sub-region of each double-opponent cell. The $f_{(do\text{-}c)}$ has a Gaussian spatial-weight function. A similar exemplary mathematical formulation for the three-color do-surround expressions that serve as both responses and filters is given by:

$$L_{(do-s)} = \iint_{center\_serround} R^*_{op(l-)} f_{(do-s)}(x,y)\,dxdy \quad (6)$$
$$M_{(do-s)} = \iint_{center\_serround} R^*_{op(m-)} f_{(do-s)}(x,y)\,dxdy$$
$$S_{(do-s)} = \iint_{center\_serround} R^*_{op(s-)} f_{(do-s)}(x,y)\,dxdy$$

where $R^*_{op\ (l-)}$, $R^*_{op\ (m-)}$, and $R^*_{op\ (s-)}$ are each a spatial as well as a spectral filter convolved with $f_{(do\text{-}s)}$ (the spatial weight function of the surround sub-region of each double-opponent cell). These filters are similar to $R^*_{op\ (l+)}$, $R^*_{op\ (m+)}$, $R^*_{op\ (s+)}$. However, here they used as filters convolved on an area of the surround sub-region of the double-opponent cells. $f_{(do\text{-}s)}$ is located as an annulus around the center area of these double-opponent cells. The $f_{(do\text{-}s)}$ has a Gaussian spatial-weight function with an opponent sign.

The next step is obtaining the outputs of the double-opponent cells fed by the receptive fields of both the On-center opponent (Eq. 5) and the Off-center opponent (Eq. 6) color-coded cells. The double-opponent responses (or "do-outputs") of the three On-center, double opponent color coded cells: L^+M^-/L^-M^+, M^+L^-/M^-L^+, $S^+(L+M)^-/S^-(L+M)^+$, before the adaptation stage, are given by:

$$L_{do} = L_{(do-c)} - M_{(do-s)} \quad (7)$$
$$M_{do} = M_{(do-c)} - L_{(do-s)}$$
$$S_{do} = S_{(do-c)} - (L_{(do-s)} + M_{(do-s)})$$

For the simulation we optionally used the fourth (yellow) do-output that obtained by subtracting the blue do-surround from the yellow do-center. Another option was used for the achromatic contrast enhancement by the opponent cells or the double-opponent cells.

Remote Area: The 'Remote' signal represents the peripheral area which extends far beyond the borders of the double opponent classical receptive field of the V4 area.[10] The color coded cells in area V4 were found to have large suppressive surrounds, each of which has a spectral sensitivity similar to that of the center of the receptive field. The 'remote' area has the shape of an annulus around the entire RF region. Since the remote area is located outside the 'classical' RF region, its internal diameter was set to be larger than the external diameter of the 'surround'. The four remote signals ($L_{(do\text{-}remote)}$, $M_{(do\text{-}remote)}$, $S_{(do\text{-}remote)}$ and

$(L+M)_{(do\text{-}remote)}$ are defined in Eq. 8 as the convolution or inner product of each filter of the double-opponent cell signal with a remote spatial function f_r applied to the do-remote area for each location in the remote area: The four 'remote' signals, L_{remote}, M_{remote}, S_{remote} and $(L+M)_{remote}$ that feed the double opponent cells level, were defined as:

$$\begin{aligned} L_{(do-remote)} &= \iint_{remote\,area} L^*_{(do-c)}\, f_r(x,y)\,dxdy \\ M_{(do-remote)} &= \iint_{remote\,area} M^*_{(do-c)}\, f_r(x,y)\,dxdy \\ S_{(do-remote)} &= \iint_{remote\,area} S^*_{(do-c)}\, f_r(x,y)\,dxdy \\ (L+M)_{(do-remote)} &= \iint_{remote\,area} Y^*_{(do-c)}\, f_r(x,y)\,dxdy \end{aligned} \tag{8}$$

where $L^*_{(do\text{-}c)}$, $M^*_{(do\text{-}c)}$, $S^*_{(do\text{-}c)}$ and $Y^*_{(do\text{-}c)} = (L+M)^*_{(do\text{-}c)}$ are spatial and spectral filters which act on the do-remote areas. f_r was chosen as an exponentially decaying spatial-weight function. f_r also can be a Gaussian function.

$$f_r(x,y) = \frac{exp\left[-\sqrt{(x^2+y^2)}\,/\,K_{remote}\right]}{A_{remote}} \tag{9}$$

K_{remote} is a constant, which defines the slope of the weight function, and A_{remote} is a factor of normalization to a unit:

$$A_{remote} = \left(\iint_{remote\,area} exp\left(-\frac{\sqrt{x^2+y^2}}{k_{remote}} \right) \right)^{-1} \tag{10}$$

Adaptation: The color-coded double-opponent cells are adapted[10,14,16] (corrected) by a remote adaptation in a manner similar to a mechanism based on psycho-physical findings, as shown in Singer & D'Zmura.[8] Singer & D'Zmura found that modulating the contrast of an annulus induces an apparent modulation of the color contrast of a central disk, under isoluminance conditions. Adaptation in the visual pathway is not necessarily related only to remote or surround regions. It can also be related to the stimulus itself, as has been described for local adaptation.[17,6,11]

The suggested mechanism for adaptation at the level of cortical color coded cells (contrast adaptation, i.e., second order) is similar to the adaptation at the retinal level (intensity or color adaptation, first order). Thus, cortical color-coded cells are adapted by a "curve-shifting" mechanism,[12,11,14] expressed here as a dynamic Naka Rushton equation, Eq. 11. The response, *R*, of each of the adapted On-center color coded double opponent cells is therefore expressed by:

$$R_{(do-a)}(G,t) = R_{max}\frac{G(t)}{G(t)+\sigma(G,t)} \tag{11}$$

where,

$$\sigma_{remote} = cG_b + \beta \tag{12}$$

and where G_b stands for L_{do}, M_{do} and S_{do} for the responses of double opponent receptive fields (Eq. 8), and R_{max} is the maximum response used as a normalization factor. c and β are constant parameters. The constant c describes the degree of 'curve-shifting', i.e., it determines the shift of the response curve after a certain amount of contrast has been viewed. The constant β is related to the 'transition contrast' level which determines the degree of color contrast at which the gain is affected. A detailed explanation of the 'transition contrast' relating to illumination domain can be found in Dahari and Spitzer.[14]

Based on psychophysical[8,9] and on physiological experiments[10] the remote adaptation factors, σ_r (Naka-Rushton type semi-saturation constants) given by Eq. 12 and Eqs.11-15 were chosen such that they consist of the same spectral composition as the relevant center area of the receptive field.

The adaptation is reflected in a shift of the response curve as a function of time. Consequently, if the change from the previous stimulation is sufficiently large, each time a new range of input color contrast to a color coded channel is viewed, the curve will shift and will bring the system to a new adaptation state. This curve shift occurs according to the temporal filter which reflects the temporal apparent decaying function of the response.

The adapting component $G_b(t)$ for the remote adaptation of each double-opponent receptive field region can be expressed functionally as a convolution of G with a low-path temporal filter f_b.[11,14]

$$G_b(t) = G(t) * f_b(t) \tag{13}$$

where

$$f_b(t) = [1/\tau_b]\exp(-t/\tau); \quad t \geq 0 \tag{14}$$

and where τ_b is a time semi-constant (or alternatively a constant) of the low-pass filter which depends on the stimulus history. Its dependence on stimulus history preferably takes the form of:

$$\tau_b(t) = \frac{\tau_m}{1+\frac{|G(t)-G_b(t)|}{G_n}} \tag{15}$$

where τ_m is a constant that represents the maximum value of τ_b (typically ~500msec) and G_n is a normalization constant. Aside from corresponding to known physiological phenomena (e.g. as explained in Dahari and Spitzer and the references therein), the significance of applying a variable dynamic temporal component becomes evident upon observation of the dynamic color contrast adjustment algorithm performance in the absence of such a component. In such a dynamic case the rate of adaptation (Eqs. 13-15) changes as a function of the signal magnitude of each contrast channel.

When t=∞ (for both the 'center' and the 'surround') at a steady state, G_b for the L (red) for example is given by:

$$G_{b(t=\infty..} = L_{(do\text{-}remote)} \tag{16}$$

III. Transformation of the Adapted Color Coded Cells' Response to a Perceived Image

In order to perform contrast enhancement on real images, the activation levels of the simulated (Eq. 17) double-opponent cells (at any location in the retina or in the image) into a perceived color must be inversely transformed. The calculated perceived color contrast is the color contrast that would stimulate the triplet of $P_{do\text{-}a}$

LMS to the same responses, with a uniform non-contrast surface present in their "remote" areas. The following equations relate to the three (or four) main color-coded cells. All these equations can also be applied to the yellow double-opponent and opponent cells.

For the sake of clarity we rewrite Eq. 11, but after substituting G with the relevant color channels. The responses of the double-opponent cells that include the adaptation are given by:

$$L_{do-a} = \frac{L_{do}}{L_{do} + \iint\limits_{remote} L_{do-remote} f_r(x,y)dxdy} \qquad (17)$$

$$M_{do-a} = \frac{M_{do}}{M_{do} + \iint\limits_{remote} M_{do-remote} f_r(x,y)dxdy}$$

$$S_{do-a} = \frac{S_{do}}{S_{do} + \iint\limits_{remote} S_{do-remote} f_r(x,y)dxdy}$$

A key assumption in performing an inverse function as described above is that the contrast in the "remote" areas ($L`_{do\text{-}remote}$, $M`_{do\text{-}remote}$ and $S`_{do\text{-}remote}$) is equal to that in the double-opponent center area. This is expressed as:

$$L'_{do-remote} = L_{do-a} \quad M'_{do-remote} = M_{do-a} \quad S'_{do-remote} = S_{do-a} \qquad (18)$$

The purpose of this procedure is used for inversely calculating the functions of double opponent and opponent responses to the cone responses.[11,18,19] The adapted cone responses may then be converted to the CIE RGB color space or to any other color space.[15]

Simulations

The cones' quantum-catches were calculated from a given set of (CIE XYZ) values, using a normalized 'standard observer' matrix (Ref. 15, p. 612). Each pixel was simulated as observed by one cone-triplet (L, M, S). Thus, the 'center' size was one pixel. The 'remote' was usually an annulus with an inner diameter of 9 pixels, and an outer diameter of 63 pixels. Other parameters were optimally determined according to a wide collection of real images simulations and algorithm performance.[18]

Performance of the Model

Figure 1a presents an example of a still image before correction, and Fig. 1b shows the same image after color contrast enhancement by the color contrast algorithm. The algorithm caused color enhancement which resulted in higher saturation of the colors and better identification of some of the details in the image, for example the colorful bushes on the left side of the image.

Figure 2 presents an additional example of applying of the algorithm with only the color enhancement (Fig. 2b) and with the luminance enhancement as well (Fig. 2c). A clear color enhancement of the yellowish reddish flower can be seen at the left bottom part of the image and in the colored landmarks in the images.

Figure 3 demonstrates the ability of the algorithm to modulate the spatial enhancement. The fine (small) details are presented in Fig. 3c and the more crude details in Fig. 3b. This contrast enhancement modulation is performed by changing the size of the spatial mask of the double opponent receptive field (Eqs. 5-7). Figure 3d presents an additional luminance enhancement which further emphasizes the details in the image.

Discussion and Conclusions

A biological model based on physiological color coded receptive fields and physiological adaptation mechanisms is presented. This model succeeds in performing automatic color contrast on real images (patent pending[19]).

The relevant visual pathway site described in the model for color contrast adaptation mechanisms is in the visual cortex (areas V1, V2 and V4). It is based on physiological findings: the double opponent receptive fields and the remote area which extends beyond the classical receptive field as well as on psychophysical findings: contrast-contrast induction and its spatial properties.[8,9,10,17] The current model suggests that contrast adaptation is a second order mechanism, whereas the color adaptation, perceived color (as occurred at color constancy mechanism) is regarded as being of the first order. Such an order of color performances, of first dealing with the color and then with the color contrast, has a computational advantage since color corrections become more cost-effective. This enables the visual system to first perform perceived color calculations and color constancy and then modulation of contrast in order to enhance the color texture and the color differences. Note that modulation of color contrast can somewhat affect the perceived color. This is also true for intensity contrast and perceived intensity.

Comparison with Other Models: Previous studies on color contrast or color enhancement can be divided into human-perception oriented (and/or biologically oriented) and machine-vision oriented approaches. As far as we know, few computational models have been published which aimed to combine the two approaches. Several psychophysical models were suggested and aimed to describe the effect of color contrast or color contrast perception,[17,9,21] even though they did not consider the physiological receptive fields of the color coded cells as we did. However, these models share several common spatial properties of the spatial masks and their character of general interaction. Most of the psychophysical models have not, as far as we know, been applied to real images, except for a recent model of D'zmura[20] in which the algorithm for the contrast gain control equalizes contrast levels across space in real images. The model of D'Zmura & Singer[8,9,20] includes luminance induction which is dependent on the spatial frequency as observed experimentally. The building blocks of their and our algorithm differ in the degree of linearity, in applying surround regions and not applying remote regions and inverse function. These differences exist, even though both algorithms were motivated by the same psycho-physical data.

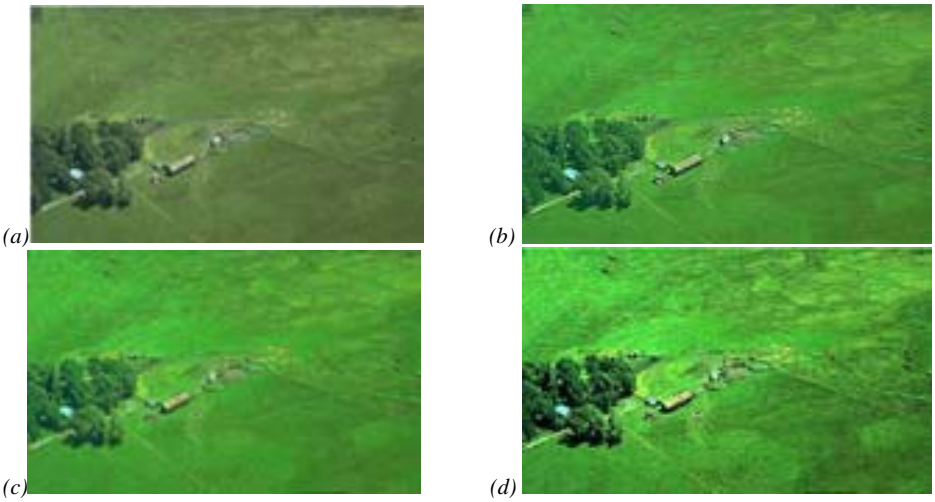
Most of the color enhancement or color contrast methods dealing with image processing approach the subject of improving or adjusting contrast and/or intensity using principles unrelated to the visual system and are not discussed here, because of the scope of the paper. Nevertheless comparison of performances between our algorithm and other algorithms which also derived from

(a) (b)

Figure 1. An origina l image (a) and its color contrast enhancement (b).

(a) (b) (c)

Figure 2. An original image (a) and its color contrast enhancement (b) and after additional correction by a combination of achromatic and chromatic contrast enhancement (c). (figure 2a was taken with permission from the study of Ref. 21.



(a) (b) (c) (d)

Figure 3 . The ability of the algorithm to modulate the spatial enhancement. An original image (a) and its color contrast enhancement (b) and additional correction with smaller spatial masks (outer diameter of the double opponent masks (Eqs. 5,6)) of 6 pixels versus 18 in the upper corrected image (c). Additional correction by a combination of achromatic and chromatic contrast enhancement (d) on the correction with the smaller spatial mask

different approaches have to be performed in the future. Additional algorithms aimed at performing color contrast are based on human vision mechanisms,[21,22] but did not refer to the contrast-contrast effects. The former study performs a transformation of the image to cone responses and chromatic edge enhancement.[21] The latter study performs the algorithm by lateral inhibition mechanism and adaptation mechanism is based on On and Off cell types and an S-shaped curve modeled by the Naka-Rushton equation.[22]

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Biography

Hedva Spitzer received B.A degree from the Hebrew University in Jerusalem, and MA and Ph.D in Electro-physiology from the Hebrew University. She directs the Vision Research Lab in Biomedical Engineering department in Engineering faculty at Tel Aviv University. Her research interest in the recent years are concentrated on color and adaptation mechanisms with applications also to technology.

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