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Color Constancy:
Small overall and large local changes

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ABSTRACT

This is a two-part study of the human visual system's mechanism for normalization in color constancy phenomena. Part I uses a viewing technique shown by Maximov. The viewing box consists of a cardboard shoe box with a hole cut in the top to pass light, a color correcting filter and a viewing tube. The viewing tube restricts the field of view on the opposite wall where small five-area Mondrians, called Tatami are mounted.

For the Part I Tatami Control we chose two illuminations and prepared a pair of Tatami (A & B). The product of one illuminant and Tatami A reflectances equaled the product of the other illuminant and the Tatami B reflectances. Corresponding pixels in the two Tatami cause identical quanta catches at the retina. Thus, the two Tatami look identical, even though they have very different reflectances. These Tatami contradict everyday experience that complex displays exhibit color constancy.

The Tatami Experiment is the addition of the same white reflectance area to both Tatami. All pixels, except those replaced by white area, are the same as in the control experiment. Nevertheless, all of the areas in both Tatami no longer match. Each Tatami looks much closer to its appearance in the room. The introduction of the white area has destroyed the color match and has initiated the human color constancy mechanism.

Part II Control uses even simpler displays: a pair of Center-Surround targets. The experiment uses two transparencies on an overhead projector. The first transparency represents a pair of uniform "Illumination" components and the second a pair of two-area, "Reflectance" components. First, the two different illumination transmittances are selected. Then, the transmittances for two sets of "Reflectance Components" (A & B) are chosen so that the product of one "Illumination" and "Reflectances" A components are equal to the product of the other "Illumination" and "Reflectances" B components for corresponding pixels. This is analogous to the control part of the Tatami experiments. As before, these Center-Surround targets contradict everyday experience that complex displays exhibit color constancy.

The Part II Experiment uses the Center-Surround target described in the control with one modification. Thin bands of a new "Reflectance," called *Constancy Test Patches* are added to the target. The same "Reflectance" is added to both targets, A and B. Some test patches destroy the color match by initiating the color constancy mechanism; others have no effect. In all, 16 different *Constancy Test Patches* are tested. The results help to understand the mechanism controlling the human color constancy mechanism.

The introduction of any *Constancy Test Patches* with a new maximum quanta catch for any cone causes a reset of color appearance. The introduction of any new maximum quanta catch for any cone type turns on the color constancy, or match destroying, mechanism. It follows that the mechanism controlling color constancy uses the individual maxima in each wave band to calculate color sensations. This is the Retinex hypothesis.

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1. INTRODUCTION

Colors of objects tend to be constant regardless of the color of the illuminant, therefore, regardless of the quanta catch of the retinal cones. Various color-constancy mechanisms including *context recognition,* (Helmholtz[1]), *adaptation* of retinal sensitivities (von Kries[2]) and *independent processing by receptor types* (Retinex[3]) have been proposed to explain these observations.

The present experiments test three hypothesizes related to the Retinex explanation. The first is that colors are determined by the *normalized relationship* between all quanta catches in the field of view. By this hypothesis, colors are constant in classical experiments simply because changes of the illuminant do not disrupt the relationship of quanta catches in the field of view. The second hypothesis is that the normalization process is controlled by the maxima in the field of view. The third hypothesis is that this process functions independently for long-, middle- and short-wave cones.

The most important problem in understanding human's color constancy mechanism is not the separation of "Reflectance" from "Illumination." It is simply an understanding of spatial mechanisms - global vs. local. Global changes in quanta catch cause small appearance changes[4]. This is true of overall color shifts due to the color temperature of the illuminant and true of gradients created by nonuniformities in illumination or reflectance. Local changes in quanta catch cause large changes in color appearance. Whether the local changes in radiance are from reflectance, illumination or transmittance does not matter. Color-constancy mechanisms use local contrast information to normalize the image in the calculation of color sensations.

2. TATAMI EXPERIMENT

Part I of this paper is an extension of Tatami Experiments described in the Contrasts in Vision Festspiel in honor of Fergus Campbell.[5] A Tatami is a five area Mondrian designed in the style of a Japanese floor mat. The Tatami Experiments consist of making pairs of color displays, each with the same *relative quanta catches*, but different *absolute reflectances.*

The Tatami uses a viewing technique shown by Maximov[6] (Fig. 1a). The viewing box consists of a cardboard shoe box with a hole cut in the top to pass light, a color-correcting filter and a viewing tube. The viewing tube restricts the field of view on the opposite wall where the Tatami are mounted.

2.1 Tatami Control

The Tatami Control experiment uses two illumination filters: Wratten CC 40R and Wratten CC 40C. We measured the total chromaticity and luminance shifts between these filters. We then prepared a pair of Tatami (A & B) in which each corresponding pixel had the same chromaticity and luminance shift as the illuminant (Fig.1b). Color Tatami" arrays of five color reflective patches were printed on paper using a Canon CLC 500 copier. Each color was created by entering a series of digits that controlled the amounts of yellow, magenta, cyan and black toners deposited on the paper. When these "Color Tatami" arrays are viewed in the room, each array has very different colors. Tatami A has light and

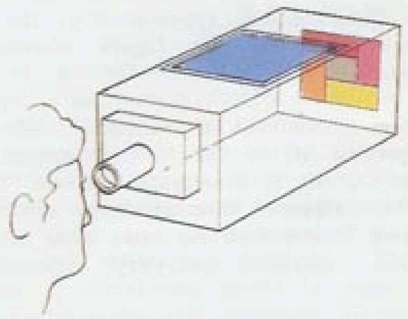

Fig. 1a. Maximov viewing apparatus.

Tatami Control

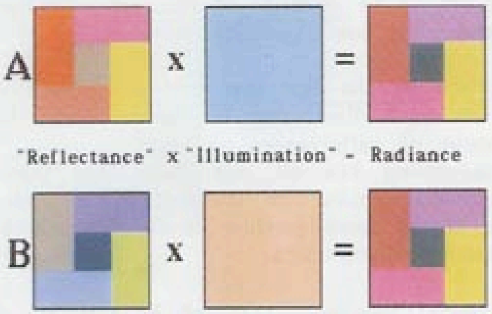

Fig. 1b. Appearance of components that add to a match.

Tatami Experiment

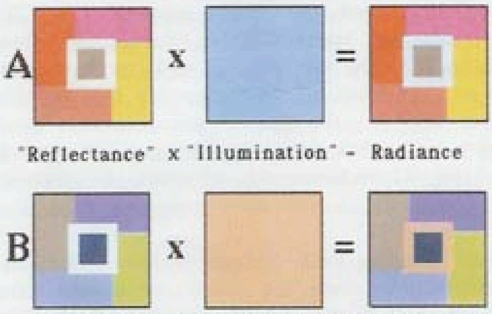

Fig. 1c. Appearance of components that add to a nonmatch.

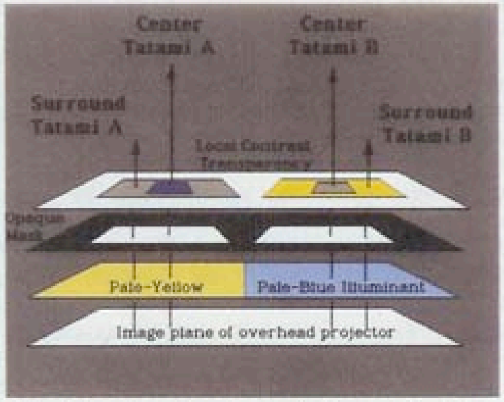

Fig. 3a. Overhead projector-side view.

Center-Surround Control

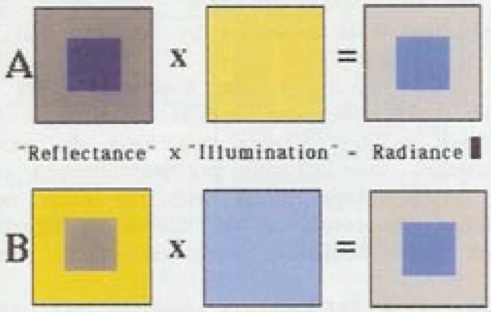

Fig. 3b. Appearance of components that add to a match.

Center-Surround with Constancy Test Patches

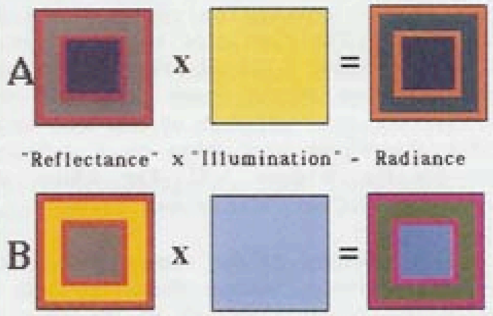

Fig. 3c. Appearance of components that add to a nonmatch.

middle-tone pinks, a yellow, a red and a gray. Tatami B has a gray, a green, light and middle-tone blues and a cyan. The left side of Fig. 1b illustrates Tatami A and B as they appear in the room. The center of the figure illustrates the appearance of the uniform color-correcting filtered illumination. The right side of the figure illustrates the appearance of the combination in the Maximov box.

When the Tatami are viewed in the Maximov boxes with a restricted field of view, both arrays appear the same. Pixel by pixel, the product of the CC 50 C illuminant and the Tatami A reflectances equaled the product of the CC 50 R illuminant and the Tatami B reflectances. Except for experimental errors, the radiances coming from corresponding pixels in the two Tatami are identical. Thus, the two Tatami look the same even though they have very different reflectances. These Tatami contradict everyday experience that complex displays exhibit color constancy.

Although placing the Tatami in shoe boxes surprises the observers, the experiment so far is a logical certainty. Two identical fields of radiances, regardless of the observers' knowledge about the reflectances of the papers, must appear identical. If they do not appear the same, there has to be an experimental error. In a sense, the creation of a match is the destruction of color constancy. Whatever is in control of the color constancy mechanism it is overcome by the fact that both displays are physically identical.

One of the reasons that people are surprised by the fact that two different sets of paper reflectances can appear identical in two different illuminants is that it is extremely difficult to find papers that have the same ratio of reflectances. David Stork[7] in our laboratory searched for pre-manufactured papers among Munsell and Color Aid samples. He found several papers with the same relative reflectances. He found that the observer matched the colors in the simplified Mondrians to the same patches in the Munsell Book when the reflectances were viewed in compensating illumination.

2.2 Tatami Experiment

So far we have created an elaborate null experiment. Null because the products of two sets of different reflectances and two illuminants are the same, and appear the same. The experiment begins when we add a new white (95% reflectance) paper to both Tatami (Fig.1c). As above, the left side of the figure illustrates Tatami (with white) A and B as they appear in the room. The center of the figures illustrates the appearance of the filtered illumination. The right side of the figure illustrates the appearance of the combination in the Maximov box. The observers report two facts. First, the papers look much closer to their appearance in the room outside of the shoe boxes. In other words, the white has destroyed the color matches of the five areas that send to the eye identical quanta catches. Second, the whites have taken on a definite color tint, pink for the Wratten 50R and blue green for the Wratten 50C. The whites show the dependence on absolute brightness as reported by McCann, McKee and Taylor.[8]

The addition of the same white reflectance area to each Tatami destroys the match. All pixel radiances, except those replaced by white area, are the same as in the control experiment. Nevertheless, all of the areas in both Tatami no longer match. Each Tatami looks much closer to its appearance in the room. The introduction of the white area has destroyed the match and has initiated the color constancy mechanism. This is essentially the same result as David Stork found in his thesis research.[7].

3. CENTER-SURROUND EXPERIMENT

In an attempt to simplify the manufacture and viewing of different targets, we changed the experimental design from the Maximov box to simultaneous viewing of two displays, using an overhead projector. The intent was to be able to change the local contrast components just as we did by changing the reflectance displays in the shoe box. The experimental design uses two transparencies: one uniform to represent the "Illumination" component and the second to represent the "Reflectance" or local-contrast component. These two transparencies multiply transmittances in the same manner that illumination and reflectance multiply. However, by replacing two targets mounted on a single sheet of transparent media is more efficient than replacing two papers in two shoe boxes. Furthermore, this apparatus allowed observers to view two different targets at the same time. This greatly simplified the comparison of colors between targets.

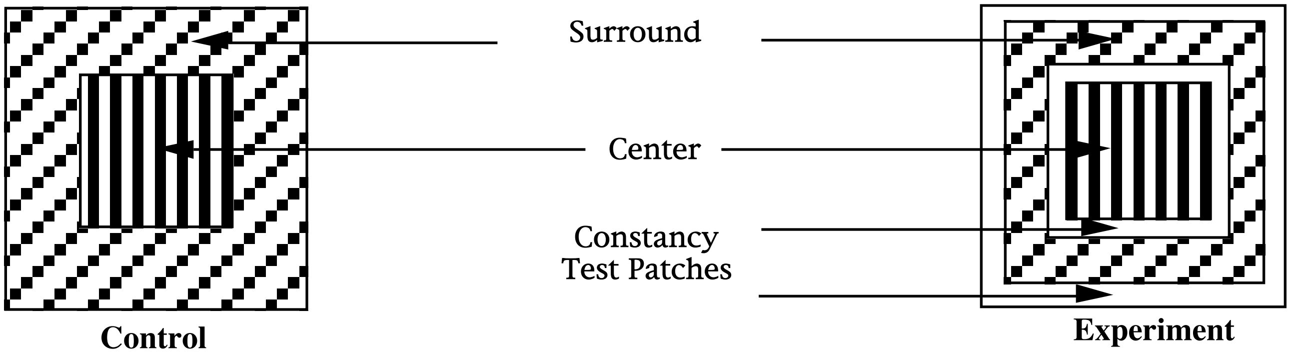

Fig.2. Layout of the Center-Surround targets. The left diagrams show the control target, used in the present experiment. The right diagram shows the target used in later experiments. It shows the location of the two *Constancy Test Patches* that are added to the display on the left.

Fig. 3a is a diagram of the transparencies on the top of the overhead projector. The bottom layer illustrates the glass on the top (image plane) of the projector. The second layer illustrates the left (pale-yellow white) and right (pale-blue white) uniform "Illumination" components. The third layer shows the opaque mask that restricts the field of view to just the areas of interest. The top layer shows the "Reflectance" components (Fig. 2) that contain the local contrasts. In all the Center-Surround experiments the illumination and mask layers are fixed. Only the top layer representing the “Reflectance” or local contrast components is variable. Thus, changing the top transparency is equivalent to changing both Tatami in two Maximov boxes.

Two observers sat 3 meters from the projection screen. The control target was a *Center* square subtending 6 degrees in the middle of a *Surround* square of 12 degrees. The two Center Surround Targets were separated by 5 degrees. The size of the display on the retina varies with viewing distance. This type of display shows very little change with change of visual angle.[9] Observers sitting at different distances report the same results.

As in the previous experiment the color patches were made on the Canon CLC 500 laser printer under digital control. This time they are printed on a transparent substrate. The search for highly constrained transmittances is greatly simplified by using the same dye set to generate both "Illumination" and "Reflectance" components. Since the dye sets are the same, it is possible to make convenient densitometer measurements while adjusting digits in the printer. All final measurements are confirmed using a colorimeter.

3. 1 Center-Surround Target--Control

First, the two different illumination transmittances are selected. They are made on the CLC 500 on transparent media by painting with uniform digital values for yellow, cyan, magenta and black toners. The digital values were chosen so as to have a weak blue filter and a weak yellow of about the same luminance. The pale-yellow "illuminant" had toner values of Y=50%, M=0%, C=0% and K=30%; the pale-blue "illuminant" had toner values of Y=0%, M=75%, C=75% and K=0%.

The next step in the experiment is to find the transmittances of a pair of Centers and the transmittances of a pair of Surrounds that satisfy the following four constraints:

° The ratio of quanta catches for A center to A surround equals the ratio of quanta catches for B center to B surround, for all three cone types.

° The absolute quanta catches for A center is different from the quanta catches for B center for all three cone types.

° The sum of optical densities of the pale-yellow "Illuminant" and A center equals the sum of the pale-blue "Illumination" and B center.

° The sum of optical densities of the pale-yellow "Illumination" and A surround equals the sum of the pale-blue "Illumination" and B surround.

The left side of Fig. 3b illustrates Center-Surround A and B as they appear projected by themselves. On the far left are the "Reflectances." The A *Surround* is gray; the A *Center* is a saturated blue. The B *Surround* is yellow; the A *Center* is gray. In the middle, the A *Illumination* is pale-yellow; the B *Illumination* is pale-blue. These uniform patches illustrate the appearance of the uniform "Illuminations" projected by themselves using a tungsten lamp in an overhead projector. The right side of Fig. 3b illustrates the appearance of the combination of "Reflectances" and "Illuminations" on the screen. The consequence of above constraints is that the A Center-Surround Target in pale-yellow "Illumination" is identical to the B Center-Surround Target in pale-blue "Illumination." This is an equivalent experiment to the Tatami control described above. As in the Tatami control, the two Center-Surround targets appear the same colors; they both have gray surround (slight yellow tint) and a medium saturation, bright blue center. They look the same because they are identical quanta catches everywhere in the field of view.

Table 1 lists the YMCK digits for toners that were used in the experiment. The first two rows report on the "illuminant" transparencies. The next four describe the centers and surrounds. The next 16 describe the different *Constancy Test Patches that* are added to the Center-Surround displays.

Color Name	Location	% Yellow	% Magenta	% Cyan	% Black
Pale-Yellow White	"Illumination"	45	0	0	35
Pale-Blue White	"Illumination"	0	67	75	0
Gray	Center A	53	60	60	0
Yellow	Surround A	100	0	0	35
Blue	Center B	0	75	100	33
Gray	Surround B	53	60	60	0
White	Constancy Test Patch	0	0	0	0
Black	Constancy Test Patch	100	100	100	100
Gray	Constancy Test Patch	20	20	20	100
Dk Yellow	Constancy Test Patch	100	20	20	100
Br Yellow	Constancy Test Patch	100	0	0	35
Dk Magenta	Constancy Test Patch	20	100	20	100
Br Magenta	Constancy Test Patch	0	100	0	0
Dk Cyan	Constancy Test Patch	0	0	100	100
Br Cyan	Constancy Test Patch	0	0	100	40
Dk Red	Constancy Test Patch	100	100	0	100
Br Red	Constancy Test Patch	100	100	0	0
Dk Green	Constancy Test Patch	100	0	100	100
Br Green	Constancy Test Patch	100	0	100	25
Dk Blue	Constancy Test Patch	20	100	100	100
Br Blue	Constancy Test Patch	0	100	100	0

Table 1. List of color name, use in displays as an "Illumination", center or surround, % maximum deposit for yellow, magenta, cyan and black toners.

3. 2 Center-Surround Target -- Experiment

Fig.3c illustrates the combination of the "Reflectance" and "Illumination" components, this time with the addition of the *Constancy Test Patches.* This experiment adds new transmittances to the local contrast transparency. Does the addition of the new areas destroy the match, as the white did for the Tatami? The right side of Fig. 2 shows the spatial pattern of the Center-Surround target with the added *Constancy Test Patches.* As described above, the observer was shown the display without the added color and reported that the two centers matched and the surrounds matched. The experiment consists of 16 transparencies (see Table 1) replacing the outer edge of the center and the surround areas. This new color replaces portions of both A and B targets (see right side of Fig. 2.). In the control, all "Reflectances" in target A are proportional to those in target B. Now, the introduction of a new area, that has the same transmittance in both the A and the B displays, destroys the proportional relationship.

Model Predictions

The introduction of new arrays of radiances, or *Constancy Test Patches* has different implications for different models of human vision. For example, let us compare the CIE model of colorimetry[10] and the Retinex model[11]. The fundamental difference in the models is that colorimetry evaluates a single pixel, whereas a Retinex evaluates all pixels in the field of view. Colorimetry evaluates pixels in a real-life complex image as a set of completely independent points. The Retinex model is a field model. Each pixel is evaluated relative to all the other pixels in the field of view.

Colorimetry Prediction

The CIE colorimetry model predicts the following results:

- Adding new values in other parts of the image do not enter into the calculation of X,Y,Z or x,y.
- Pairs of pixels that match should continue to match, regardless of the presence of other areas.
- New patches will take on colors appropriate for their quanta catch at that pixel

Retinex Prediction

The Retinex model predicts the following results:

- Adding new values in other parts of the image could change the appearance of all pixels in the image.
- Matches should continue to match if the new patch does not introduce a new maximum in any waveband.
- Matches should not continue to match if the new patch does introduce a new maximum.
- New patches will take on colors appropriate for their relationship to other pixels.
- The introducing a new maxima for any one of the three cone types will reset the color appearance of the entire field.

The Colorimetry and Retinex predictions are very different. *Constancy Test Patches* test the effects of maxima on the entire image. Furthermore, they test the influence of a new maxima in each cone type independently.

3. 3 Center-Surround Target-Results

Observers were shown the Control Center-Surround Target and asked if both left and right Centers and left and right Surrounds matched. They reported that they did. Next the experimenter sequentially replaced the control "Reflectances" transparency with each of the sixteen targets with the *Constancy Test Patches.* Two observers were asked if the two centers still matched. Then they were asked if the two surrounds still matched. The results are shown in Table 2 below.

	New Max Long	New Max Middle	New Max Short	Match Destroyed Center	Match Destroyed Surround
White	Yes	Yes	Yes	Yes	Yes
Black	No	No	No	No	No
Gray	No	No	No	No	No
Dk Yellow	No	No	No	No	No
Br Yellow	Yes	Yes	No	Yes	Yes
Dk Magenta	No	No	No	No	No
Br Magenta	Yes	No	Yes	Yes	Yes
Dk Cyan	No	No	No	No	No
Br Cyan	No	Yes	Yes	Yes	Yes
Dk Red	No	No	No	No	No
Br Red	Yes	No	No	Yes	Yes
Dk Green	No	No	No	No	No
Br Green	No	Yes	No	Yes	Yes
Dk Blue	No	No	No	No	No
Br Blue	No	No	Yes	Yes	Yes
White & Bk	Yes	Yes	Yes	Yes	Yes

Table 2 lists the name of the *Constancy Test Patch* in the left column. Br is the abbreviation of the word Bright; Dk is the abbreviation of the word Dark. The next three columns report whether the Constancy Test Patch introduced a new maxima in either of the displays. In other words, it reports whether the new Test Patch has sufficient radiance to become the area in the field of view with the highest quanta catch of one of the cones in the retina. The data is reported independently for the long-, middle- and short-wave cones. Two observers gave exactly the same verbal response for all of the Constancy Test Patches. The rightmost pair of columns list the observers' reports for the Center and the Surround areas.

Sixteen *Constancy Test Patches* were used. Eight patches destroyed the color match; eight did not. Whenever the match was destroyed for the Center, it also was destroyed for the surround. The colors that destroyed the match caused a reset of all the colors in the field of view. All Constancy Test Patches that destroyed the match are listed in Table 3 below.

	New Max Long	New Max Middle	New Max Short	Match Destroyed Center	Match Destroyed Surround
White	Yes	Yes	Yes	Yes	Yes
Br Yellow	Yes	Yes	No	Yes	Yes
Br Magenta	Yes	No	Yes	Yes	Yes
Br Cyan	No	Yes	Yes	Yes	Yes
Br Red	Yes	No	No	Yes	Yes
Br Green	No	Yes	No	Yes	Yes
Br Blue	No	No	Yes	Yes	Yes
White&Bk	Yes	Yes	Yes	Yes	Yes

Table 3. List of all **Constancy Test Patches** that reset the appearance of the display and destroyed the color match. A new maximum quantum catch for any cone type correlates with failure of color match.

The last *Constancy Test Patches* were added at the suggestion of Andrew Moore in order to test a gray world assumption. Here we have a set of white black white stripes that have the same average radiance of a dark gray that fails to destroy the match. Does this white-black-white stripes have the same effect as a white, destroying the match? Or, does it behave as a dark gray, not destroying the match? As shown in previous work,[12] experiments designed to find "gray world" effects fail to find them. The presence of local contrasts that reset the relationships control color appearance. The white-black-white stripe behaves the same as the white *Constancy Test Patch.*

The results are quite simple. If the *Constancy Test Patches* are not the highest quanta catch in any waveband, the color match is unchanged. Nothing happens. If the *Constancy Test Patches* are the highest quanta catch in any waveband, the color match of both the center and the surround is destroyed. The bright red, green and blue *Constancy Test Patches* introduce a maximum for only one of the cone types. The yellow, magenta and cyan *Constancy Test Patches* introduce new maxima for two of the cone types. The white *Constancy Test Patch* introduces maxima for all three cone types. In all of these cases, the color matches of the identical quanta catches are destroyed. The introduction of any new maximum causes a reset of color appearance. The introduction of any new maximum turns on the color constancy, or match destroying, mechanism. It follows that the mechanism controlling color constancy uses the individual maxima in each wave band to calculate color sensations. This is the Retinex hypothesis.

4. CONCLUSIONS

This is a two-part study of the human visual system's mechanism for normalization in color constancy. By combining the Tatami and the Center-Surround experiments we can draw a number of important conclusions about the human color-constancy mechanism.

Exact color constancy is achieved by exactly equal quanta catches everywhere in the field of view. The introduction of global changes in quanta catch cause small appearance changes. This is very different from local changes in quanta catch that cause large appearance changes.

The human color constancy mechanism normalizes sensations to the maxima in the field of view. The addition of the same white to two Tatami, destroys the match of all of the areas in both Tatami. Each Tatami looks much closer to its appearance in the room. The introduction of the white area has destroyed the color match and has initiated the color-constancy mechanism.

The human color constancy mechanism normalizes sensations to the maxima in the field of view; it normalizes each waveband separately (Retinex). *Constancy Test Patches* in Center-Surround targets showed that the introduction of any patch with a new maximum quanta catch for any cone causes a reset of color appearance. The introduction of any new maximum quanta catch for any cone type turns on the color-constancy, or match-destroying, mechanism. It follows that the mechanism controlling color constancy uses the individual maxima in each wave band to calculate color sensations.

5. ACKNOWLEDGMENTS

This research was started many years ago with David Stork's early work. The author wishes to thank Andy Moore for his helpful discussions.

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