Color appearance under chromatic adaptation varied along theoretically significant axes in color space

Jianping Wei and Steven K. Shevell

Department of Psychology and Department of Ophthalmology and Visual Science,
The University of Chicago, 939 East 57th Street, Chicago, Illinois 60637

Received April 1, 1994; revised manuscript received July 25, 1994; accepted July 27, 1994

Changes in color appearance caused by chromatic adaptation were measured with a wide range of adapting fields. Observers viewed a 39°–55° annular test field composed of an admixture of lights from the red phosphor and the green phosphor of a CRT. The annular mixture field was centered and superimposed upon a 4.7° steady, circular background field. After the observer was completely adapted to the background, the luminance of the red phosphor in the test was held fixed while the observer adjusted the luminance of the green phosphor until the test appeared neither reddish nor greenish. Twenty-two equiluminant backgrounds (4.5 cd/m², ~50 Td) were systematically selected along two axes in Judd chromaticity space. One axis was along tritanopic confusion lines, with middle-wavelength-sensitive- (M-) and long-wavelength-sensitive- (L-) cone stimulation held constant. The other axis maintained constant short-wavelength-sensitive- (S-) cone stimulation. The results show that adapting backgrounds that were varied along tritanopic confusion lines do not have a differential effect on color appearance at high test levels (well above the adapting level). At lower test levels there is a systematic change in color appearance of the test light, which is quantitatively described by additive redness. Along constant S-cone-stimulation lines, adapting backgrounds differentially affect color appearance in a systematic way, reflecting changes in receptoral gain and the additive contribution. The measurements taken with adapting fields throughout color space are described by the two-process model of chromatic adaptation.

1. INTRODUCTION

The perceived color of a light can be affected by many factors, one of which is the state of adaptation of the eye. The change in color appearance caused by chromatic adaptation may be confined to a change in only one attribute of color perception—that is, brightness, hue, or saturation—or any combination of these attributes.1 The complex nature of chromatic adaptation makes the color appearance of a light difficult to predict.

The changes in color appearance caused by chromatic adaptation were once thought to depend solely on the sensitivity change of each of the three types of cone, as specified by the von Kries coefficient law. Many studies of chromatic adaptation, however, have shown that the coefficient law is an incomplete account of the changes in color appearance under chromatic adaptation. In the late 1970’s a controversy developed concerning the effect of a chromatic background on the perceived color of a smaller incremental test light. For the case in which an incremental test consisted of a mixture of long-wavelength (660-nm) and middle-wavelength (540-nm) lights and was superimposed upon a long-wavelength (660-nm) background, Walraven proposed that chromatic adaptation results in subtraction of the background light from the area covered by the incremental test, with the effect of the background on perceived color of the increment resulting from only shifting the relative sensitivities of the cones.2,3 He claimed that a chromatic background is discounted completely when a test stimulus is superimposed upon it, so the only effect of the background is to produce a gain change described by the von Kries coefficient law. Shevell, however, found that the background is not discounted completely.4–6 His results were consistent with a two-process theory of chromatic adaptation7,8 in which the adapting field produces both a gain change and an additive contribution to the color of the test. Similar conclusions were reached by Drum9 and Adelson.10

The chromaticity of the adapting background is varied, at constant luminance, along two theoretically significant axes in color space: tritanopic confusion lines, with middle-wavelength-sensitive- (M-) and long-wavelength-sensitive- (L-) cone excitation held constant, or constant short-wavelength-sensitive- (S-) cone-stimulation lines where there are equal and opposite changes in L- and M-cone excitations, with S-cone excitation constant.11 Detection data have shown that thresholds along each of the two axes are selectively raised following adaptation to temporal modulation along the axis in question but not along the other. This suggests that chromatic signals varying along these two axes are processed separately and independently at an early opponent level.12

The two cardinal axes derived from detection studies...
support a chromatically opponent pathway in the visual system, but it is now known that the axes differ from the opponent responses inferred from color appearance. The pure S-cone cardinal axis with constant M- and L-cone stimulation is coincident with the tritanopic confusion line, not with the red–green equilibrium line. Another discrepancy is that S cones contribute to perceptual redness.\(^{12-18}\) The response along a cardinal M–L line at constant S-cone stimulation is assumed not to depend on the level of S-cone quantum absorption, but the red–green opponent response derived from color appearance combines excitations from S, M, and L cones. The purpose of the current study is to measure the changes in color appearance caused by adapting chromaticities that are varied along the cardinal axes derived from detection measurements.

### 2. METHODS

#### A. Apparatus and Calibration

Stimuli were presented on a CRT (Sony color display) with a Pixar II image processor controlled by a Sun 3 workstation. The CRT was viewed monocularly through a natural pupil. The distance from the eye to the face of the CRT was \(\sim 1.2\) m.

All stimuli used in this experiment were specified in Judd chromaticity space. The spectral power distribution of each phosphor was measured at the maximum light level with an International Light Model IL1700/780 spectroradiometer. The radiance was measured at wavelength intervals of 0.83 nm and then converted to 1 nm by interpolation. On the basis of the results of spectroradiometric measurement, we calculated the Judd chromaticities \((x', y', \text{and} \ Y')\) of each of the three phosphors by using the Judd color-matching functions.\(^{19}\) The chromaticities of the three phosphors define the range of stimuli that can be displayed by the monitor.

For each phosphor the relative radiance of the output was measured with an International Light radiometer/photometer (ILII700) at 32 equally spaced levels of digital output (that is, the digital values that specify the voltage supplied to the CRT). A lookup table was constructed with use of linear interpolation to give the relation between each nine-bit integer value and the phosphor’s luminance. An absolute photometric calibration was done with an EG&G photometer that had a temporal integrator measuring luminance seconds over 10-s bins. We measured the absolute luminance of each individual phosphor and of their combinations at their maximum levels to check the additivity of the three guns. The independence of the three phosphors was further confirmed by additional additivity tests. We performed transformation between Judd tristimulus values \((x', y', Y')\) and integer gun values of the three phosphors by using the results of these measurements.

#### B. Stimuli

The experiments in this study required that an incremental test field be presented upon a large, steady chromatic adapting background. The spatial representation of the stimuli is shown in Fig. 1. The test was a 39°–55° annular field composed of a mixture of lights from the red phosphor, denoted \(\Delta R\) (dominant wavelength 610 nm, chromaticity coordinates \(x' = 0.62, y' = 0.34\)), and from the green phosphor, denoted \(\Delta G\) (dominant wavelength 538 nm, chromaticity coordinates \(x' = 0.27, y' = 0.59\)).

The annular mixture was centered and superimposed upon a 4.7° steady, circular background.

Twenty-two equiluminant backgrounds (4.5 cd/m\(^2\), \(\sim 50\) Td) were systematically selected along two axes in the Judd chromaticity space. Stimuli were varied along tritanopic confusion lines (denoted here as T lines), where only the level of S-cone excitation was changed, or along constant S-cone-stimulation lines, denoted here as ML lines, where there were equal and opposite changes in L- and M-cone excitations [Fig. 2(a)]. In the Judd chromaticity diagram the T lines radiate from the tritanopic copunctal point with coordinates \((x' = 0.175, y' = 0)\), and the ML lines converge to the point \((x' = 1, y' = 0)\).\(^{11}\) The chromaticities of the adapting backgrounds were determined by the intersections of four T lines, four ML lines, and a line denoted RB that connects the chromaticities of the red and the blue phosphors. The circles and the square labeled G in Fig. 2(a) show the 22 adapting backgrounds used in the experiments. The squares are chromaticity coordinates of the three phosphors. The adapting backgrounds that can be tested are restricted to the interior of the triangle defined by the three phosphors.

In order to appreciate how these adapting backgrounds stimulate each of the three types of cone, we replotted the chromaticities of the adapting backgrounds in Fig. 2(b) in the MacLeod–Boynton cone-excitation space.\(^{11}\) The quantities \(s, m, \text{and} \ l\) are the cone excitations, based on Smith–Pokorny cone fundamentals.\(^{20}\) This diagram represents a constant-luminance plane. The underlying assumption is that there is no contribution to luminance from S cones. The luminance therefore is determined by only M and L cones, so that \(l + m\) is constant. The M- and L-cone excitations, which change equally in opposite directions (the sum of them always equals 1), are expressed as \(m/(l + m)\) or \(l/(l + m)\) on the horizontal axis.

![Fig. 1. Luminance profile (top) and spatial representation (bottom) of the stimuli.](image-url)
Fig. 2. (a) Representation of equiluminant adapting backgrounds (4.5 cd/m², ~50 Td) along two axes in the Judd chromaticity diagram. T’s, tritanopic confusion lines; ML’s, constant S-cone-stimulation lines. Circles (and the square labeled G) represent the adapting backgrounds used in this study. Squares represent the CRT phosphors. (b) Representation of the chromatic adapting backgrounds in MacLeod–Boydton cone excitation space. S-cone excitation is on the vertical axis; L- and M-cone excitations, which change equally in opposite directions, are on the horizontal axis. Symbols as in (a).

The S-cone excitation, expressed as $s/(l + m)$, is plotted on the vertical axis. As in Fig. 2(a), circles represent the adapting backgrounds and squares show the three CRT phosphors. The vertical lines in this space are tritanopic confusion lines, and the horizontal lines are constant S-cone-stimulation lines. We selected the adapting backgrounds so as to observe changes in chromatic adaptation as the adapting chromaticity is varied independently along these two axes.

The composition of the test field is restricted to the red and the green phosphors. These phosphors minimally stimulate S cones [squares labeled R and G, Fig. 2(b)]. The maximal level of S-cone stimulation by the test light is ~40 S Td, which is approximately the same as 2000 photopic Td of 540-nm monochromatic light. We assume that any deviation from red–green linearity that is due to S-cone stimulation by the test light is negligible, and we have found no evidence to the contrary.

C. Observers

Two male observers with normal color vision, as determined by Rayleigh matching, participated in this experiment. One (LC) was a paid undergraduate volunteer, who was naïve as to the design and purpose of the experiment. The other (JW) is one of the authors. Between five and ten 1-hr practice sessions, depending on the repeatability of the measurements over days, preceded collection of experimental data. Observers wore their normal nontinted prescription lenses.

D. Procedure

Changes in color appearance were measured with a red–green hue cancellation technique.2,4 The luminance of the red phosphor in the test was held fixed while the observer adjusted the luminance of the green phosphor until the annular test appeared neither reddish nor greenish. Before each setting the stimulus was randomly offset up or down from the previous one. Six or seven (depending on the adapting background) luminance levels of $\Delta R$, separated by 0.3 log unit, were presented during each session. These luminance levels of $\Delta R$ were presented in random order within each session. One of the 22 adapting backgrounds was presented in each session. The order of the 22 backgrounds was random.

An experimental session began with 5 min of dark adaptation followed by 5 min of adaptation to the adapting background (for the condition with no adapting field the dark-adaptation period was 10 min). At each test level the observer made a preliminary setting followed by 2 min of additional adaptation and then made settings in five successive trials. The mean of the five equilibrium-color settings was taken as the measurement for the day. Each condition was repeated on at least two separate days; standard errors are based on the variability of the mean measurement from separate sessions on different days.

3. RESULTS

The effects of chromatic adaptation on the color appearance of the incremental test light are quite different when the state of adaptation varies along each of the two cardinal axes in color space (trianopic confusion lines and constant S-cone-stimulation lines). One can see a qualitative impression of the changes in color appearance by comparing different sets of red–green equilibrium-color measurements along a line in color space.

A. Chromatic Adaptations along the Tritanopic Confusion Lines

The quantal absorption by S cones increases as the adapting background is varied along a tritanopic confusion line toward the copunctal point [point T in Fig. 2(a)]. S-cone stimulation is approximately 10–25 times higher at the lowest points than at the highest points on the tritanopic confusion lines. Because quantal absorption by the two other types of cone is unchanged for backgrounds along a tritanopic confusion line, the difference between any two adapting backgrounds on a tritanopic confusion line is due only to adapting S cones.
Fig. 3. Measurements with adapting backgrounds along the T-1, T-2, T-3, and T-4 lines for observer LC. The luminance of ΔG in the test light was adjusted by the observer so that the test appeared neither reddish nor greenish. Each set of points represents a different adapting background. Dashed lines with circles represent dark-adapted measurements. Error bars indicate ±1 SEM. Solid curves through the measurements are from the two-process model. The dominant wavelength λd as well as the fitted values of f and g for each background are shown in the insets at the lower right of each panel (see text).

Measurements with five equiluminant adapting backgrounds along the T-1 line are shown in Fig. 3(a) for observer LC. The luminance (cd/m²) of the green phosphor in the test mixture, ΔG, is plotted on the vertical axis as a function of the luminance level (cd/m²) of the red phosphor in the test mixture, ΔR. Each set of points with the same symbol is for a single adapting background. Each plotted point is the mean of the measurements on two separate days. Error bars indicate ±1 standard error of the mean (SEM). The dashed line with circles in this and subsequent figures shows dark-adapted measurements (ΔG + ΔR mixture presented with no background), included here to show the magnitude of the change in color appearance caused by the adapting backgrounds. Under dark adaptation the luminance ratio ΔG:ΔR should be a constant, because equilibrium yellow is luminance invariant. The luminance of all adapting backgrounds is 4.5 cd/m² (~50 Td).

As shown in the MacLeod–Boynton cone-excitation space, the quantal absorption by S cones increases (~25-fold) when the adapting background is changed from T-1/ML-1 to T-1/RB, while M- and L-cone stimulation is constant. The measurements show that a substantially higher level of the green phosphor in the test is required with background T-1/RB (triangle) than with background T-1/ML-1 (open square with cross) at lower test levels. The increase is more than 3-fold (0.5 log unit). This means a test light that appears neither reddish nor greenish on the background T-1/ML-1 (the green CRT phosphor alone) becomes reddish when the adapting field changes to background T-1/RB. The additional redness contribution must be due to S cones, because M and L cones cannot detect a difference between backgrounds on a tritanopic confusion line. Therefore the S cones contribute redness to the test patch.14,16,17

The relation between test level and adapting backgrounds along the T-1 line shows a general pattern. The different backgrounds on the T-1 line result in substantially different levels of the green phosphor in the test (ΔG) at low test levels, but the difference is much smaller (even negligible) at higher test levels. The measurements are systematically dispersed at low test levels (ΔR less than ~0.5 log cd/m²) but tend to converge as the test level increases. The results are quantitatively con-
consistent with stimulation of the S cones by the background adding a fixed amount of redness to the appearance of the test while the sensitivity of the photoreceptors is not affected.4,16

If sensitivity of the M and the L cones were the only mechanism of chromatic adaptation affecting the results, the measurements with these adapting backgrounds along the T-1 line would fall together on a single 45° line. The data in Fig. 3 do not do this. In fact, they do not fall along any straight line, which confirms that the von Kries coefficient theory alone cannot account for chromatic adaptation. The solid curves through the measurements are from the two-process model (the model is discussed quantitatively below). Sensitivity changes implicit in the two-process model are reflected by the 45° line approached asymptotically at higher test levels, and the additive effect in the model implies curvature at lower test levels. These fits indicate that the two-process theory can account well for the effects of changing the adapting background along a tritanopic confusion line. The inserts at the lower right of the four panels of Fig. 3 show the dominant wavelengths of the backgrounds and the parameters of the fits for each background (discussed below).

Figures 3(b), 3(c), and 3(d) show the results with adapting backgrounds along the T-2, T-3, and T-4 lines, respectively, for observer LC. Measurements with adapting backgrounds along the T-1, T-2, T-3, and T-4 lines for observer JW are plotted in Figs. 4(a), 4(b), 4(c), and 4(d), respectively. Symbols are explained in the insets at the upper left of Figs. 3 and 4. The measurements in Figs. 3 and 4 do not fall along 45° lines. The plot of log ΔG versus log ΔR can be a downward curve or an upward curve, depending on the chromatic background. The two observers show similar patterns. Increasing the S-cone stimulation along each T line increases the required amount of ΔG test light. This is indicated by the changes in curvature within each panel. At low test levels, the increase in the required amount of test light from the green phosphor when backgrounds are varied along a tritanopic confusion line is 2- to 3-fold (−0.3−0.5 log unit) for observer LC (Fig. 3) and 2.5- to 6-fold (0.4−0.8 log unit) for observer JW (Fig. 4). At higher test levels all measurements with backgrounds along a single T line converge to similar values, reflecting unchanging desensitization of M and L cones. The relative desensitization of M to L cones decreases as the adapting background is changed from the T-1 line to the T-4 line. Measurements at higher test levels with backgrounds on the T-1 or the T-2 line are above the dark-adapted values because of the relatively greater desensitization of M than L cones.
B. Chromatic Adaptations along the Constant S-Cone-Stimulation Lines

Results with five adapting backgrounds along the ML-1 line are shown in Fig. 5(a) for observer LC. These measurements are replotted from the four panels in Fig. 3 to show the effect of variation along the ML-1 line of constant S-cone stimulation. The interpretation of the axes is the same as for Figs. 3 and 4. The measurements change as the adapting background varies along the ML line, with a pattern that is different from the pattern found for the tritanopic confusion lines. The measurements with different backgrounds are separated at low and also at higher test levels. For background ML-1/T-1 (open squares with crosses), the downward curvature indicates that the background contributes a fixed amount of greenness to the test color. Results at higher test levels approach a 45° line that is above the dark-adapted measurements because of the greater desensitization of M than L cones caused by the ML-1/T-1 background. As the adapting background is changed toward ML-1/RB (triangles), the horizontal plateau and the upward curvature indicate that the background contributes a fixed amount of redness to the test. The 45° line approached at higher test levels is below the dark-adapted measurements. This shift toward greenness reflects the greater desensitization of L than M cones caused by the background ML-1/RB.

Figures 5(b), 5(c), and 5(d) show the results with adapting backgrounds along the ML-2, ML-3, and ML-4 lines, respectively, for observer LC. Measurements with adapting backgrounds along the ML-1, ML-2, ML-3, and ML-4 lines for observer JW are shown in Figs. 6(a), 6(b), 6(c), and 6(d), respectively. The interpretation of the axes is as for Figs. 3–5. For both observers the measurements along each ML line at lower test levels spread out systematically, then cross one another, and then at higher test levels spread out again. Changing the adapting background from ML-1/T-1 to ML-1/RB lowers the 45° asymptote and results in more upward curvature at the left-hand side of the plot. This is true also for other ML lines. The measurements approach different 45° lines at higher test levels because of changes in the ratio of M- versus L-cone desensitization. The relative desensitization of the L cones increases (and desensitization of M cone decreases) as the background changes from left to right along an ML line (see Fig. 2). This causes the 45° line approached at higher test levels to move downward. Meanwhile, the changes in the cur-

![Fig. 5. Measurements with adapting backgrounds along the ML-1, ML-2, ML-3, and ML-4 lines (constant S-cone-stimulation lines) for observer LC. Axes as in Fig. 3.](image-url)
Fig. 6. Measurements with adapting backgrounds along the ML-1, ML-2, ML-3, and ML-4 lines for observer JW. Axes as in Fig. 3.

A. Redness Contribution from Adapted S Cones
A background that stimulates S cones has a substantial influence on the color appearance of an incremental test light. This influence is shown by a comparison of the effect of luminance-equated adapting backgrounds that fall upon a tritanopic confusion line. More test light from the green phosphor is required at low test levels as backgrounds along a tritanopic confusion line are varied toward the tritanopic copunctal point. This means that a test light that appears neither reddish nor greenish on, for example, the background T-1/ML-1 appears reddish on the background T-1/RY [see Fig. 3(a)]. Since the quantal absorption by S cones increases when the background changes from T-1/ML-1 to T-1/RY but the stimulation of M- and L-cones is constant, the additional redness contribution must be due to S cones alone. This is consistent with the finding of Shevell and Humanski,16 who used a tritanopic pair of monochromatic wavelengths and found that S cones add a fixed amount of redness to the appearance of an increment detected by only M and L cones.

B. Two-Process Theory of Chromatic Adaptation
According to opponent-color theory,15 the responses of the red–green and yellow–blue color-opponent mechanisms depend on particular combinations of excitations in the three types of cone. The transformation from the...
S-, M-, and L-cone excitations to the red–green chromatic response is now known to be nonlinear. A linear model implies that unique hue loci (for example, the set of lights that are neither reddish nor greenish) fall on straight lines in chromaticity space. Direct experimental tests have shown that unique blue lights fall along a curve, and thus the red–green chromatic response systematically deviates from linearity in the short-wavelength region of chromaticity space. It has been suggested that red–green response nonlinearity is due to S-cone stimulation, which contributes redness to the red–green opponent system. Under conditions in which S-cone stimulation is minimal, however, red–green linearity is a reasonable approximation. We use test lights here that minimally stimulate S cones.

A mathematical expression of the two-process model, based on red–green linearity, was proposed by Jameson and Hurvich and later modified by Shevell. Under dark adaptation the red–green chromatic response was modeled as a linear combination of the spectral sensitivities of the three types of photoreceptor. Thus, in the dark, the red–green \((r-g)\) response to light \(e\) is

\[
r - g = \sum a_i [e_i (S_i + M_i + L_i)],
\]

where \(S_i, M_i,\) and \(L_i\) represent the spectral sensitivities of the three types of cones and \(a_1, a_2,\) and \(a_3\) are weighting coefficients. The first process of chromatic adaptation is expressed by values of \(a_1, a_2,\) and \(a_3\). An adapting light that alters differentially the sensitivities of the three cone types is modeled by changes in these weights. The second process in the model is the additive effect, which alters chromatic signals by a fixed amount. Therefore under chromatic adaptation the model can be expressed as

\[
r - g = \sum [e_i (a_1 S_i + a_2 M_i + a_3 L_i)] + K_{r-g},
\]

where \(K_{r-g}\) is the additive effect of the adapting stimulation and equals zero under dark adaptation. The two effects together account for the changes in color appearance under a wide range of adapting conditions.

For conditions under which red–green linearity is a good approximation, the two-process model predicts that red–green equilibrium-color settings follow the relation

\[
\Delta G = (\Delta R + f)g,
\]

or, equivalently,

Fig. 7. Values of two-process model parameters \(f\) (cd/m²) and \(g\) for adapting backgrounds varied along tritanopic confusion lines, plotted as a function of the level of S-cone excitation. (a), (b) The arrows on the vertical axes indicate the \(g\) values for the dark-adapted condition. (a), (c) Observer LC; (b), (d) observer JW.
Fig. 8. Values of two-process model parameters \( f \) (cd/m\(^2\)) and \( g \) for adapting backgrounds varied along constant S-cone-stimulation lines, plotted as a function of the level of L-cone excitation. (a), (b) The arrows on the vertical axes indicate the \( g \) values for the dark-adapted condition. (a), (c) Observer LC; (b), (d) observer JW.

\[
\log_{10}(\Delta G) = \log_{10}(\Delta R + f) + \log_{10}(g). \tag{4}
\]

The quantities \( \Delta G \) and \( \Delta R \) in this case are, respectively, the levels of incremental test light from the green and red phosphors mixed together and adjusted to appear neither reddish nor greenish. Under this model the parameter \( g \) may be interpreted as the sensitivity of the red–green chromatic response to light from the red phosphor relative to sensitivity to light from the green phosphor, and it is the ratio \( \Delta G/\Delta R \) for a neither-reddish-nor-greenish test of arbitrarily large luminance (i.e., when \( \Delta R \gg f \)). The parameter \( f \) reflects the additive contribution from the adapting background. \(^4\)

Template curves defined by Eq. (4) for \( f > 0 \) and \( f < 0 \) are fitted to the measurements shown in Figs. 3–6. The plateau and the curvature of the template curves are characteristics of the two-process model. According to the model, the redness sensation to be canceled by \( \Delta G \) depends on the sum of the redness of \( \Delta R \) and the additive redness (or greenness) contributed to the test by the adapting background. The additive contribution is equivalent to presenting a fixed amount of redness (or greenness) in the superimposed test field. Each template is shape invariant. The parameters \( f \) and \( g \) shift the templates only along the logarithmic coordinate axes. \(^4,6\) The values of the parameters \( f \) and \( g \) depend on the adapting background. If for any given adapting background there exists a positive value \( f \) such that \( \Delta G/(\Delta R + f) \) is constant, then the data must fall along one of the template curves \( f > 0 \); similarly, if there exists a negative value of \( f \) such that the ratio \( \Delta G/(\Delta R + f) \) is constant for any given adapting condition, then the template for \( f < 0 \) must fit the data. A negative value of \( f \) implies that the additive contribution is greenish.

If the additive contribution is reddish \( (f > 0) \), at lower test levels more \( \Delta G \) in the test is needed to cancel the additive redness, compared with the adapting effect of only receptoral desensitization. With an adapting background that contributes additive greenness rather than redness \( (f < 0) \), the amount of \( \Delta G \) required to cancel the redness of \( \Delta R \) in the test is less, because part of the redness of \( \Delta R \) is canceled by the additive component of greenness. The level of \( \Delta G \) approaches zero at a particular level of \( \Delta R \): the amount of \( \Delta R \) in the test that precisely cancels the additive contribution of greenness. As the level of \( \Delta R \) increases, the relative significance of the additive contribution becomes smaller. Finally, at sufficiently high levels the effect of the additive compo-
nt is negligible. The fit of the template to the data expresses the degree to which the model describes the measurements. The correspondence is excellent for both observers.

The patterns in the data with backgrounds varied along tritanopic confusion lines or along constant S-cone-stimulation lines can be summarized by changes in the two parameters $f$ and $g$ of the model. The values of parameters $f$ and $g$ along tritanopic confusion lines, shown in the insets of Figs. 3 and 4, are plotted in Fig. 7 as a function of S-cone excitation from the background. The arrows on the vertical axes of Figs. 7(a) and 7(b) indicate the $g$ values for the dark-adapted condition. For both observers the relative sensitivity of L:M cones, which is implicit in $g$, is nearly constant for each T line [Figs. 7(a) and 7(b)]. The redness contribution, expressed by parameter $f$ in candelas per square meter, increases with S-cone stimulation [Figs. 7(c) and 7(d)], corroborating the substantial contribution to redness from S cones.

We also fitted the data from each subject with a reduced form of the two-process model in which all backgrounds on a single tritanopic confusion line share a single value of $g$ (gain component). Using a likelihood-ratio test of hierarchical models, we found that this model gives an adequate account of the measurements (criterion $P < 0.05$) for all tritanopic confusion lines for both observers, with the exception of the T-3 line for observer JW [filled squares, Fig. 7(b)]. The $g$ values along the T-3 line for observer JW, however, do not show any trend, so this one significant result out of eight may be spurious. We conclude that the measurements are consistent with S-cone stimulation not affecting L- or M-cone sensitivity.

When the adapting background is varied along the constant S-cone-stimulation lines, the additive contribution and the relative sensitivity of L:M cones, expressed by parameters $f$ and $g$, vary in opposite directions (Fig. 8). The $g$ value decreases with greater $l/(l + m)$ stimulation, indicating a decrease in the relative sensitivity of the L cones [Figs. 8(a) and 8(b)], while the $f$ value increases, indicating a larger additive contribution of redness to the test as L-cone stimulation increases from left to right along an ML line in color space [Figs. 8(c) and 8(d)]. Both observers show this pattern.

All the measurements with different adapting backgrounds are well described by Eq. (4), with either $f > 0$ or $f < 0$. For some adapting backgrounds the measurements for the two observers require different template curves. For example, observer LC requires small positive $f$ values for backgrounds T-1/ML-3 and T-1/ML-4 on the T-1 line (Fig. 3), but observer JW requires negative $f$ values for the same backgrounds (Fig. 4). The systematic nature of the measurements indicates that these differences are not the results of random variation. Instead, there appear to be between-subject differences in the effects of the adapting backgrounds.

In summary, the complete set of measurements with adapting backgrounds varied along either tritanopic confusion lines or constant S-cone-stimulation lines throughout color space are described accurately by the two-process model of chromatic adaptation [Eq. (4)]. The von Kries coefficient law accounts for color-appearance differences at higher test levels when adaptation is varied along constant S-cone-stimulation lines. The systematic spread of the measurements at lower test levels reflects a change in the additive component of chromatic adaptation along both tritanopic confusion lines and constant S-cone-stimulation lines.

**ACKNOWLEDGMENT**

This research was supported by U.S. Public Health Service grants EY-04802 and EY-07390.

**REFERENCES**


