Color constancy in variegated scenes: role of low-level mechanisms in discounting illumination changes

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For a visual system to possess color constancy across varying illumination, chromatic signals from a scene must remain constant at some neural stage. We found that photoreceptor and opponent-color signals from a large sample of natural and man-made objects under one kind of natural daylight were almost perfectly correlated with the signals from those objects under every other spectrally different phase of daylight. Consequently, in scenes consisting of many objects, the effect of illumination changes on specific color mechanisms can be simulated by shifting all chromaticities by an additive or multiplicative constant along a theoretical axis. When the effect of the illuminant change was restricted to specific color mechanisms, thresholds for detecting a change in the colors in a scene were significantly elevated in the presence of spatial variations along the same chromatic axis as the simulated chromaticity shift. In a variegated scene, correlations between spatially local chromatic signals across illuminants, and the desensitization caused by eye movements across spatial variations, help the visual system to attenuate the perceptual effects that are due to changes in illumination. © 1997 Optical Society of America [S0740-3232(97)01610-4]

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1. INTRODUCTION

A visual system can be said to possess the property of color constancy if the color percepts assigned to individual objects are invariant across illumination conditions. In terms of the responses of neurons or signal processing units, color constancy results if at some stage of the visual system the chromatic signals from objects in a scene vary by less than a discriminable difference across varying illumination.[1] In this study we calculated the nature of the changes in signals from variegated scenes as the illumination is changed and have examined whether low-level mechanisms can contribute to color constancy by attenuating the effects of this change.

We first computed the signals evoked in the human visual system at the first stage of cone photoreceptors from a large number of natural and man-made objects[2,3] and then calculated signals at the second stage of opponent-color mechanisms. The results showed that there is a high degree of correlation between cone absorptions across spectrally different natural illuminants, thus making it easy to simulate the effect of illumination changes on variegated scenes and to examine the effects of these changes on isolated color mechanisms. Next, we measured thresholds for detecting changes in perceived color by second-stage mechanisms when changes in the spectral composition of the illuminant were stimulated. We used textured backgrounds colored along axes or planes of cardinal color space[4] and found that the presence of spatial structure in scenes could raise chromatic thresholds, depending on the chromatic and spatial frequency content of the scene. This masking occurred relatively independently within opponent-color mechanisms.

In the discussion (Section 4), we address the relevance of the experimental results to color constancy in natural scenes and to previously proposed models for color constancy, including models based on estimating reflectance or illumination spectra,[5–7] Von Kries or opponent-channel adaptation,[1,8–19] or the physical invariance of relative colors.[2,3,20,21]

2. COLORIMETRIC SIGNALS FROM OBJECTS UNDER DIFFERENT ILLUMINANTS

The spectral composition of the light reaching the eye from an object is a wavelength-by-wavelength product of the spectral reflectance of the object $\Theta(\lambda)$ and the spectral composition of the illuminant $\Gamma(\lambda)$. For our sample of objects, we used the 170 natural and man-made objects whose reflectance spectra were measured by Vrhel *et al.*[22]

The relative spectral compositions of five phases of natural daylight measured by Taylor and Kerr[23] were used as illuminants. We examined the effect of changes between all pairs of these five illuminants. The largest change in signals from individual objects occurs when illumination by zenith skylight (illuminant Z) is compared with direct sunlight (illuminant T). The spectrum labeled Z was measured by pointing the measuring instrument at the sky, and it has the highest relative energy in the short wavelengths, as a result of Rayleigh scattering. Of the five spectra, direct sunlight at ground level (T) has the least relative energy in the short wavelengths and the most in the long wavelengths. The three other spectra contain mixtures of direct sunlight and light reflected from the sky. In the presence of clouds, the illuminant spectrum is very close to equal energy at all visible wavelengths.[24]

In the human visual system, color vision under photopic conditions is initiated by the transduction of light quanta into nerve signals by three classes of cone photoreceptors: short-, middle-, and long-wavelength-sensitive. The absorption spectra of these photopigments, $s(\lambda)$, $m(\lambda)$, and $l(\lambda)$, were taken from Smith and Pokorny.[25] The relative heights of the spectra used were similar to those for an ideal observer.[26] Quanta are absorbed independently by the three classes of cones from each object Θ_i illuminated by Γ_j and are given by the expressions

$$S_{ij} = \int s(\lambda)\theta_i(\lambda)\Gamma_j(\lambda)\mathrm{d}\lambda,$$

$$M_{ij} = \int m(\lambda)\theta_i(\lambda)\Gamma_j(\lambda)\mathrm{d}\lambda,$$

$$L_{ij} = \int l(\lambda)\theta_i(\lambda)\Gamma_j(\lambda)\mathrm{d}\lambda, \qquad (1)$$

where the integration is performed over the range of visible wavelengths $\lambda = 400$ to 700 nm. Signals from the photoreceptors are combined by neurons at the second stage into signals of the form $L - M$, $S - (L + M)$, and $L + M$.[4,27]

The cones transform the infinite-dimensional wavelength space of light into a three-dimensional affine space that can be represented by S, M, and L quantal absorptions as the three axes. This space can be transformed to another affine space defined by three cardinal axes that each represent the exclusive stimulation of one class of second-stage mechanism. The two chromatic axes are $L/(L + M)$ and $S/(L + M)$. Dividing by the luminance $L + M$ projects all points onto the plane of unit luminance; therefore $L/(L + M)$ and $S/(L + M)$ form an equiluminant chromaticity plane when plotted as orthogonal axes.[28] Under neutral adaptation a line drawn through the achromatic point and parallel to the $L/(L + M)$ axis represents hues ranging from reddish on the right to greenish on the left. For mnemonic purposes we will refer to this axis as the RG axis and to the two color directions from the achromatic point as R and G. A line through the achromatic point and parallel to the $S/(L + M)$ axis represents hues from yellowish at the bottom to violet at the top. We will refer to this axis as YV and

the two directions as Y and V. The three-dimensional positive cone of all visible lights can be represented by connecting the dark point, where $S = M = L = 0.0$, to each point on the spectrum locus on the equiluminant plane and extending upward.[29] Within the cone each plane parallel to the unit-luminance plane will represent a chromaticity diagram at some luminance less than or greater than unity, and the (L, M, S) coordinates of all visible lights will be meaningful in this space. The third cardinal axis is the $L + M + S$ axis passing through the dark point and progressively lighter achromatic points; hence the LD axis. For a three-dimensional depiction of this space in terms of cone excitations, see Sachtler and Zaidi.[30]

In Fig. 1 are shown the excitation of the three cone classes and the chromatic and luminance mechanisms from each of the Vrhel *et al.* objects under illuminants Z and T. The L, M, and S signals are proportional to the total quanta absorbed by each of the three cone types for each illuminant–object combination. These plots represent the extreme case of comparing signals from an object under direct sunlight with that same object shadowed from the sun and reflecting pure skylight. In each plot the solid line along the diagonal is the locus of equal signals under the two illuminants. Each point represents an individual object. The open circles at the top right corners in each of the L, M, and S plots represent direct cone absorptions of the two daylights. The most noticeable aspect of all three of the top plots is that the points lie close to lines, i.e., there is a strong correlation ($r^2 > 0.998$) between the quanta absorbed by each cone type from different objects across daylight illumination changes. Comparable correlations also exist for cone absorptions from other samples of objects and illuminants.[2,3] In addition, the slope of the line formed by the points representing L-cone absorptions from the objects is only slightly less than unity, whereas the line formed by the M-cone absorptions is slightly greater than unity. The slope for the S-cone absorptions is considerably greater than unity, reflecting the relatively larger amount of short-wavelength energy in illuminant Z. Those objects with fairly uniform reflectance spectra appear in roughly the same relative positions in the three plots, whereas objects whose spectra have pronounced peaks or troughs fall high on some of the plots and low on the others.

It is worth emphasizing that these extremely high correlations are evident only after lights have been absorbed by the photopigments of the eye. We could not discern any systematic pattern when we plotted the changes in the spectral compositions of the lights entering the eye. The high correlations are due in large part to the relative smoothness of the illumination and reflectance spectra and to integration within fairly broad absorption bands. In each of the L, M, and S plots, the points all lie close to the line joining $(0, 0)$ and the open circle representing the illuminants' absorptions, indicating that the light absorbed by most objects reduces cone absorptions by a similar fraction for the two illuminants.

In the bottom left panel, the $L/(L + M)$ axes represent hues going from greenish to reddish (left to right and bottom to top). The points representing the objects all lie
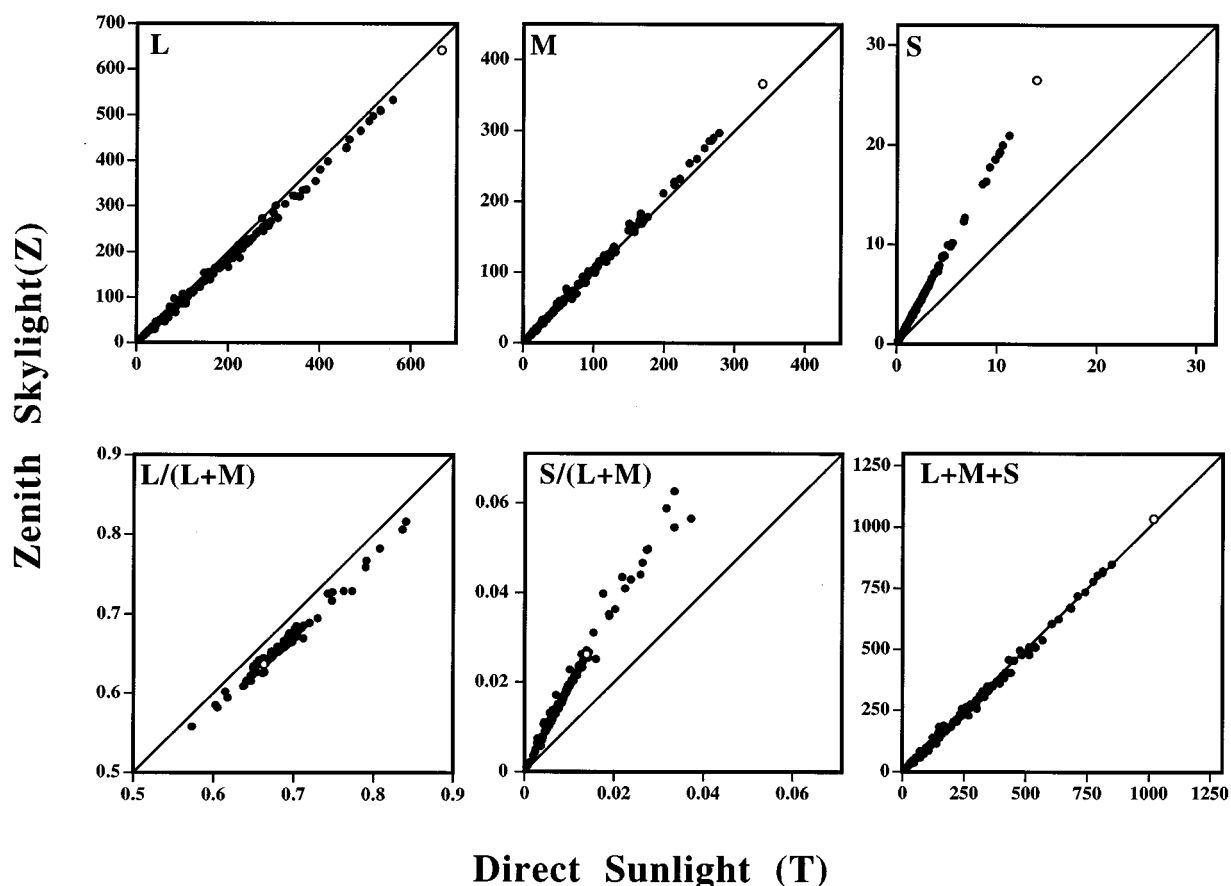
Fig. 1. Excitation of the L, M, and S cones (top three plots) and the exclusive excitation of the chromatic and luminance mechanisms along the $L/(L + M)$, $S/(L + M)$, and $L + M + S$ axes (bottom three plots) from each of the 170 objects from Vrhel *et al.*[23] under illuminants T [direct sunlight (abscissa)] and Z [zenith skylight (ordinate)]. The open circles represent the object of unit uniform spectral reflectance.

below the diagonal, indicating that the chromaticities of all the objects have shifted toward green under illuminant Z as compared with the case under illuminant T. Within the spectrum locus, the effect of the illuminant change is like a shift of chromaticities parallel to the diagonal line: The mean of the differences between $L/(L + M)$ signals under the two illuminants is equal to 0.0256, the standard deviation of the differences is equal to 0.0047, and the best-fitting regression line has a slope of 0.96 (but a line of slope 1.0 provides almost as good a fit). The $S/(L + M)$ axes represent hues going from yellowish to violet (left to right and bottom to top). The effect of an illuminant change is a shift in all of the chromaticities by approximately the same multiplicative factor, indicating that the chromaticities at the violet end are shifted the most. The slope of the best-fitting line is 1.74 ($r^2 = 0.98$). Because of normalization by the luminance $(L + M)$ signal, the correlation across illuminants is lower in the $S/(L + M)$ plot than in the S plot. The $L + M + S$ plot represents radiance changes at constant hue and saturation and is dominated by L- and M-cone absorptions. Because the daylight spectra were equated for illuminance, a shift from T to Z causes almost no change in the total cone absorptions.

In general, illuminants differ in total radiant power as well as in spectral composition. Because of the linearity

of cone absorptions [Eqs. (1)], if the energy in illuminant T or Z were multiplied by a factor other than unity, it would multiply absorptions by all three cone classes from all objects by the same factor. Consequently, in the L, M, S, and $L + M + S$ plots, the slopes of the lines formed by the points would change, but the correlations would remain the same. The $L/(L + M)$ and $S/(L + M)$ plots would remain unaltered, as the numerators and the denominators would be multiplied by the same factor.

To examine the generality of the preceding analyses, we also considered the set of spectral reflectances of natural formations that was published by Krinov[31] and has been analyzed extensively in the literature.[32] The first- and second-stage signals from these formations under illuminant T are compared with signals under illuminant Z in Fig. 2. The patterns of change are similar to those for the Vrhel *et al.* objects, (Fig. 1), though the gamut of chromaticities is more restricted for the Krinov formations.

There are four main implications of the results that for a scene composed of a sample of Vrhel *et al.* objects or Krinov terrains the total effect on the visual system of a shift in the phase of natural daylight can be decomposed into three systematic changes at the second stage, i.e., an additive shift in chromaticities parallel to the $L/(L + M)$ axis and multiplicative shifts along the $S/(L$

$+ M$) and $L + M + S$ axes. First, the illuminant-caused shifts in chromatic signals correlate well with everyday observations. Objects look appreciably more bluish green in shadows and more orange in sunshine. More systematic documentation is available in paintings made in the open air from the second half of the 19th century. A good example is Corot, who used to sketch the scene first and then paint it patch by patch, reproducing colors in each patch. In cases in which a wall is both lighted and shadowed, only on the shadowed bricks can be found traces of blue pigment. Second, since signals from different objects maintain their relative positions, no additional physiological process is required to make sure that an object that appears, e.g., redder than another under one illuminant, will also appear redder under a different daylight illuminant. Third, any low-level adaptation process that modifies cone signals so that they fall along the diagonals in the top plots of Figs. 1 and 2 or modifies second-stage signals so that they fall along the diagonals in the bottom plots will additionally lead to constancy of perceived colors. Fourth, once the chromaticities in a scene have been calculated under one phase of daylight by Eqs. (1), the effect of a change in daylight phase on each second-stage mechanism can be simulated rapidly as the corresponding correlated shift in all the chromaticities, without having to repeat the calculations in Eqs. (1). This implication will be used in setting up the experimental conditions of this study.

3. DISCOUNTING THE EFFECT OF ILLUMINATION CHANGES ON SECOND-STAGE SIGNALS

A. Methods

Human color constancy has been studied with a number of measurement techniques and spatial and chromatic arrangements.[33–39] We present an alternative method. A slight change in illuminant slightly changes the light reflected from objects and, consequently, the neural signals. Therefore the question of how much change in illumination can be tolerated must be answered in terms of how much change in neural signals from a scene is to be tolerated. In the first three experiments of this study, we asked our observers to perform a simple task: In a dark room, view a $14.14° \times 10.67°$ illuminated scene continuously and report if the colors in the scene appear to change when the effect of an illuminant change is simulated. We separately measured the thresholds for detecting the effects of an illuminant change by each of the second-stage mechanisms exclusively. As shown in Section 2, the effect of a change in the phase of natural daylight on the $L - M$ mechanism can be simulated by adding a constant to all $L/(L + M)$ chromaticities, and on the $S - (L + M)$ and $L + M$ mechanisms by multiplying all $S/(L + M)$ and $L + M + S$ chromaticities, respectively, by constants. This enabled us to quantify the tolerance within each second-stage mechanism for changes in illumination.
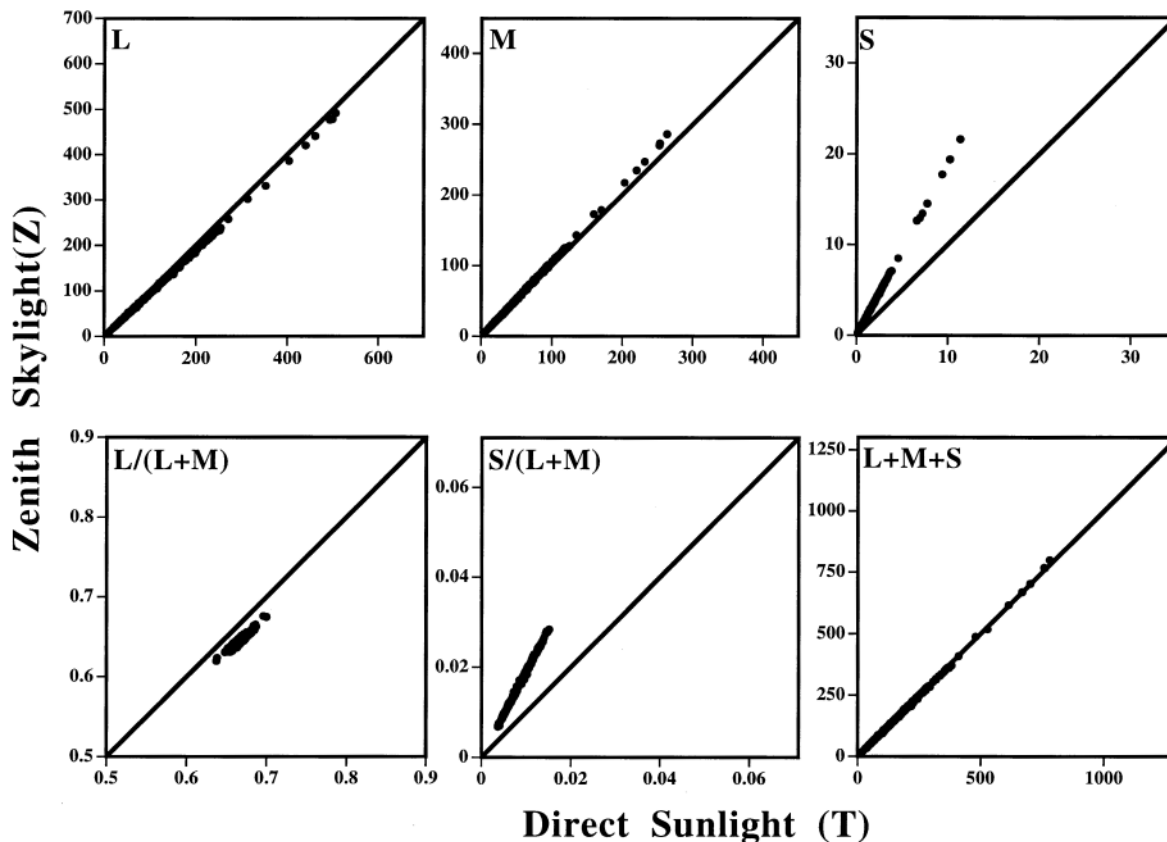

Fig. 2. Excitation of the L, M, and S cones (top three plots) and the exclusive excitation of the chromatic and luminance mechanisms along the $L/(L + M)$, $S/(L + M)$, and $L + M + S$ axes (bottom three plots) from each of the 335 natural formations from Krinov[31] under illuminants T (abscissa) and Z (ordinate).

Since we were interested in the effect of the spatial complexity of scenes on color constancy, we used random binary and quaternary distributions of squares of uniform size and manipulated the spatial frequency content of the scene by changing the size of the squares in the texture. We tested for the effect of spatial variations on second-stage mechanisms exclusively and in combination by coloring the binary textures exclusively along each of the $L/(L + M)$, $S/(L + M)$, and $L + M + S$ axes and the quaternary textures along each of the planes of the color space formed by pairs of these axes. Though the set of these textured fields does not provide an efficient basis for natural scenes, any natural scene can be decomposed into the sum of binary random textures varying in sizes of squares over the limited range of scales that are resolved by the human visual system. To keep the space-averaged chromaticity and luminance of all fields equal to that of an achromatic light of fixed luminance, we restricted the stimuli to uniformly distributed chromaticities equidistant from the achromatic point.

Thresholds for detecting the simulated effect of illumination changes on a textured field were compared with thresholds for detecting changes in the R, G, Y, V, L, and D color directions from a spatially extended uniform achromatic field whose chromaticity and luminance were equal to the space average of the variegated scene. We used 3-s intervals in which the illuminant on a scene was changed gradually toward and back from a different illuminant as a half-cycle of a sinusoid. To control for criterion effects, each trial also included another interval in which the illuminant was not altered. The observers indicated the interval in which they perceived a color change. The observer adapted to the background for 2 min at the initiation of each session and readapted for 2 s after each trial. The experimental paradigm that we used is illustrated in Fig. 3.

The adaptation state of the observer during the 3-s test interval that we used can be considered to be in flux, because chromatic adaptation is not complete even after 10 s.[40,41] However, there is considerable adaptation of early signals even within a second, and since we were measuring thresholds, the required changes in adaptation state were small. We also informally tried several 6-s trials to stabilize adaptation states further, but this made the measurements excruciatingly slow without affecting the results qualitatively. For an observer viewing a complex scene with eye movements, a completely steady adaptation state is not possible for any patch of retina even under a uniform unchanging illuminant. In addition, a mobile observer is likely to see objects like bricks and leaves in both shade and sunlight, sometimes in adjacent patches, so that temporal variation may be more desirable than steady adaptation in simulating natural observing conditions.

All stimulus presentations and data acquisition were computer controlled. Stimuli were displayed on the $14.14° \times 10.67°$ screen of a BARCO 7651 color monitor with a refresh rate of 100 frames/s. Images were generated by using a Cambridge Research Systems video stimulus generator (CRS VSG2/3), running in a 90-MHz Pentium-based system. Through the use of 12-bit digital-to-analog converters, after gamma correction, the VSG2/3 is able to generate 2861 linear levels for each gun. Any 256 combinations of levels of the three guns can be displayed during a single frame. By cycling though precomputed lookup tables, we were able to update the entire display each frame. Phosphor chromaticity specifications supplied by BARCO and gamma-corrected linearities of the guns were verified by using a Spectra Research Spectra-Scan PR-650 photospectroradiometer. Calibration and specification of colors were performed according to the methods detailed in Zaidi and Halevy.[42] The (L, M, S) coordinates of the principal points were $W = (0.652, 0.348, 0.017)$, $D = (0, 0, 0)$, $L = (1.304, 0.696, 0.034)$, $R = (0.706, 0.294, 0.017)$, $G = (0.598, 0.398, 0.017)$, $Y = (0.652, 0.348, 0.003)$, and $V = (0.652, 0.348, 0.031)$. The mean luminance of the screen, 30 cd/m^2, was considered to be unit luminance corresponding to $L + M = 1.0$. Since W, R, G, Y, and V fall on the unit-luminance plane, their (L, M, S) coordinates can be referred to the MacLeod–Boynton chromaticity diagram.[28] All L, M, and S units in the remainder of this paper correspond to the scales defined by the principal points along the cardinal axes. The mean chromaticity of the screen was metameric to W. It is worth pointing out that the range of equiluminant chromatici-
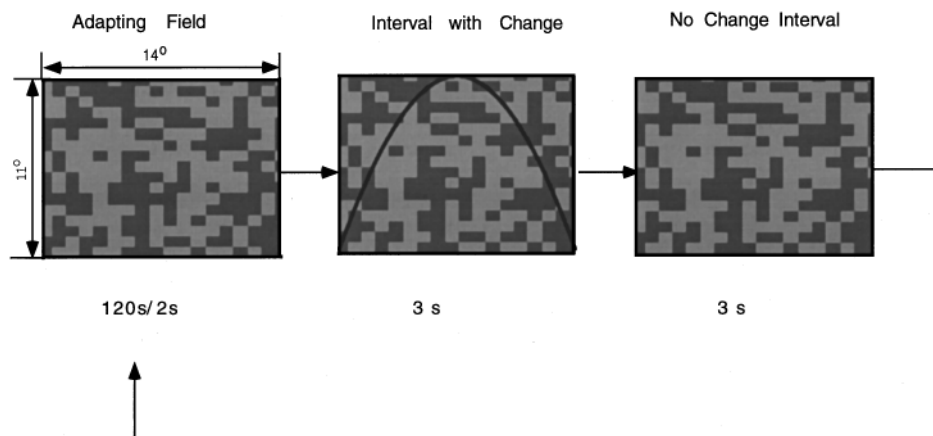

Fig. 3. Spatial configuration and temporal sequence of stimuli for experiments 1–3. The initial adaptation period was 120 s. Each trial consisted of a 2-s period of readaptation, followed by two 3-s intervals, of which one contained a simulated illumination change with a time course of a half-sinusoid.

ties available on the monitor includes all of the Krinov terrain chromaticities in Fig. 2 and a large majority of the Vrhel *et al.* object chromaticities in Fig. 1.

B. Experiment 1: Baseline Thresholds

In the first experiment, we measured thresholds to be used as baselines for subsequent comparisons. The background was spatially uniform and set to W. For all the conditions in this study, the room was dark, as was the border of the display, so that simulated illumination changes could be restricted to the display. The chromaticity or the luminance of all the pixels of the screen was changed over 3 s as a half-cycle of a sinusoid. The changes were parallel to and toward one or the other end of the three cardinal axes: $L/(L + M)$ (R or G direction), $S/(L + M)$ (Y or V direction), and $L + M + S$ (L or D direction). In each trial the observer indicated in which of two intervals any color change had been perceived. A double-random staircase procedure was used for each test direction, and trials in the six directions were randomly interleaved. Measurements were made on two color-normal female observers, including one of the authors. Thresholds were taken as the average of 16 transitions and are shown for the two observers in Fig. 4. All thresholds are expressed in terms of total change in cone excitations, $|\Delta L| + |\Delta M| + |\Delta S|$. Since parallel to the $L/(L + M)$ axis, $|\Delta S|$ is equal to zero, the change is equal to $|\Delta L| + |\Delta M|$. Likewise, since, parallel to the $S/(L + M)$ axis, $|\Delta L|$ and $|\Delta M|$ are both equal to zero, the change is equal to $|\Delta S|$. (Note that each color axis has its own vertical scale.) Two features of the results are relevant. First, thresholds in opposite directions along an axis are roughly equal. Second, under these spatiotemporal conditions, observers are considerably more sensitive to R or G changes than to L or D changes: The $L + M$ level of the background was 1.0, and observer BS required a change of 0.12% in total cone excitation to reliably detect the chromatic change, but a change of 12% to detect a luminance change ($|\Delta S|$ is a minuscule portion of the luminance threshold).

C. Experiment 2: Color Selectivity of Masking Effects

In the second experiment, we measured the tolerance by each second-stage system for illumination changes on variegated scenes. The same procedures as those for experiment 1 were used, except that the background consisted of variegated scenes simulated by random textures consisting of uniform-sized squares. There were 8.52 squares per square degree of visual angle. To enable one-dimensional spatial scale comparisons, in this paper we will refer to texture size in units of squares/degree, which refers to the number of squares transversed per horizontal or vertical degree of visual angle. The texture size in experiment 2 was thus 2.92 squares/degree. Three types of binary texture were used, which will be termed LD, RG, and YV for mnemonic purposes. Each type of texture consisted of equal numbers of randomly intermixed squares of two different colors, whose chromaticities and luminances were equal to points halfway between W and the extreme points on the corresponding cardinal axis. We also used three types of quaternary
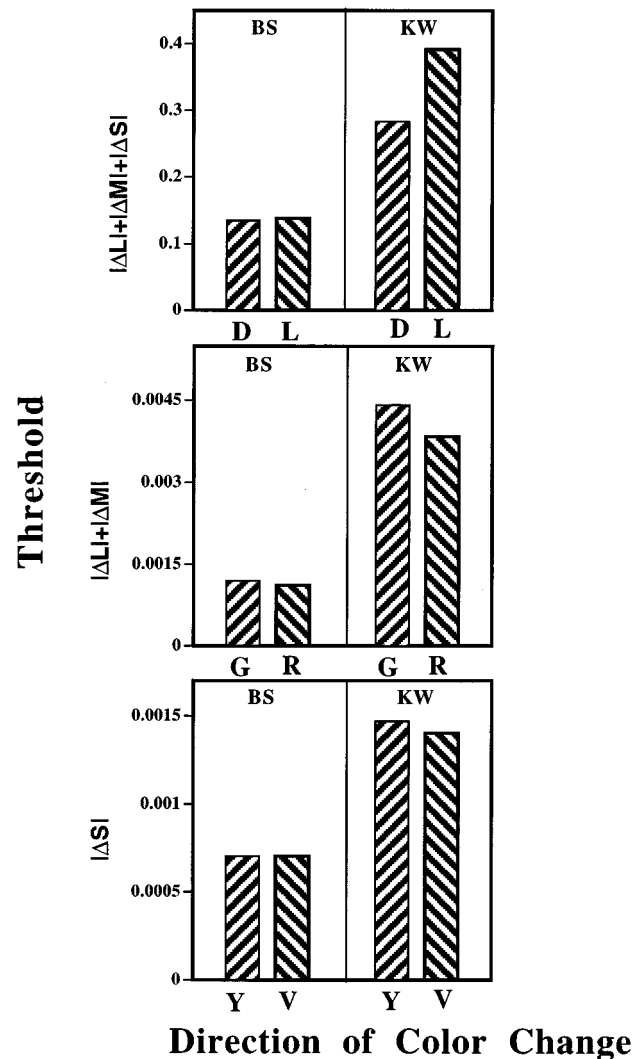

Fig. 4. Results of experiment 1 for observers BS (left-hand plots) and KW (right-hand plots). Shown are thresholds in cone excitation units for detecting changes along the cardinal color axes. Letters on the horizontal axis indicate the direction of test color change.

texture, $LDRG$, $RGYV$, and $YVLD$, formed by adding the corresponding pairs of binary textures. For example, the $LDRG$ texture consisted of light red, dark red, light green, and dark green squares. In all six types of textures, the space-averaged chromaticity and luminance was equal to W, which was also the background in experiment 1. A different random arrangement was presented on each trial.

The purpose of this experiment was to measure thresholds for detecting illuminant-caused changes by each of the second-stage mechanisms. To restrict the effects of illumination changes on each second-stage system, we exploited the nature of the systematic changes revealed in Figs. 1 and 2. To simulate the exclusive effects of illumination changes on the $L - M$ system, the chromaticities of all elements of the display were shifted by an equal amount toward either R or G. For exclusive simulation of the $S - (L + M)$ system, the steady-state S-cone signal from each element was divided by a constant ($0.0 < x < 1.0$) to shift all chromaticities proportionately to-

ward *V*, or multiplied by a constant $(0.0 < x < 1.0)$ to shift all chromaticities proportionately toward *Y*. Finally, to simulate the exclusive effect of illumination changes on the $L + M$ system, the luminance of each element was increased or decreased proportional to its steady-state luminance, without altering the chromaticity.

The results for the two observers are shown in Fig. 5. The chromatic content of the background texture is indicated on the abscissa. The log-threshold elevation for detecting a change in each color direction as compared with the baseline threshold (experiment 1) for that color direction is plotted on the ordinate. For the *R* or *G* direction, this quantity was calculated as the log of the ratio of the constants added to the background chromaticities at the corresponding thresholds, and for the four other direc-

tions it was calculated as the log of the ratio of the corresponding multiplicative constants. We are interested not in whether there is a small but statistically significant increase in thresholds on the background but whether certain backgrounds functionally mask the effect of illumination changes. Therefore we have used a much more conservative criterion; the dashed horizontal line at 0.3 indicates a doubling of threshold magnitude and identifies the conditions that increased the tolerance for an illumination change by at least a factor of 2. The results are systematic and similar for the two observers. The presence of chromatic spatial variations makes it less likely that full-field chromaticity changes will be perceived, but thresholds for detection of full-field luminance changes are not affected by the presence of spatial variations. Except for one case out of 36, changes toward a
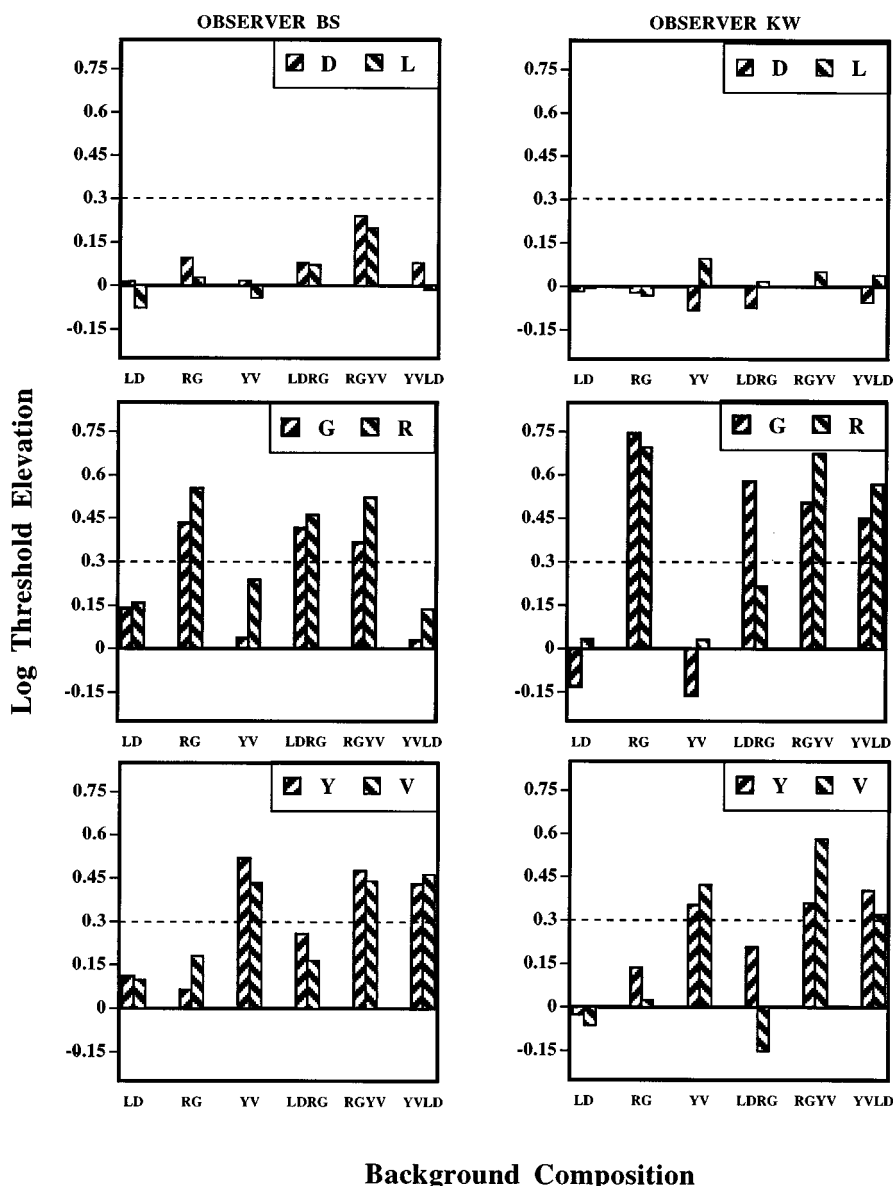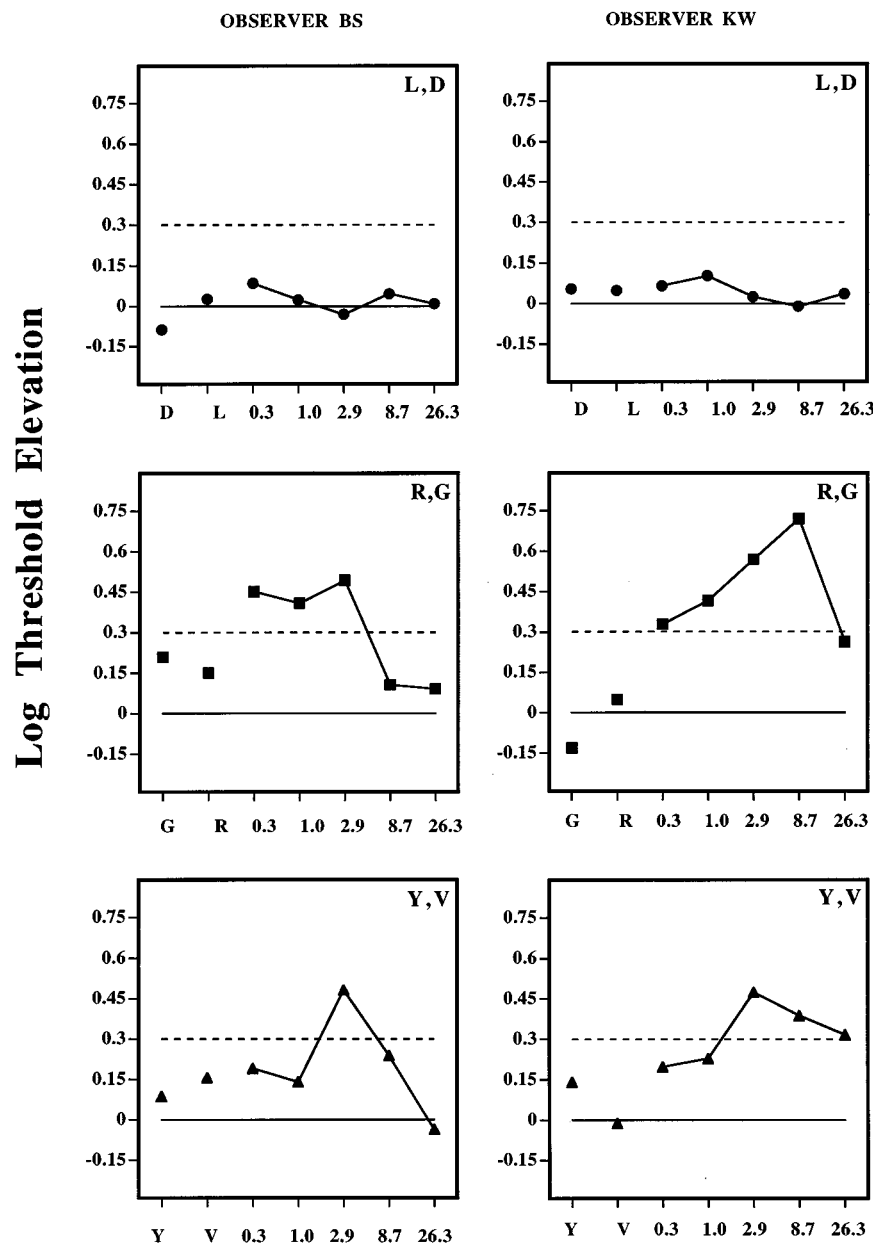

Fig. 5. Results of experiment 2 for observers BS (left-hand plots) and KW (right-hand plots). The log of the threshold for detecting a change in each color direction minus the log of the baseline threshold for that color direction (experiment 1) is plotted against the chromatic content of the background texture (see the text). Symbols representing the color direction of the test are shown in the insets. Dashed horizontal lines are drawn at 0.3 to indicate a doubling of threshold magnitude.

Fig. 6. Results of experiment 3 for observers BS (left-hand plots) and KW (right-hand plots). Log-threshold elevations for color changes along the same color axis as that of the texture are plotted versus the number of squares/degree in the texture (logarithmic scale). Letters on the abscissa indicate the spatially uniform adapting fields of the denoted color. Each point represents the mean of the threshold elevations in the complementary directions along each color axis.

chromatic direction are affected only when there is spatial contrast along the same axis. There was no systematic effect of superimposing spatial contrast along a color axis orthogonal to the color direction of the simulated illumination change. The results indicate that the masking effect of spatial contrast is relatively independent within each of the two chromatic mechanisms.

In summary, when the illumination changes, an observer is less likely to perceive changes in the chromaticities in the scene if the scene contains spatial variations than if it is spatially uniform, i.e., the presence of spatial

variations *per se* can contribute to color constancy. Could these results simply reflect spatial frequency specific masking in the three color mechanisms? The receptive field properties of cells in the primate lateral geniculate nucleus would not be inconsistent with this view, since these cells are fairly narrowly bandpass for luminance spatial variations but are low pass for chromatic spatial variations.[27,43] The hypothesis that these threshold elevations are due to spatial frequency specific masking was tested in experiment 3 by using background textures containing different spatial frequencies.

D. Experiment 3: Spatial Frequency Selectivity of Masking Effects

Within each color mechanism, we measured the magnitude of the threshold elevation as a function of the spatial frequency content of the scene. We manipulated the spatial frequency content by setting the size of the squares constituting the texture to 0.07, 0.32, 0.97, 2.92, 8.76 or 26.28 squares/degree. The full field over which the illumination change was simulated was 14.14° horizontally and 10.63° vertically. If the texture were a perfect checkerboard, the maximum energy would be along the diagonals of the display with a fundamental frequency equal to squares/degree divided by $2\sqrt{2}$. Uniformly distributed random binary textures have a more complex frequency spectrum, but the value of squares/degree can still be used as an indicator of the scale of spatial variability. Each background consisted of binary texture along the RG, YV, or LD axis with chromaticities similar to those of experiment 2. For the lowest spatial frequency, the complete display was set to one of the constituent colors of the texture. Thresholds were measured for simulated illumination changes along the same color axis as that of the background texture. The same procedure was used as that in experiment 2, and thresholds from experiment 1 were again used as the baseline.

In Fig. 6 log-threshold elevations for color changes along the same axis as that of the texture are plotted versus the number of squares/degree in the texture (on a logarithmic scale). The spatially uniform adapting fields consisting of the full display are indicated on the horizontal axis by the letter denoting the background color. Each point is the average of the thresholds in the complementary directions along the relevant color axis. The points are joined by lines only for graphical clarity. For all the textured backgrounds that were tested, thresholds for L or D changes were not significantly elevated from the baseline. Since the largest constituent squares in the textures were always smaller than a quarter of the full field, the absence of elevations along L or D is consistent with previous spatial frequency masking results.[44] For changes in the chromatic directions, however, threshold

magnitudes were a bandpass function of the spatial scale. Since chromatic thresholds are elevated significantly more by textures containing a range of spatial frequencies than they are by uniform backgrounds, the results cannot reflect masking within spatially low-pass mechanisms. Parenthetically, in an auxiliary condition, we measured contrast thresholds for the detection of the RG textures on a W background and found a low-pass sensitivity curve as a function of squares/degree, i.e., detection of the textures was mediated by spatially low-pass mechanisms.

The results also rule out spatially local adaptation to the individual patches of the texture as the explanation for the threshold elevation. If adaptation to the texture was equivalent to spatially independent adaptation to the two constituent colors, thresholds on the texture would at most be equal to the maximum of the thresholds on the uniform fields. For the chromatic cases, thresholds were considerably higher on many textured fields than on the uniform chromatic backgrounds.

The observers in these experiments were instructed to fixate the center of the screen, but small eye movements are unavoidable when trying to maintain fixation.[45] If the main effect of eye movements were integration over space within receptive fields,[46,47] the adaptation level would be set by the mean chromaticity and luminance. Since the space-averaged colors of all the backgrounds in experiments 1–3 were identical to W, the presence of threshold elevations on the textured backgrounds rules out spatial integration as a major factor. In our view, however, eye movements lead to transient stimulation of receptive fields at the borders of the squares, thus creating temporal modulation of stimulation to individual neurons, and prolonged temporal modulation has been shown to cause chromatically selective elevation of thresholds.[4,48]

The best clue for explaining why habituating to textures raises thresholds for large-field chromatic changes but not for luminance changes is provided by the study of Krauskopf and Zaidi,[49] which showed that habituating to modulation of a large disk raised thresholds for a concentric smaller disk in the chromatic case but not in the lu-
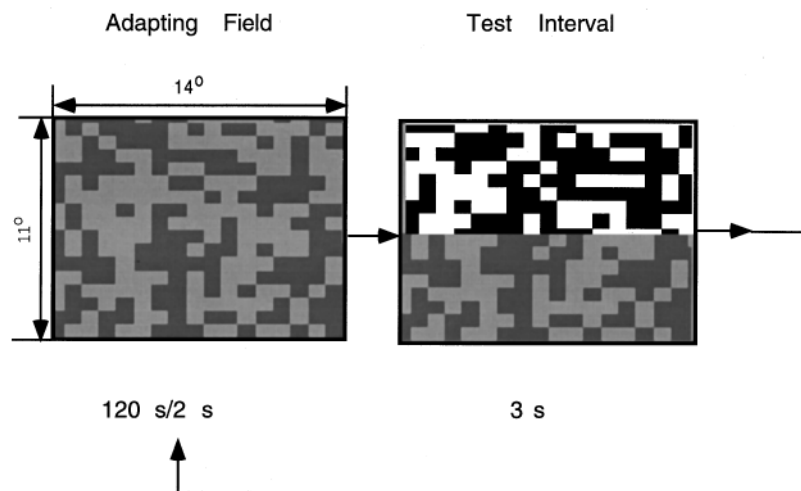

Fig. 7. Spatial configuration and temporal sequence of stimuli for experiment 4. The initial adaptation period was 120 s. Each trial consisted of a 2-s period of readaptation, followed by a 3-s interval in which the screen was divided into two vertical or horizontal halves, which contained simulated illumination changes in opposite directions along a color axis with a time course of a half-sinusoid.
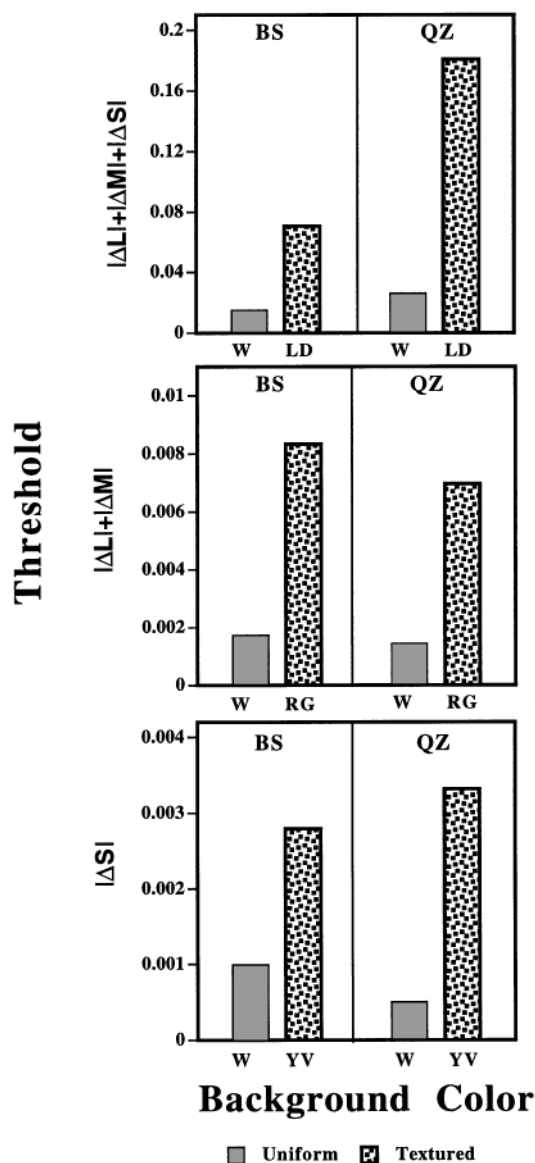
Fig. 8. Results of experiment 4 for observers BS and QZ. Shown are thresholds in cone excitation units for detecting changes along the LD (top plot), RG (middle plot), and YV (bottom plot) cardinal color axes on a spatially uniform W background and on textures colored along the same axis as that of the color change.

minance case. Habituation to luminance modulation occurred only when the habituating stimulus shared the edge of the test stimulus. In the visual system, beginning from ganglion cells in the retina, neurons are spatially bandpass for luminance variations and hence insensitive to variations that are uniform over their receptive fields.[50] It is likely that the extremely high thresholds for the L and D directions on the uniform background in experiment 1 are due to detection of these changes at the boundaries of the screen. If detection of the large-field luminance changes on the textured background also occur at the same edges, then habituation to luminance modulations will not alter luminance thresholds. Neurons with receptive fields wholly within the boundary do not participate in the detection of luminance changes at the

boundary, and habituation of neurons that are stimulated by eye movements across the boundary will be common to all conditions in experiments 1–3. On the other hand, since chromatically sensitive cortical neurons are responsive to chromatic variations that are uniform over their receptive field,[51] large-field chromatic changes are detected inside the boundary and most probably near the fixation point. Habituation of neurons in the central field by eye movements across the internal edges in the texture will therefore raise chromatic thresholds. If the squares are too large, there will be few neurons whose receptive fields oscillate across boundaries, and if the squares are too small, there may be too much integration within receptive fields for there to be substantial modulation of responses. Therefore receptive field sizes and amplitudes of eye movements will jointly determine the sizes of the squares that elevate thresholds the most.

E. Experiment 4: Masking Effects inside Variegated Fields

In experiment 4 we tested the conjecture presented in Subsection 3.D, namely, that for all three cardinal axes, units inside the variegated fields habituate under the conditions of this study. The spatiotemporal paradigm is illustrated in Fig. 7. Four types of backgrounds were used: a uniform field at W similar to that of experiment 1 and RG, YV, and LD binary textures similar to those of experiment 2. Observers initially adapted to the background for 120 s and readapted for 2 s after each trial. Each trial consisted of one 3-s interval, during which, by a random assignment, the screen was divided into horizontal or vertical halves that changed as a temporal half-sinusoid toward and back from opposite ends of the RG, YV, or LD color axes. For example, if the top half changed slowly toward and back from R, then the bottom half concurrently changed an equal amount toward and back from G. For each of the textured backgrounds, test color changes were restricted to opposite directions along the same color axis as that of the texture. Each textured half-field underwent a similar change as one of the full fields in experiments 2 and 3. In each trial the observer indicated whether the division was vertical or horizontal. For each test–background pair, this two-alternative forced-choice procedure was incorporated into a double-random staircase procedure. Threshold was estimated as the difference between the peak space-averaged level of the two halves at which, with a probability of 71%, the observer could correctly identify the orientation of the division. Two of the authors, BS and QZ, served as observers.

The results are shown in Fig. 8. For each color axis, thresholds on the textured field are plotted next to textures on the W field. The units on the vertical axes are the same as those in Fig. 4. Comparing the thresholds on the W backgrounds in Fig. 8 with the thresholds in Fig. 4 shows that in experiment 4, where the observers' task was to detect a spatial difference in the middle of the adapting field, thresholds for detecting a slow luminance change were considerably lower than those for full-field luminance changes in experiment 1. For observer BS, thresholds for detecting the split-field chromatic changes in Fig. 8 are a little less than twice the thresholds for de-

tecting full-field chromatic changes in each of the constituent directions in Fig. 4. Since thresholds in Fig. 8 are plotted in terms of the difference between the two simultaneous changes in opposite color directions, whereas in Fig. 4 they are in terms of magnitude of change in one color direction, this result is consistent with probability summation of independent detection of the color changes in the two half-fields. It is likely that detection of these mechanisms is subserved by neural mechanisms sensitive to the direction as well as the axis of the color change[42] and that these mechanisms have the properties of low-pass spatial filters.

In experiments 2 and 3, the presence of LD texture did not raise thresholds for detecting full-field luminance changes, but if there is habituation of neurons inside the textured field, thresholds for detecting the spatial division in the middle of the field should be higher on the LD texture. The results in the top plot in Fig. 8 show that LD-textured backgrounds elevate thresholds for detecting slow split-field luminance changes by a factor of 5, similar to the factor by which chromatic textures raise thresholds for chromatic changes (bottom two plots). Since the half-fields were more than 16 times the size of each texture element, these threshold elevations are not caused by what has traditionally been called masking within spatial-frequency-tuned mechanisms.[44] Instead, this result indicates that habituation is as effective inside fields varying in luminance as it is in fields varying in color. As predicted above from receptive-field structure considerations, habituation should impair the detection of large-field chromatic changes but should not affect the detection of large-field luminance changes. It is likely that with a larger adapting field, thresholds for detecting large-field luminance changes would be even higher but would still be similar for uniform and textured backgrounds.

4. DISCUSSION

In this study we began by showing the systematic nature of the chromaticity shifts that occur when one phase of natural daylight is substituted for another. Because these shifts are systematic, there is a chance that the human visual system can attenuate their perceptual effects through the use of simple adaptation strategies without having to estimate reflectance or illumination spectra.[5–7] The relative success of gamut matching theories of color constancy in machine vision[52,53] is also attributable to the high correlations in sensor signals across illuminants for most sets of objects.

The physical changes that are likely to occur in natural scenes can be compared with the experimentally measured thresholds. In Fig. 1 the effects of a shift from illuminant T to Z on the chromatic signals from natural and man-made objects may not seem large, but the differences are extremely salient in their visual effects. The average shift of signals along the $L/(L + M)$ axis is 21.3 times the threshold for a similar shift on the W background for observer BS, and 6.4 times for observer KW. Even for the most desensitizing textured background, only 15% of this shift could be tolerated by observer BS, and 97% by observer KW. The average multiplicative shift along the $S/(L + M)$ axis is 18 times the threshold

for a similar shift on the W background for observer BS and nine times for observer KW. On the most desensitizing textured background, BS could tolerate only 19% of the shift, and KW 36%. In general, then, an acute human observer will perceive changes in colors of objects when the illumination shifts between different phases of natural daylight. Painters who try to match the color of local patches of paint to the perceived colors of objects have long been aware of these changes. For example, Delacroix[54] wrote: "From my window I see a man stripped to the waist, working at the floor of the gallery. When I compare the colour of his skin with that of the wall outside, I notice how coloured the half-tints of the flesh are compared with those of the inanimate material. I noticed the same yesterday in the Place St. Suplice, where a young urchin had clambered on to one of the statues of a fountain, standing in the sun. Dull orange was his flesh, bright violet the gradations of the shadows and golden the reflections in shaded parts turned towards the ground. Orange and violet predominated in turn, or became intermingled. The golden colour was slightly tinged with green. The true colour of the flesh can be seen only in the sun and in the open air. If a man puts his head out of a window its colouring is quite different from what it is indoors. Which shows the absurdity of studies done in a studio, where each one does his best to reproduce the wrong colour." The results of the present study show that the presence of spatial variegations in most natural scenes will attenuate the perceived magnitudes of the changes, and it is possible that less demanding observers may consider many colors to be constant.

Historically, computational schemes for human color constancy have involved early adaptation mechanisms. In terms of our linking hypothesis, color constancy would be achieved at an early stage if neural processes equated first- or second-stage signals from each object in a scene across illumination conditions. As a result of this processing, the outputs of the second-stage mechanisms (and possibly even those of the first stage) should be transformed under each illuminant in a manner that, when plotted similarly to Fig. 1, all the points should fall on the diagonal of unit positive slope. The simplest mechanism that has been proposed for accomplishing this purpose is Von Kries adaptation,[1,55] where each photoreceptor signal is gain controlled by its own time-integrated signal, i.e., for each object the signals (L, M, S) are transformed to

$$\left(\frac{L}{\int L \; \mathrm{d}t/L_E}, \frac{M}{\int M \; \mathrm{d}t/M_E}, \frac{S}{\int S \; \mathrm{d}t/S_E} \right). \qquad (2)$$

For a steady uniform field, the value of each integral is equal to the cone absorption from that field, and the ratio of cone absorptions for the integrated value is transformed to be equal to the ratios for an equal-energy light $(L_E:M_E:S_E)$. This transformation could thus provide a simple explanation for the progressive desaturation of the perceived color of a continuously viewed uniformly colored field.[56] In his numerical simulations of color constancy, Ives[1] assumed that the integral for each photoreceptor was equal to the quantal absorptions by that class of receptors from the steady illuminant. Thus the result of

the transformation was to make the illuminant appear achromatic, like an equal-energy light. When we applied Ives's assumption separately for the two illuminants to signals from each object in Fig. 1, the result was rigid rotations of the lines between (0, 0) and the open circles representing the illuminants in the S, M, and L plots, in a manner in which the open circles were shifted to the unit diagonals. Since all the points representing individual objects lie on or close to these lines, the transformed chromatic signals from individual objects were also fairly well equated across the illumination conditions, thus predicting color constancy. However, there are a number of conceptual problems in accepting this transformation as an explanation of human color constancy. First, the values of the integrals for free viewing of a variegated scene cannot be determined *a priori*. In viewing a variegated scene, the ratios of time-integrated cone absorptions will be equal to the absorption ratios of the illuminant spectrum only if the integrated object reflectance spectrum for each photoreceptor is uniform; a condition that is unlikely for most natural scenes, even with spatial averaging of reflectances as a result of active scanning.[57] In reality, the spatially local values of the integrals will vary across the visual field, and to the extent that the gain for each photoreceptor is set by the spatially local signal it receives from the particular region imaged on it, the transform in expression (2) will shift the chromaticity of that object toward the achromatic point. A realistic version of this transform will thus not lead to color constancy. The second problem has to do with the stage in the visual system that is important for color-constancy transformations. It is difficult to imagine why an equal-energy light would have a privileged status for an individual photoreceptor, i.e., there is no theoretical justification for the L_E, M_E, and S_E terms in the denominators of expression (2). On the other hand, in color-opponent cells, the achromatic signal can have a privileged position as the zero point toward which the response of the system is shifted by a high-pass temporal filter. However, in a variegated scene, discounting the integrated values of opponent signals creates problems similar to those discussed in the context of the integrals in expression (2). Since it is unlikely that the integrals of the opponent signals will be proportional to the values from the illuminant, spatially local adaptation will shift all colors toward the achromatic point. This process would be consistent with and an alternative explanation for the progressive desaturation of a colored scene that is stabilized on the retina, but, similarly to local photoreceptor adaptation, it could equate chromatic signals across illuminants only at the cost of losing perceived color differences in the scene. Third, and most important, the empirical results of experiments 2 and 3 and of other studies[58–62] show that when viewing a variegated field, neither the limen of discrimination nor the appearance of colors is determined by the space-averaged level of stimulation. Consequently, models of color adaptation or constancy that rely on spatial- and/or temporal-integrated levels as the controlling parameters[8–16] may be consistent with some sets of empirical data but will not be sufficient to explain the results of experiments that isolate individual color mecha-

nisms and hence will not provide adequate theories of human color-constancy mechanisms.

It has sometimes been proposed that color induction can lead to color constancy.[13] This assertion has usually been based on the results of studies that measure perceived shifts in colors of just one test patch rather than over the whole scene and seems irreconcilable with the finding that juxtaposing two patches shifts their appearances in complementary color directions.[63,64] Simultaneous color induction will shift the signals from juxtaposed objects in opposite directions and therefore cannot discount the effect of an illumination change by shifting signals from all objects in a scene in a correlated fashion, as, for example, toward the diagonals in Figs. 1 and 2. In some cases it is possible that induced contrast will counter a shift in the spectrum of the illuminant. This discounting is most likely to occur for unsaturated hues that are surrounded by more saturated hues. For saturated hues the induced shift is more likely to be in a direction that exacerbates the effect of the illuminant change. Constancy of the appearance of an individual test patch could therefore be due to color induction but is unlikely to be a good measure of color constancy over the extent of a variegated scene. This objection applies particularly to methods that measure achromatic loci of a test patch under different illuminants.[40]

Another chain of theorizing about human color constancy has been based on the physical invariance of relative colors across illumination conditions. As pointed out by Dannemiller[2] and Foster and Nascimento,[3] the high correlations within cone absorptions, as in Figs. 1 and 2, make color constancy possible if color percepts are computed on the basis of rank orders or ratios of cone excitations. Other relational theories have invoked factors like mental judgments conditioned by experience with complex scenes,[20] and local spatial contrast.[21] The results of experiment 2 show that invariance of relative signals, though possibly a necessary factor, is in itself insufficient for color constancy. For example, a full-field change in the Y or V direction left relative excitations unchanged in all six textured backgrounds. However, the change was as easily perceived on the RG and LD textured backgrounds as it was on a spatially uniform achromatic background. For all four chromatic directions, the effect of the simulated illuminant change on perceived colors was discounted only if the texture contained spatial contrast along the same color axis. Consequently, the operative mechanism in color constancy is likely to be habituation of independent color mechanisms rather than invariance of relative signals. There is no question that higher-level percepts can influence color appearance, but these results show that a complex scene can retain a somewhat constant appearance across a variety of illumination changes, simply by providing spatial contrast along multiple color axes.

We view the present paper as the first step in the application of this approach to color perception in complex scenes. This study emphasizes the often overlooked fact that color perception in natural scenes is an active process and that spectral and spatial properties of natural scenes, sizes, and types of neural receptive fields, and the

amplitudes and the frequencies of eye movements, all have to be included in theories of color perception.

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