Use of a Model of the Human Visual System to Determine the Attributes of Aperture Colors
—HUE, BRIGHTNESS, and SATURATION—

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Abstract

A previously developed model of the human fovea is modified for analysis of colored stimuli. Psychophysical data on perception of aperture colors are used as a guide for the development of color perception by the model. The channels carrying information about color are represented by the summed responses of midget C- and L-type cells. The spectral energy distribution of any colored stimulus produces within the cell types a unique pattern of activities from which the amounts of each of the hues (i.e. RED, GREEN, BLUE, and YELLOW), WHITENESS, BRIGHTNESS, and SATURATION can be determined. The present analysis is restricted to the blue-cone region of the parafovea, which surrounds the blue-cone-free central fovea. For aberration-free dispersion and for no or little self-adaptation, the psychophysical and model data are in good agreement as to the 3 attributes HUE, BRIGHTNESS, and SATURATION. As a result of univariance, information as to the spectral distribution of the stimulus can not be used, and this creates a problem as how to normalize colored stimuli to a common set of standards. A method based on normalization of the outputs of the retinal cells to a common white is presented. The model starts with a mosaic of 44% red, 44% green, and 12% blue cones, using human data for the absorption spectra of the cones and for preretinal filtering. Aberration and light adaptation are incorporated into the model. The output of the mosaic of cones are used to develop a mosaic of C- and L-type bipolar cells, i.e. color and noncolor coded, which are used to develop the parvo and magno-cellular pathways for carrying information concerning color coding to the higher centers of the human visual system. Single and double opponent cells among others are used to develop the variables used for determining the attributes of aperture colors. The determination of the percents of the various hues depends on comparing the set of variables to a lookup table of 1330 different color combinations. BRIGHTNESS is determined by the activity of the noncolor L-channel, and SATURATION is determined by comparing the chromatic BRIGHTNESS to an equivalent achromatic WHITENESS level.

1. Introduction

A previously developed[7-16] model of the human has been adapted for determining color perception. The present model is restricted to aperture colors, i.e. color stimuli in which all information about the material composition and spatial location of the stimuli have been eliminated. The 3 attributes of aperture colors are HUE, i.e. name of the perceived color such as REDDISH BLUE, etc., BRIGHTNESS, i.e. the intensity of the color, and SATURATION, i.e. that attribute of color perception that permits a judgement to be made of the degree to which a chromatic color differs from an achromatic color regardless of their lightness. The present model is capable of determining these 3 attributes with a number of restrictions:

Only the parafovea is considered, i.e. that portion of the fovea containing red, green, and blue cones, no surround is present, i.e. the colored stimulus is situated on a black background, intensity of the stimulus is such that no adaptation occurs, the intensity is such that the model can be considered as linear, and the model is static, i.e. the responses occur after an "infinite" period of time.

2. Model

2.1. Summary

Figure 1 presents a summary of the sequential steps performed by the computer program of the model. The 1st step is the importing of various flags that control the information flow and cone matrix type, and the input values for the colors of the image and its surround and achromatic or chromatic adaptation. The 2nd step involves computing cone response templates for the image and its surround, and adaptation gains. The 3rd step involves importing the image and determining the matrix of cone responses. The next 2 steps involve computing the matrices of C- and L-type cells. Finally, the information of the summed C- and L-type cells are used to compute the 3 attributes of aperture colors.

2.2. Inputs

Figure 2 presents a detailed look at the 1st step in the program, i.e. the inputs. The flags adp_flag and srd_flag are involved with adaptation and the presence of a surround color, respectively and for the present purpose are set equal to 0. Blue_flag determines if the blue-cone-free fovea (0) or the blue-cone-present parafovea (1) is used. Spectral and color_flag are used to determine the spectral composition of the colored image. Each of the 3 values of x_red, x_grn, and x_blu, where x = a, s, or c, can vary from 0 to 60 (maximum). These 3 values are set equal to 0 for adapt and surround for the present purpose.

2.3. Cone Response Templates

Figure 3 presents the steps used to compute cone

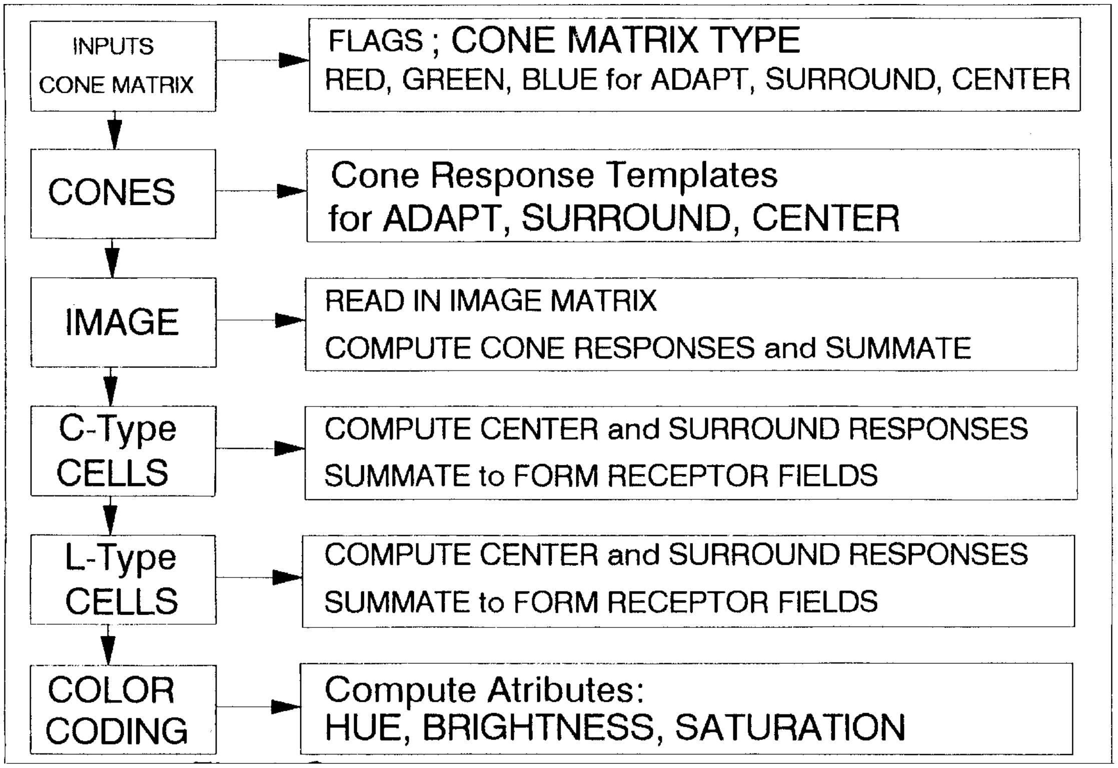

Figure 1. Summary

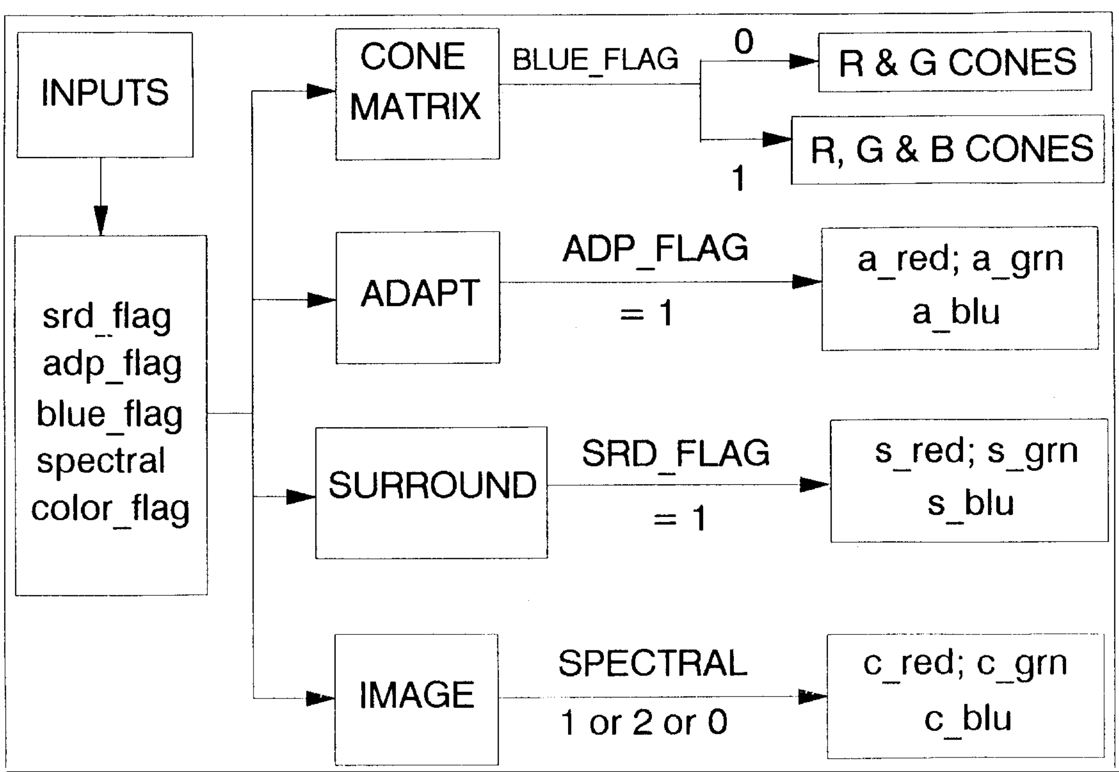

Figure 2. Inputs and Cone Matrix

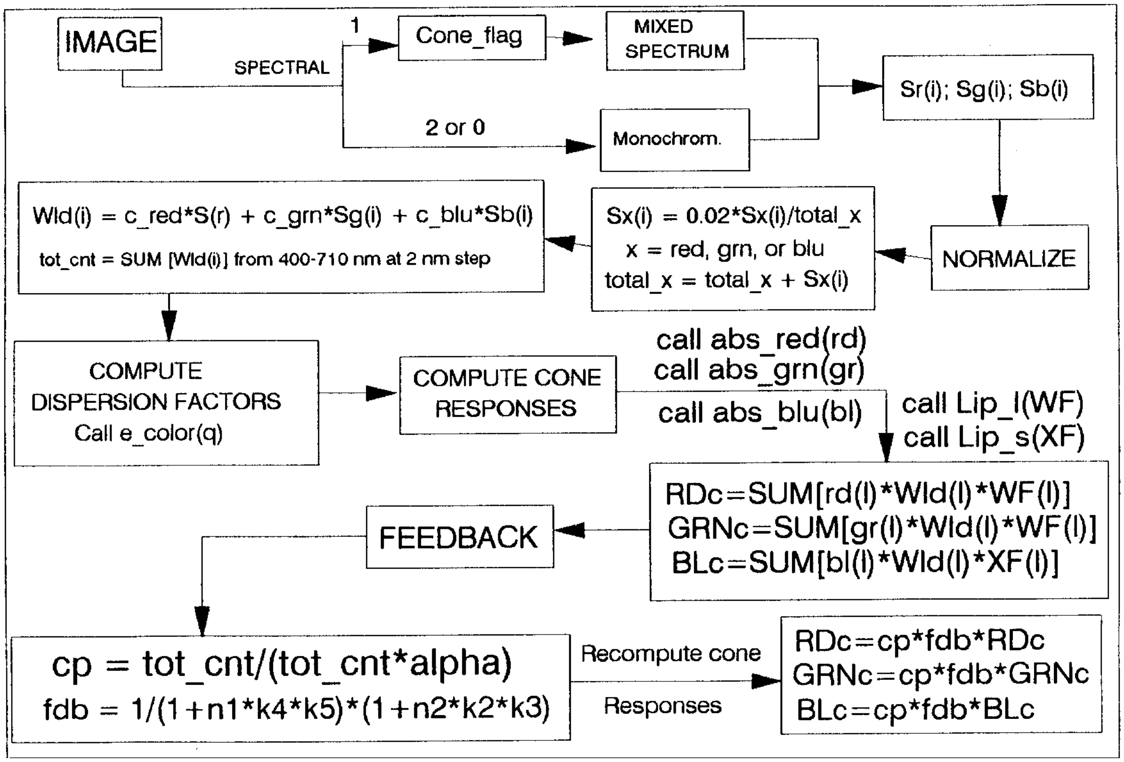

Figure 3. Cone Response Template for Image

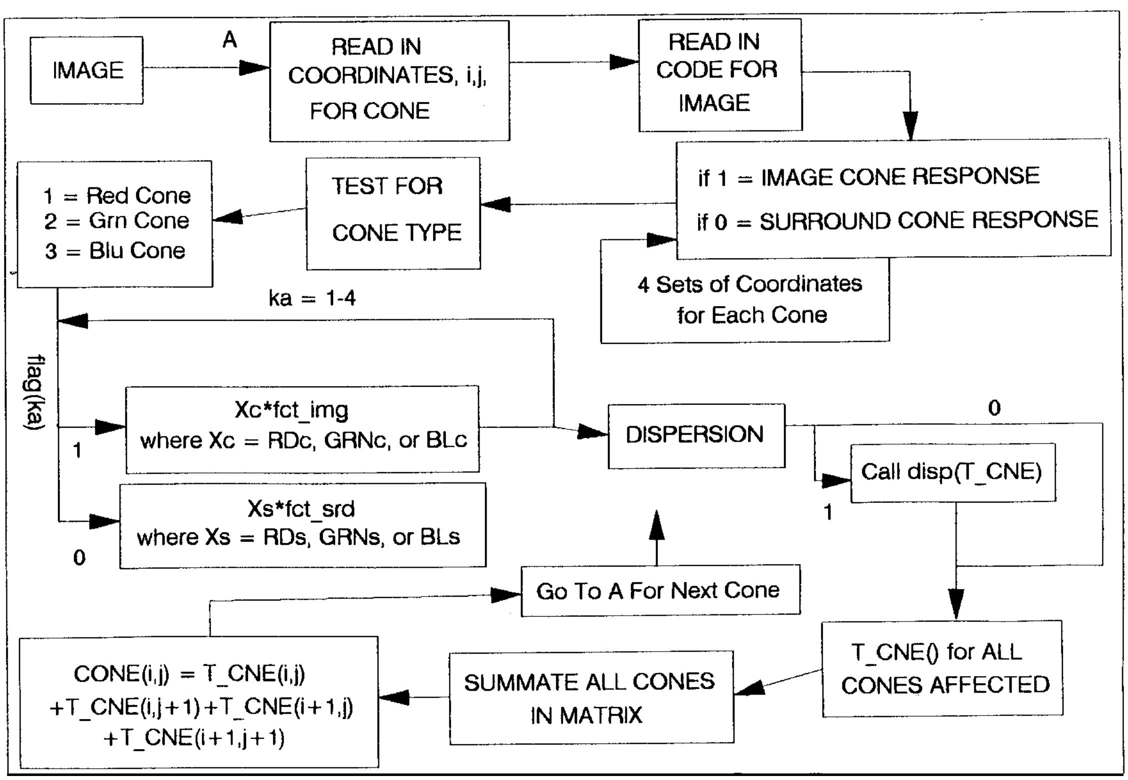

Figure 4. Import Image and Compute Cone Responses

responses for the colored image. Surround cone responses as well as adaptation gains are ignored for the present. Spectral determines if the color used is monochromatic (2 or 0) or consisting of a diverse spectral energy distribution (1). If monochromatic then for 0 the bandwidth is infinitely narrow, i.e. restricted to a single wavelength; if 2 the bandwidth is 20 nm for each wavelength. If spectral is 1 then cone_flag can vary from 1-6, which determines the spectral energy distribution of the 3 primary colors, red (Sr), green (Sg), and blue (Sb). Each of the primaries is then normalized so that its total energy is 0.02 with the spectrum summated from 400-710 nm at a 2 nm step. The spectral energy distribution of the colored image, Wld(l), is produced by multiplying each primary by the input values of c_red, c_grn, and c_blu for each wavelength (l) and then summated from 400-710 nm at a 2 nm step. The next step is to compute dispersion factors using an algorithm based on Airys disc.[13] There are 2 types of dispersion-aberration-free and chromatic. Aberration-free dispersion occurs when light passes through a nonhomogeneous media such as the retina, while chromatic dispersion occurs when a colored light passed through the media with dispersion varying according to wavelength. For the present only aberration-free dispersion is considered since for the psychophysical testing[15] there was no evidence for chromatic dispersion occurring. The cone responses (RDc, GRNc, and BLc) are computed by multiplying at each wavelength WLD(l) by the action spectra of the cone, rd(l), gr(l), or bl(l), at that wavelength and by the prefiltering factor[2] with WF(l) used for red and green cones and XF(l) used for the blue cone. The cone response is the sum from 400-710 nm at a 2 nm step. The next utilizes the compressiog factor (cp), and "internal" and "external" negative feedback circuits.[3-6] The compression factor, cp, is necessary to produce the typical S-shaped input-output response of the cones with alpha = 0.2 and tot_cnt is the total energy for the colored image. The "internal" negative feedback circuit resides within the cone with n1 = 1, and the feedfoward and feedback gains k5 = 5 and k4 = 0.2. The "external" negative feedback circuit involves a cone-L-type horizontal cell circuit with n2 = 7, and the feedfoward and feedback gains k3 = 0.05 and 0.2. The final step is to correct cone responses for compression and negative feedback.

2.4. Image

Figure 4 presents the steps used to import the colored image and compute the matrix of cone responses. Each cone is formed by 4 sets of coordinates—(i,j); (i,j +1); (i - 1, j); and (i - 1, j + 1). The cone is referred to by the 1st set of coordinates, (i,j). By dividing the cone 4 sets of coordinates the cone matrix can be made into a "honeycomb" type of organization. The cones in every other row are shifted to the right by 1. At the 1st step, A, 4 sets of coordinates are read in along with the code 0 or 1 for each set of coordinates; zero

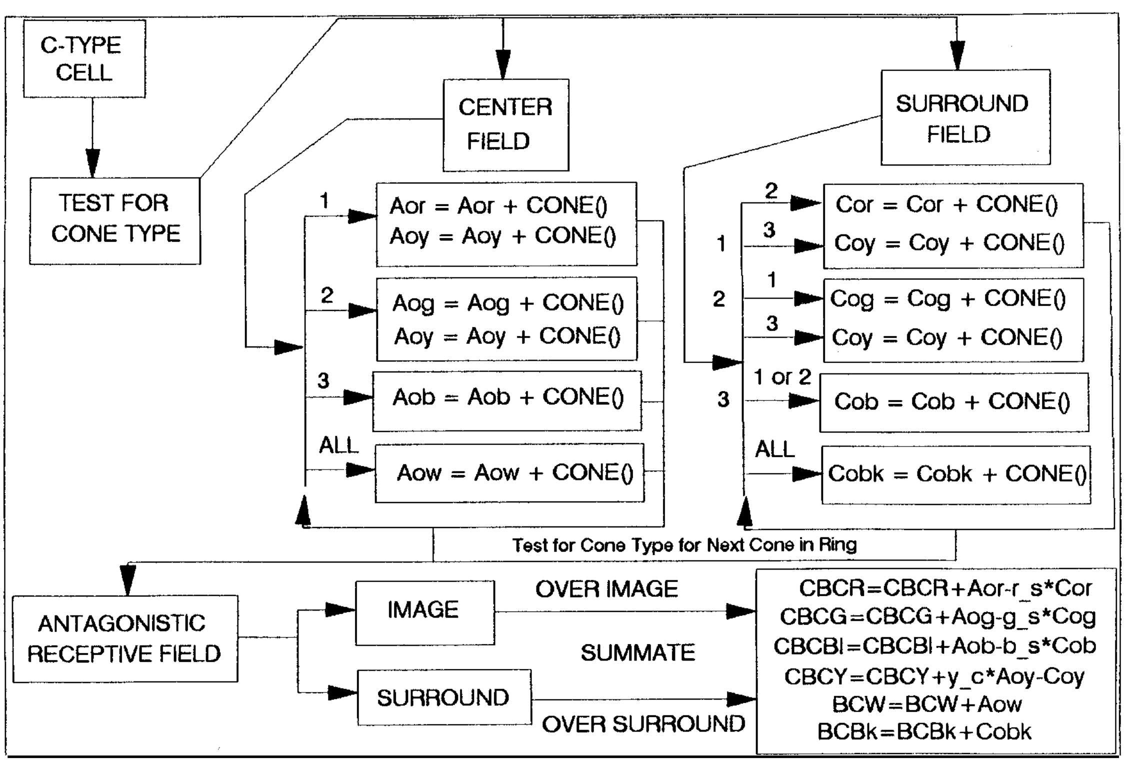

Figure 5. Computer C-Type Cell Responses

signifies that the colored image does not overlay that portion of the cone, while 1 signifies that the colored image does overlay that portion of the cone. Next the cone is tested for conetype and for each of the 4 sets of coordinates, Xc*fct_img is determined if the cone is 1 and 0 if the code is 0, where fct_img is a scaling factor and Xc is RDc, GRNc, ar BLc. Aberration-free dispersion is determined using the factors q() as determined in Figure 3. T_CNE()s, after determining aberration-free dispersion, are calculated for the cone in question and all cones surrounding it that are affected by the dispersion. For each cone that is affected, the T_CNE()s are summated for the 4 sets of coordinates. Starting with the 1st cone in the 1st row and 1st column, the same procedure is used until the entire matrix of cone is processed. At each cone, the CONE()s are added to the previous values so that at the end of the processing, each cone response represents the direct activation plus any activations due to dispersion.

2.5. C-type Cell

Figure 5 presents the steps used to compute the responses of the C-type cells to the colored image. The receptive field of the C-type cell consists of an excitatory center field and an inhibitory surround field. The center field consists all cones of the appropriate type within a unit hexagon consisting of the cone in question and the 6 surrounding cones. If the central cone is red or green then all red or green cones (usually 3) within the unit hexagon are included into the center field; if the central cone is blue then due to the lower distribution of blue cones only 1 blue cone is included in the center field. The surround field consists of the all cones of the opposite opponency within 3 rings surrounding the center cone. Four types of C-type cells are used: red-center/green-surround (CBCR), green-center/red-surround (CBCG), blue-center/yellow-surround (CBCB1), and yellow-center/blue-surround (CBCY). Yellow is produced by including both red and green cones. Two other cells are included, which strictly speaking are not C-type, but are formed in the same way[16] so are included; these are white-center/black-surround (BCW), which is formed by including all 7 cones in the center field and no cones in the surround, and black-center/white-surround (BCBk), which is formed by no cones in the center field and including all cones within the 3 rings in the surround field. Each cone has a CBCx, a BCW, and a BCBk, where x = red, green, or blue and each red and green cone has a corresponding CBCY. In computing the C-type cell responses, the factors r_s and g_s are such that the unique loci for CBCR and CBCG are both 578 nm, while b_s and y_c are such that the unique loci for CBCBl and CBCY are both 518 nm. BCW and BCBk do not have unique loci since they are monotonic with peaks at about 540 nm. The same procedure is followed for each cone in the matrix and the responses of the 6 cell types are added to the pools giving final summated responses for the 6 cell types over the color image and its surround, which for the present purpose can be ignored.

2.6. L-type Cell

Figure 6 presents the steps used to compute the responses of the L-type cells to the colored image. The L-BC is a construct used to compute the Ltype cell response. The center field is formed by including all 7 cones in the central unit hexagon. The surround field (which may not be necessary) is formed by the inclusion of all cones within 6 rings of the central cone. Cfa and sfx are scaling factors. The L-BC is then formed by adding the antagonistic center and surround fields with fct a scaling factor such that LBC() = 0 when its entire receptive field is activated. The AC response is obtained by the convergence of the absolute values of the 4 indicated L-BCs. AC-red, AC_grn, and AC_blu are then added to give the summated response of the L-type cell (am) over the colored image.

Thus for the C-type cells there is a one-to-one correspondence between cone and C-type cells. For the L-type cell no such one-to-one correspondence occurs, but rather a L-type cell corresponds to 4 cones.

2.7 Compute Attributes

2.7.1. Hue. Figure 7 presents the steps used to compute the hue of the aperture color. The 1st step, CORR, imports the 7 summed responses for CBCR (red), CBCG (green), CBCBl (blue), CBCY (yellow), BCW (white), BCBk (blk), and L-type (am). Next the responses are normalized by dividing each of the 1st 6 by the summed response for the L-type cell. Next the values are adjusted with cor_g, cor_bl, and cor_bk such that rd = gr, bl = yl, and wh = bk when the colored image is white, i.e. the amounts of the 3 primary colors are equal. These 3 criteria are based on the opponency rule that red and green are never seen simultaneously nor are blue and yellow.[15-16] Next 9 variables are computed where r, g, bu, y, w, and ba are the percents of red and green in the red-green pair, blue and yellow in the blue-yellow pair, and white and black in the white-black pair. These 9 variables are imported into RATIO as the input. STD() contains a list of the 9 variables computed for 2196[12] different colored images. Each variable for the unknown is compared against the equivalent variable of the 2196 standards and Z() computed and the absolute values of the Z()s summed for each of the 2196 standards. The index of the minimum all(k) is exported to FINAL. In FINAL the index is used to select the proper percents of red, green, and blue from a list of the 2196 standards. The final routing, AMT_COL, computes the hue. The lst step is to test for WHITE, the criterion being that red, green, and blue are present. Assuming R = % RED, G = % GREEN, B = % BLUE, then WHITE is present and the next step is to determine which of the 3 variables R, G, and G is the least; if B is least then W = B and WHITE = (RED=W,GREEN=W,BLUE=W) and what are left are R_1 = R-W, G_1 = G-W, and B_1 = 0. After correcting for the amount of WHITE, the presence of YELLOW is tested, the criterion being that there is still both red and green present, i.e. R_1 and G_1 are 0. If R_1 is less then G_1, Y = R_1 and YELLOW = (RED=Y,GREEN=Y,BLUE=0). What is left is R_2 = 0, G_2 = G_1 - Y, and B_2 = 0. After correcting for the presence of YELLOW, what remains is percents of RED or GREEN, and BLUE. One or more or none of these may be present after subtracting out the WHITE and/or YELLOW both of which may or may not be present. For the example used only excess GREEN is present given by GREEN =(RED=0, GREEN=G_2, BLUE=0). The procedure for determining hue gives results in terms of percents rather than absolute amounts. This is consistent with the psychophysical data.[11] One feature of the algorithm for determining hue is that the opponency rule is never violated.

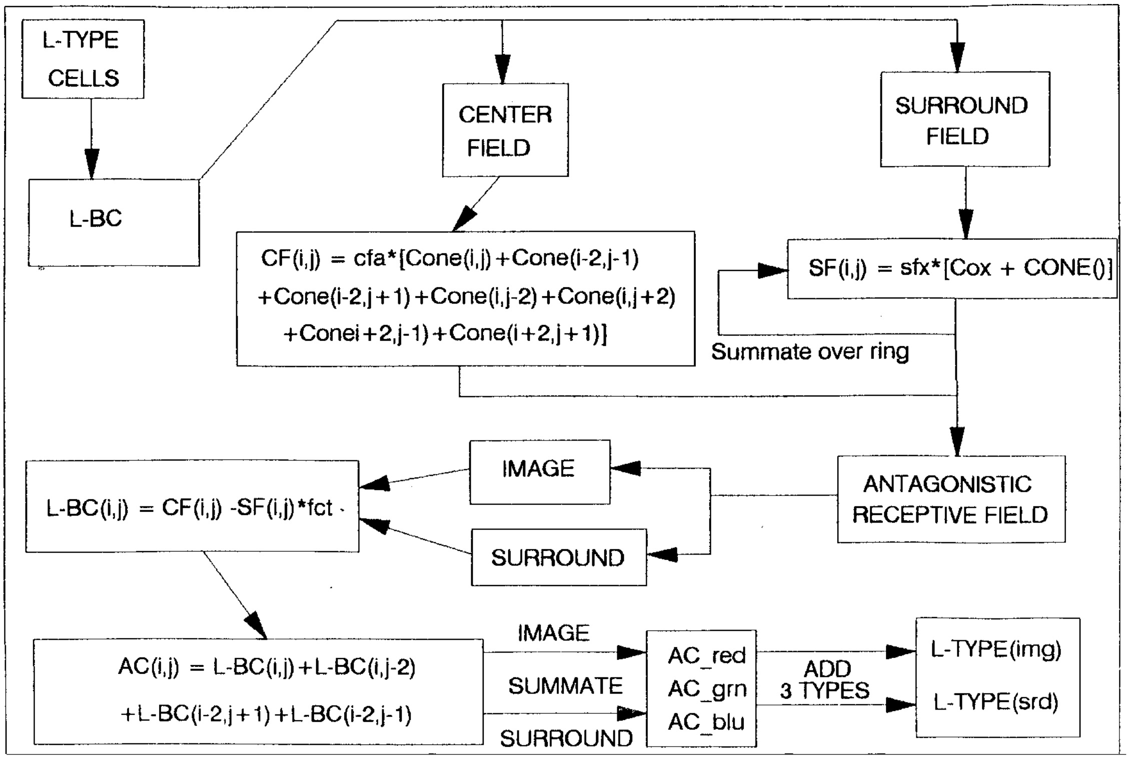

Figure 6. Compute L-Type Cell Response

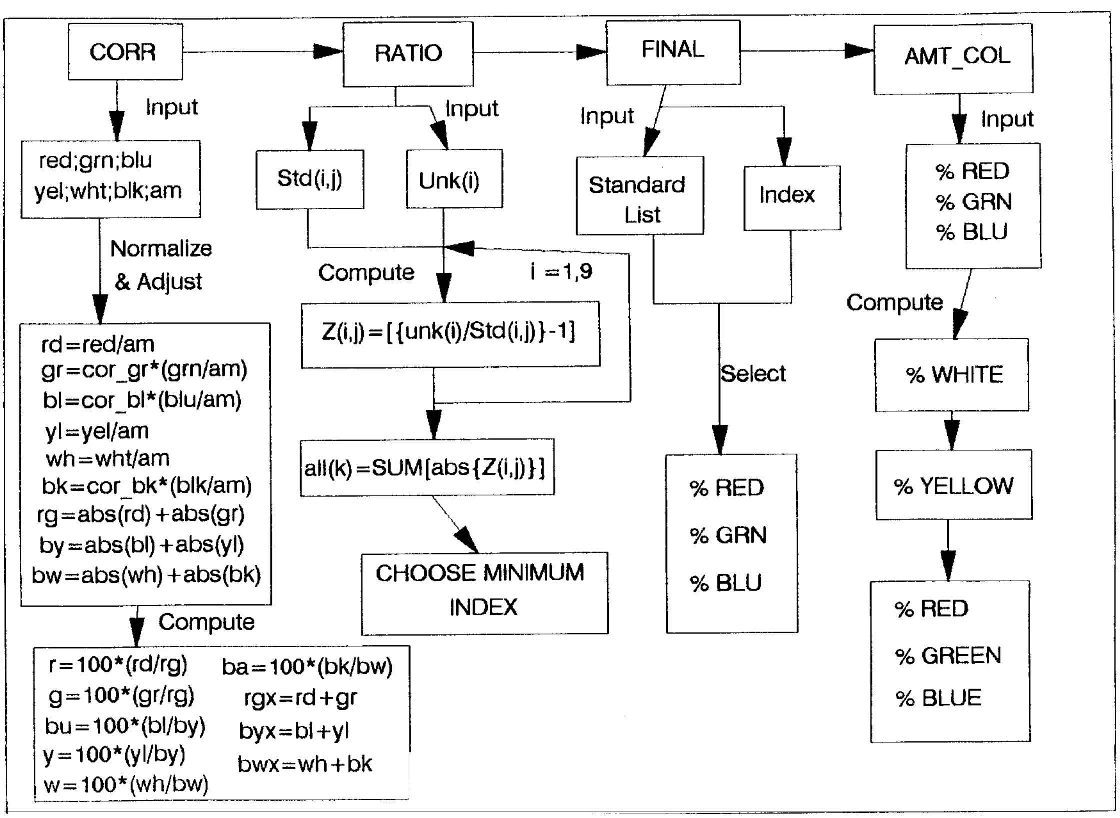

Figure 7. Determine HUE for Aperature Color

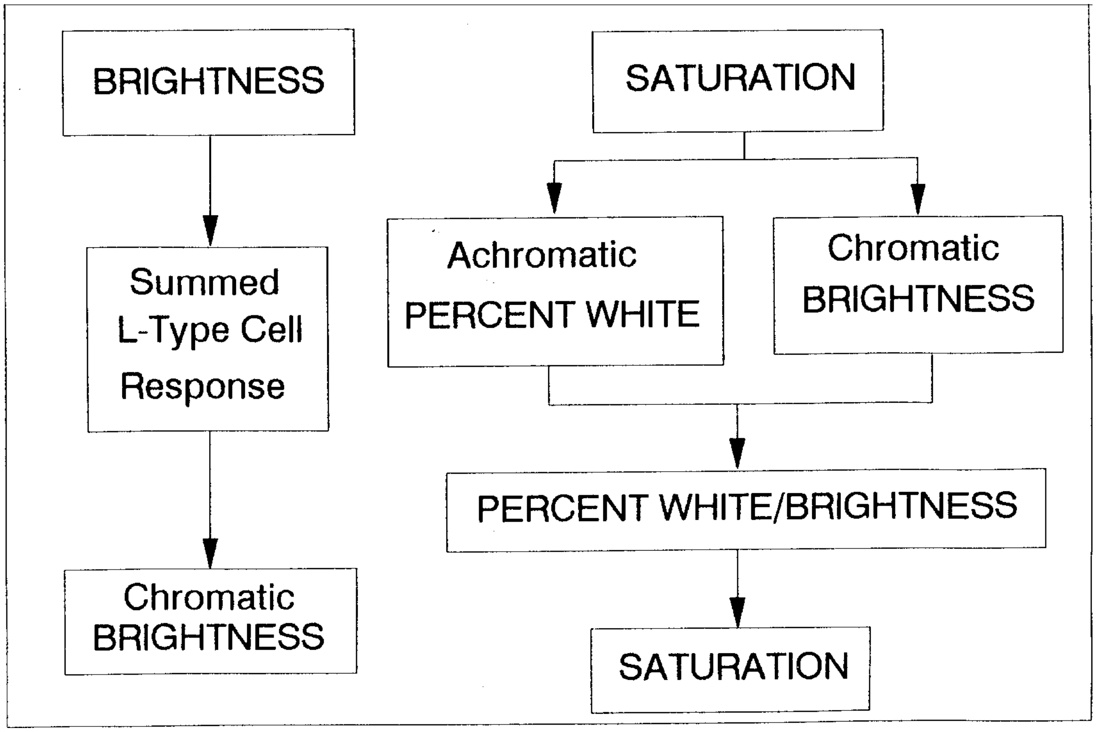

Figure 8. Determine Brightness and Saturation

2.7.2. Brightness and Saturation. As shown in the psychophysical testing[15] BRIGHTNESS can be considered as directly proportional to the summed L-type cell response (Figure 8). For SATURATION (Figure 8), summed L-type responses are determined for a series of achromatic colors, i.e. color indices of red, green, and blue are equal. For the achromatic series, ACH (red,green,blue), the color indices are varied from 0 to 5 for a step of 0.5. The total color indices, i.e. red + green + blue is 15 at the maximum of 5. Summed L-type response is plotted on the x-axis against total color index on the y-axis. For the unknown colored image, the summed L-type response is used to determine the total color index and then percent white is determined by: (1 - [total color index/15])*100. SATURATION is then found by determining the ratio of achromatic (percent white)/ chromatic brightness.

3. References

1. Dartnall, H. J. A., Bowmaker, J. K., and Mollon, J. D. Human visual pigments: microspectrophotometric results from the eyes of seven persons. *Proc. R. Soc. London Ser. B* **220**: 115-130, 1983.
2. Lipetz, L.E. Universal human visual pigment curves from psychophysical data. *Color Res. Appl*. **13**: 276-288, 1988.
3. Siminoff, R. Model of the cone-horizontal cell circuit on the catfish retina. *Biol. Cybern*. **51**: 363-374, 1985.
4. Siminoff, R. Dynamics of the cone-horizontal circuit in the turtle retina. *Biol. Cybern*. **52**: 1-14, 1985.
5. Siminoff, R. Modelling the effects of a negative feedback circuit from horizontal cells to cones on the impulse response of cones and horizontal cells in the catfish retina. *Biol. Cybern*. **52**: 307-313, 1985.
6. Siminoff, R. Dynamics of chromatic adaptation in cones of freshwater turtle. *Biol. Cybern*. **53**: 347-358, 1986.
7. Siminoff, R. Simulated bipolar cells in fovea of human retina I. Computer simulation. *Biol. Cybern*. **64**: 497-504, 1991.
8. Siminoff, R. Simulated bipolar cells in fovea of human retina II. Spectral responses of bipolar cells. *Biol. Cybern*. **64**: 505-510, 1991.
9. Siminoff, R. Simulated bipolar cells in fovea of human retina III. Effects of chromatic adaptation on bipolar cell spectral responses. *Biol. Cybern*. **65**: 357-363, 1991.
10. Siminoff, R. Simulated bipolar cells in fovea of human retina IV. Resolution. *Biol. Cybern*. **66**: 123-135, 1991.
11. Siminoff, R. Simulated bipolar cells in fovea of human retina V. Use of Fourier analysis to determine resolution. *Biol. Cybern*. **66**: 137-150, 199 1.
12. Siminoff, R. Simulated bipolar cells in fovea of human retina VI. Wavelength discrimination. *Biol. Cybern*. **65**: 365-374, 1991.
13. Siminoff, R. A simulated human fovea: the L-type cells of the magnocellular pathway. *Biol. Cybern*. **66**: 191-202, 1991.
14. Siminoff, R. and Cavonius, C.R. Simulated fovea of the human retina: psychophysical data confirming the model's ability to accurately predict resolution. *Biol. Cybern*. In press, 1993.
15. Siminoff, R. Color perception of aperture colors using a model of the human visual system: Part A. Psychophysical data. Submitted for publication, 1993.
16. Siminoff, R. Color perception of aperture colors using a model of the human visual system: Part B. Model-generated data. Submitted for publication, 1993.

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