COLOR PERCEPTION UNDER CHROMATIC ADAPTATION: EQUILIBRIUM YELLOW AND LONG-WAVELENGTH ADAPTATION

STEVEN K. SHEVELL
Department of Behavioral Sciences, The University of Chicago.
5848 S. University Avenue, Chicago, IL 60637, U.S.A.

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Abstract—Observers viewed a thin (0.8–1.3) annulus composed of a mixture of 540 and 660 nm monochromatic lights (denoted ΔC and ΔR, respectively). The annular mixture was superimposed upon a larger (2.7) 660 nm circular background field. The observer adjusted the radiance of either ΔC or ΔR so that the annulus appeared a perfect (i.e., neither reddish nor greenish) yellow. In the first experiment, the background and annulus both were presented steadily. The results showed that the background, varied over a range from 10 to 1000 td, always contributed less to the color appearance of the annular test area than would be expected from the simple admixture of lights. The second experiment examined the effect of briefly removing the background-field quanta during the period when the annulus was judged. After several minutes of adapting to the background, the background was momentarily extinguished for 1 sec once every 6 sec; the observer adjusted the radiance of ΔR so that during the 1 sec period the continuously presented annular mixture appeared equilibrium yellow.

With steady backgrounds, the ΔC to ΔR luminance ratio decreased with test annulus luminance; for judgments made while the background momentarily was extinguished, the luminance ratio generally increased with annulus luminance. All of the empirical observations can be accounted for quantitatively by a two-process theory of chromatic adaptation: in two processes are (1) gain changes and (2) a restoring signal that tends to drive back toward equilibrium the opponent response resulting from the adapting light. Results from a third experiment in which the background-off interval was reduced from 1 sec to 500, 200, or 150 msec also are consistent with this model.

INTRODUCTION

A metameric trichromatic match will not be disturbed by chromatic adaptation. This well accepted principle is not without exception (Wright, 1936, 1946; Brindley, 1953; Wyszecki, 1978; Alpern, 1979), but with adapting fields of moderate luminance the persistence of color matches is nearly exact (von Kries, 1878; Le Grand, 1957). Though two stimulus fields will continue to match under adaptation, the adapting conditions are likely to affect the color actually seen by the observer. The change in color caused by adaptation is identical in both fields and therefore the match (but not the percept) is unaffected.

This paper focuses on the change in perceived color resulting from chromatic adaptation. What are the mechanisms of adaptation that affect color appearance? It is now well known that receptor sensitivity changes alone (von Kries Coefficient Law) cannot account for color perception under chromatic adaptation (Hurvich and Jameson, 1958; Cicerone et al., 1975; Shevell, 1978; Larimer, 1981). Failure of the Coefficient Law led Hurvich and Jameson (1958; Jameson and Hurvich, 1959) to propose that an adapting light causes incremental (or decremental) contributions to color signals in addition to sensitivity changes. This view is supported by recent measurements (Shevell, 1978, 1980; Larimer, 1981).

The experiments reported here further explore the incremental signal, and test whether it is indeed additive in nature. Observers adjusted a test field mixture of 540 and 660 nm lights for an equilibrium (neither reddish nor greenish) yellow percept. Under dark adaptation, the mixture ratio of 540 to 660 nm light is constant for any (moderate) luminance level; this result (Larimer et al., 1974). If the only effect of an adapting light were receptor sensitivity changes (as proposed by von Kries), then adaptation only would change the test field mixture ratio to some new constant value that would not vary with test luminance. As mentioned above, measurements demonstrate that this is not the case; with long-wavelength adaptation the 540 to 660 nm mixture ratio varies systematically with test field luminance.

In experiments where the adapting field is presented continuously and the test superimposed upon it, a straightforward explanation may be proposed for the relationship between test field luminance and mixture ratio: the fixed intensity adapting light adds physically with the test light in the test area, thus as test luminance is increased the adapting field has a relatively smaller contribution in the test area with a consequent effect on test light mixture ratio. However, the quantitative implications of this view are inconsistent with empirical measurements: the data can be fit only by assuming the adapting light makes a much smaller contribution to the color percept of the test area than would be expected from the simple admixture of lights (Walraven, 1976; Shevell, 1978; Larimer, 1981). Again, an incremental type...
of process (specifically, a decrement) is implicated. The adapting field's reduced effect suggests that it generates a decremental signal that tends to counterbalance (and thus reduce) the effect of physical admixture.

The first experiment reported here determined for five naive observers the magnitude of the adapting field's net incremental (or "additive") effect over an adapting light intensity range from 10 to 1000 td. These estimates are more precise and are from a larger sample of naive subjects than reported previously (Shevell, 1978). The measurements also reveal the magnitude of individual subject differences (which are fairly large) and within-subject between-day variability (which is small); an accurate assessment of variability (especially between subjects) was deemed essential because of conflicting reports (Walraven, 1976, 1979).

The remaining experiments explore the counterbalancing decremental signal by briefly extinguishing the adapting light during the observer's color appearance judgments (the state of adaptation having been established prior to and between very brief test trials). If there exists a counterbalancing signal (and it does not decay very rapidly), it should be revealed during these test trials. Further, if it is truly counterbalancing (that is, opposite in sign) and additive, the 540 to 660 nm mixture ratio as a function of test field luminance should follow (for any given adapting condition) a specific functional form. This is precisely the empirical result.

**METHODS**

**Apparatus**

The experiments were conducted with a four-channel Maxwellian view optical system. A schematic diagram of the apparatus is shown in Fig. 1. The single light source S was a 24 V, 150 W tungsten-halogen lamp (General Electric DZE) powered by a well regulated DC power supply (Power-One F24-12). The channels were identical in basic design and in length of light path from the filament to its image at the observer's pupil (P).

Lenses imaged the filament on the aperture stop A (filter IR, placed between the source and A, blocked infrared light). An Inconel neutral density circular wedge was adjacent to the aperture stop on one side; adjacent to A on the opposite side was a shutter constructed from a speaker cone (rise and fall times were about 2 msec). Following the shutter, the light was collimated prior to passing through a three-cavity (Ditric Optics) interference filter and/or Inconel neutral density filters located at filter box FB. Light from channels 1 and 2 was combined at beamsplitter cube C1,2, and light from channels 3 and 4 was merged at cube C3,4. Cube C1,2,3,4 combined the light from all four channels. The final lens ML imaged the filament at the observer's pupil (the diameter of the image was 2 mm). Field stops FS were placed in the rear focal plane of lens ML. (Channel 1 was not required for the experiments reported here.)

The 660 nm adapting light was provided by channel 2. The test beam was formed by mixing 660 nm light from channel 3 and 540 nm light from channel 4. The observer (at the experimenter's option) could control the radiance of the light in any channel by manipulating a joystick. The position of the joystick was sensed by a microcomputer (Ohio Scientific Instruments C2-8P 8-inch floppy disk system) which, through an interface, altered the position of the appropriate Inconel wedge via a stepping motor. The computer also maintained a record of the position of each wedge and handled shutter-timing chores. Scattered light arriving at the observer's eye was minimized by a viewing hood which separated the observer from all parts of the optical apparatus except the final lens ML. The observer used a bite bar to maintain a fixed head position.

**Calibration**

A plate of known reflectance, placed a given distance from the image formed by lens ML, was illuminated by light from a single channel. With the channel's Inconel circular wedge set near its minimum density, the luminance of the plate was measured using an S.E.I. photometer. The retinal illuminance of the unattenuated white (tungsten) light for the channel then was computed using the method described by Westheimer (1966).

To determine the reduction in retinal illuminance for each interference filter, a 660 and a 540 nm filter were placed in channels 3 and 4 respectively. The wedge in channel 3 was set near its minimum density; the wedge in channel 4 was adjusted so that the mixture of red and green lights at the reflection plate was similar in color to the S.E.I. matching field. The S.E.I. photometer measurement allowed computation of the retinal illuminance of the light mixture. This
information, together with (1) the relative radiances of the 660 and 540 nm lights (measured with a spectrally flat PIN-10DF photodiode/filter), (2) the wedge calibrations described below, and (3) tabled values of relative photopic sensitivity, permitted computation of the reduction in retinal illuminance for each filter. The maximum light levels from channels 2, 3 and 4, respectively, were 3.91 (at 660 nm), 4.21 (at 660 nm), and 5.29 (at 540 nm) log td. Inconel wedges and neutral density filters were calibrated individually at 540 and at 660 nm using the PIN-10DF photodiode. Shutter timing was verified by placing the photodiode at the image formed by lens M1 and displaying the photodiode/amplifier output voltage on an oscilloscope.

The conclusions from Experiment 1 depend critically upon accurately calibrating the relative radiances of channels 2 and 3 at 660 nm. As an additional check, an observer made an isomeric match between two 660nm fields (one from each channel). The retinal illuminance for each matched field then was calculated using the results from the above described calibration procedure. The agreement was virtually exact (within 0.01 log unit).

Observers

Five graduate-student volunteers, all naive as to the design and purpose of the experiments, served as observers. Each observer was screened for color vision defects using the Farnsworth Panel D-15 test and a Nagel anomaloscope. The sex and age of the observers were as follows: D.H. (male, 22), D.N. (female, 21), J.D. (male, 22), J.H. (female, 23), W.S. (male, 26). Between five and ten 2-hr practice sessions preceded collection of the reported data (the exact number of practice sessions was based upon repeatability of measurements over days). Observers wore their normal prescription lenses (if any).

Procedure

In each experiment the annular test field, composed of a mixture of 540 nm light (denoted \( \Delta G \)) and 660 nm light (denoted \( \Delta R \)), was superimposed upon the larger 660 nm circular adapting field (denoted \( R \); see Fig. 2). The radiances of the adapting field always was constant in a given experimental run; either the radiances of \( \Delta R \) was fixed by the experimenter and the observer adjusted the radiances of \( \Delta G \) (Experiment 1), or \( \Delta G \) was fixed and the observer adjusted \( \Delta R \) (experiments 2 and 3). The observer's task always was the same: adjust the appearance of the test field for a perfect (neither slightly greenish nor slightly reddish) yellow percept. Between each setting, the observer-adjusted wedge randomly was repositioned by up to 0.20 log unit. The annular test was presented steadily in all experiments. The adapting field was presented continuously in Experiment 1. In Experiments 2 and 3 the adapting field was briefly extinguished (for 1 sec or less) during the test period when the observer made his color appearance judgment.

Each experimental session began with seven minutes of dark adaptation followed by seven minutes of adaptation to the appropriate adapting light (for conditions with no adapting field the dark adaptation period was extended to 14 min). During light adaptation the observer was instructed to view steadily the center of the field. When the (continuously presented) test annulus was introduced, he steadily fixated the center of the annulus.

RESULTS

Steady adapting fields (Experiment 1)

The 2.7 circular adapting field was presented continuously in the first experiment, with the test annulus superimposed upon it. On each experimental trial, lights \( R \) and \( \Delta R \) were fixed: the observer adjusted the radiance of \( \Delta G \) for equilibrium yellow. The results are plotted separately for each observer in Fig. 3. Each set of points is for a different level of the adapting field \( R \). The amount of 660 nm light in the test beam (\( \Delta R \)) is plotted on the horizontal axis; on the vertical axis is the amount of 540 nm light (\( \Delta G \)). The top curve (\( R \text{OFF} \)) in each plot is to scale: the other curves have been shifted vertically an arbitrary amount for clarity. The \( R \text{OFF} \) data points are averages from two experimental runs completed in a single session. Each point on a curve with an error bar at the extreme right is the average of at least four single-session means from runs on separate days. Error bars show plus or minus one standard deviation of the mean for the average of the four (or more) daily means. All other points show...
Fig. 3. Steady background measurements for five observers. Each plot shows retinal illuminance of the 540 nm light (ΔG) vs retinal illuminance of the 660 nm light (ΔAR) for the superimposed annular test field. Each set of points is for a given level of the steady 660 nm adapting field R (R in log td). The R OFF data (filled circles) are to scale in each plot; the other sets of points have been shifted vertically downward for clarity. The magnitudes of the shifts for R = 1.0, 1.65, 2.0, 2.3 and 3.0 are respectively: D.N. (0.3, 0.9, 1.3, 1.5, 2.5), D.H. (0.4, 0.9, 1.7, 2.5), J.D. (0.5, 0.5, 1.4, 2.5), J.H. (0.1, 0.25, 0.75, 1.0, 2.0), W.S. (0.3, 0.5, 1.0, 1.5, 2.0). Lower right: the template curve specified by $\Delta G = [\Delta R + f(R)]g(R)$, $f(R) > 0$. This curve, shifted only parallel to the logarithmic coordinate axes, has been fit to each set of open symbols (the filled symbols [R OFF] are fit by a 45° line).

*See footnote * on p. 283.
Equilibrium yellow and long-wavelength adaptation

Fig. 4. Values of log \( f(R) \) vs log \( g(R) \) determined at six levels of the steady adapting field \( R \) (\( R \) in log td). Each symbol represents a different observer. Error bars are based upon repeated observations over four or more days (see text).

*See footnote * on this page.

the mean of five measurements made in a single experimental run.*

A constant \( \Delta G/\Delta R \) ratio is represented in these coordinates by a 45° line. With the exception of the R OFF and (for some observers) \( R = 1.0 \) log td conditions, the data clearly deviate from a line of slope 1. The curve fit to each set of points is the more general form

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

where \( f(R) \) and \( g(R) \) are parameters estimated from the data (see Shevell, 1978). The values of the parameters depend upon the adapting field \( R \), but are constant for any fixed adapting level.

Equation (1) is by no means assured to fit the observations. If for any given adapting light \( R \) there exists a positive value \( f(R) \) such that \( \Delta G/\Delta R + f(R) \) is constant, then the data must fall along a well specified template curve (bottom right, Fig. 3). The template curve may be shifted horizontally and vertically (along logarithmic axes) but not otherwise adjusted. The fit of the data to the template expresses the degree to which equation (1) adequately describes the measurements; the correspondence is excellent for every observer.

Each arrow in Fig. 3 indicates the increment threshold for \( AR \) presented alone on the adapting field \( R \). As expected, \( AG \) essentially is constant when \( \Delta R \) is below threshold; this suggests the data might be accounted for by a model that specifies \( AG \) is constant when \( \Delta R \) is below threshold, and \( \Delta G/\Delta R \) is constant when \( \Delta R \) is visible. In this case the measurements should fall along two straight lines, one horizontal and the other at \( R \) (i.e. along two of the dashed lines in the lower right panel of Fig. 3). A least squares fit to the data for this model is less good than equation (1) for every observer (squared deviations about 2-4 times larger). This model has no fewer parameters than equation (1), and thus it may be rejected.

Since equation (1) accurately describes these measurements, each set of points may be summarized by values of the parameters \( f(R) \) and \( g(R) \). Each parameter has a straightforward interpretation. The value \( g(R) \) is the ratio of 540 to 660 nm light for a yellow appearing test beam of arbitrarily large luminance [i.e. when \( \Delta R > f(R) \)]. The parameter \( f(R) \) may be interpreted by considering the spatial relationship between the test and adapting fields. With steady fields, the mixture \( \Delta R + \Delta G \) is distinct from the adapting light only due to differences in size and shape. If instead of a 2.7 disk the adapting field were a 0.8 -1.3 annulus superimposed on the test, then \( R \) would cease to function as an adapting light and instead only would add physically with \( \Delta R \) and \( \Delta G \).

In that case, the ratio \( \Delta G / \Delta R + R \) would be constant (for moderate light levels: Larimer et al., 1974). Because the adapting field is spatially distinct, its additive contribution to the color percept of the test is changed from \( R \) to \( f(R) \). Thus \( f(R) \) reflects the (altered) additive contribution from the adapting light.

Figure 4 displays for the five observers values of log \( f(R) \) and log \( g(R) \) for each adapting level.† Measures of within-observer between-day variability, based upon repeated observations over four or more days, are shown for some conditions; error bars represent 1 standard deviation for a single day’s parameter estimate (they are not standard deviations of the mean). The error bars suggest the degree of variability in parameter values estimated from a single experimental run. The largest standard deviation is 0.14 log unit (log \( f(R) \) at \( R = 1.05 \) log td for observer W.S.). For observers

* Observer D.H., whose data were collected as part of a different study, had adapting fields 0.05 log unit higher than indicated (i.e. \( R = 1.05, R = 1.7 \), etc.); he was not tested with an adapting field near 2.0 log td.

†Values of the parameters were estimated using a computer algorithm that minimized the sum of squared deviations between observed and [from equation (1)] predicted logarithmic retinal illuminances. No point is shown for observer J.D. at \( R = 3.0 \) log td because his data fell on a virtually horizontal line; thus only the sum [log \( f(R) \) + log \( g(R) \)] could be estimated.

*See footnote * on this page.
D.N., J.D. and J.H. (whose data are reported below for Experiments 2 and 3) no standard deviation is larger than 0.10 log unit. Clearly, between-day variability for these practiced observers is very low.

The scatter of points in Fig. 4 indicates the magnitude of individual differences. The differences are fairly large (much larger than the day-to-day variability seen for a single subject) and show some consistency across conditions. For example, observer J.D. consistently had the lowest asymptotic ratio of 540 to 660 nm light [as expressed by \( g(R) \)]; observers D.N. and W.S. tended to have the highest ratios for adapting fields up to 100 td.

Each estimated value of \( f(R) \) is well below the retinal illuminance of the adapting field; this confirms the previously discussed reduction in the effect of quanta from the adapting light that fall in the test area. According to theory, the difference \( R - f(R) \) reflects the decremental counterbalancing signal.

Briefer extinguished adapting fields—1 sec test trials (Experiment 2)

The counterbalancing signal has been inferred from the reduced effect of the adapting light. If no quanta from the adapting light are present during the observer's color appearance judgment, then the effect of the decremental signal should be directly observable. This was tested in the second experiment. Initially the observer viewed the steady adapting field \( (R) \) for 7 min. The adapting field then was extinguished for 1 sec once every 6 sec. As before, the annulus was presented continuously. The observer was instructed to judge the annular test area only during the 1 sec interval when the adapting light was off; thus the off-

![Figure 5](image.png)

Fig. 5. Measurements for three observers made while the adapting field was momentarily extinguished for 1 sec (axes as in Fig. 3, \( R \) in log td). The \( R \) OFF data (replotted from Fig. 3) are to scale: most other sets of points have been shifted horizontally rightward for clarity. The magnitudes of the shifts for \( R = 1.0, 1.65, 2.0, 2.3 \) and 3.0, respectively, are: D.N. (0.5, 0.3, 0.5, 0.5, 1.0); J.D. (0.0, 0.0, 0.0, 0.3, 0.3); J.H. (0.0, 0.0, 0.3, 0.5, 0.7). Lower right: the template curve given by \( \Delta G = [\Delta R + f(R)]g(R) \), \( f(R) < 0 \). This curve, shifted only parallel to the logarithmic coordinate axes, has been fit to each set of open symbols. Lower right, inset: temporal representation of the stimuli for Experiment 2 (1 sec interval).
set of the adapting field signaled the beginning of a test trial. The state of adaptation was maintained by the presence of the adapting light during the 5 sec period that separated the test trials (a temporal representation of the stimuli is shown in Fig. 5 [lower right, inset]). In this experiment, the observer adjusted the radiance of AR and the experimenter controlled ΔG.

Data for three observers are shown in Fig. 5. As in Fig. 3, the level of ΔR is on the horizontal axis and the level of ΔG on the vertical axis. Each point (except for the R OFF data) is the average of five measurements made in a single session. The R OFF data, replotted from Fig. 3, are to scale; most other sets of points have been shifted horizontally an arbitrary amount.

Again it is clear that the data do not fall along 45 lines. Though the deviations from 45 lines are less obvious than in Fig. 3, there is a systematic trend for the 540 to 660 nm test beam intensity ratio to increase with test luminance. This is quite different from the results found with steady adapting fields, where the 540 to 660 nm intensity ratio decreased with increasing test field luminance. Comparing fits to the data by a 45 line and equation (1), the superior fit of equation (1) is indicated by a likelihood ratio test of hierarchical models; this test rejects the slope 1, straight line model for each observer (χ², values ranging from 26.7 to 49.8, P < 0.001). While the relatively small number of points (35) fitted for each subject requires that these statistical results be interpreted with caution, an unequivocal conclusion is reached from a nonparametric test. If the measurements were simply fluctuations about a 45 line, the fits of equation (1) to the data should yield 15 (3 subjects x 5 adapting levels) values of f(R) that randomly fall above and below zero. The resulting least squares fits yield 14 negative f(R) values; the probability of this occurring by chance is less than 0.001.

The template curve of Fig. 3 obviously cannot fit these data since the template has increasing slope and the data of Fig. 5 show decreasing slope. The Fig. 3 template assumes that f(R) is positive: a negative f(R) value in equation (1) specifies the template curve shown in Fig. 5 (lower right). If there exists a negative value of f(R) such that the ratio ΔG/[ΔR + f(R)] is constant for any given adapting condition, then the template in Fig. 5 must fit the data. The magnitudes of the parameters f(R) and g(R) only slide this curve parallel to the logarithmic coordinate axes. This template has been fit to each set of points; it is clear that equation (1) with negative f(R) values accurately describes the observations. According to theory, the negative f(R) values reflect the counterbalancing (opposite signed) decremental signal; since the adapting light is not present during the test trials, the net additive effect is negative (a more complete argument is given in the discussion section).

At the bottom of the plot for observer J.D. are four measurements (one for each of the four highest adapting levels) made in the absence of light ΔG. These observations (with ΔG at –∞ in logarithmic units) are settings for equilibrium yellow with only 660 nm light presented to the observer. Not only was the observer able to make these settings—which is somewhat surprising since these are trials with only "red" light—but the observer’s radiance settings are quantitatively consistent with the Fig. 5 template [and thus are according to equation (1)]. One might speculate that an observer may perceive a yellow field with a dim 660 nm test annulus that stimulates a patch of retina previously adapted to long-wavelength light. However, such low luminance test fields are fairly dim and often muddy. To preclude the possibility that these observations reflect only a dim achromatic percept (as opposed to an equilibrium yellow), observer J.D. was asked whether the test annulus could be made to appear reddish and then greenish by further adjustments of the joystick (which controlled the radiance of ΔR). He reported that he was able to change the perceived color of the annulus from green to yellow to orange. This guarantees that J.D.’s yellow settings are an equilibrium between reddish-yellow and greenish-yellow. (No other observer could meet this strict criterion and therefore only J.D.’s data are reported; most observers found that the annulus appeared reddish until close to threshold. The statistical analyses reported above that demonstrate these data cannot be fit by 45 lines do not include the ΔG OFF points for J.D., since he was the only observer who could satisfactorily perform the task. Obviously including these measurements would result in even poorer 45 line fits.)

Briefly extinguished adapting fields—variable length test trials (Experiment 3)

The 1 sec test trials of the previous experiment have the advantage of being relatively brief but still sufficiently long so that an observer can perform the task with little difficulty. However the adaptation effects may partially decay during the 1 sec period. Test interval length was varied to explore two issues. First, does equation (1) describe the observations for every test interval? If decay depends only on the adapting condition and the only effects of adaptation are sensitivity changes and an incremental (or decremental) effect, then there should exist for any test interval duration a value of f(R) such that ΔG/[ΔR + f(R)] is constant. Second, if equation (1) accurately describes the data, how do the adaptation effects decay over time?

Pilot experiments revealed that 150 msec is (roughly) the shortest possible test interval for which a well practiced observer reliably can make color appearance judgments. Test intervals 500 msec and shorter tended to produce more variable measurements; observers uniformly reported these shorter test trials to be more difficult. Data for 150, 200, 500 and 1000 msec test intervals are shown in Fig. 6 (open
symbols). The experimental paradigm for these observations was identical to that of Experiment 2 except for the length of the brief period when the adapting field was extinguished (the interval between test trials was 5 sec. as before). Each point in Fig. 6 is the average of five settings from a single session (the 1000 msec data are replotted from Fig. 5). Measurements were made at $R = 1.65$ and $R = 2.0$ log trolands for each of the 3 observers. These data are plotted to scale (no arbitrary shifts) for observers J.D. and J.H.; for clarity the 500 msec and shorter test interval data for D.N. have been shifted horizontally. Each set of points has been fit by an equation (1) template (either the Fig. 3 or the Fig. 5 template).

The filled symbols in Fig. 6 are observations for the 1 sec test interval paradigm but with the observer instructed to judge the color of the test field only during the 5 sec period when the adapting field was...

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**Fig. 6.** Data for three observers at each of two adapting levels $R$ ($R$ in log td). Axes as in Fig. 3. Open symbols: measurements made while the adapting field was momentarily extinguished. Each set of points is for a given test interval length (150, 200, 500 or 1000 msec; the 1000 msec data are replotted from Fig. 5). For observers J.D. and J.H., all symbols are plotted to scale (no shifts). For clarity, observer D.N.'s data at test intervals 500, 200 and 150 msec have been shifted horizontally rightward. The respective shifts are: $R = 1.65$ (0.3, 0.6, 0.9), $R = 2.0$ (0.3, 0.6, 0.9). Filled symbols: measurements using the paradigm with the adapting field briefly extinguished for 1000 msec, but made during the 5 sec interval when the adapting field was present (all filled symbols plotted to scale). Solid curves: template curve from Fig. 3 or 5 (see text).
present. Aside from instructions to the observer, the paradigm was identical to Experiment 2 (except that here the observer controlled \( \Delta G \) and the experimenter \( \Delta R \)). Differences between these measurements and the 1000-msec-test-trial open symbols of Fig. 6 are due only to the presence of adapting light quanta during the color appearance judgment (and of course, to between-session variability).

Each set of points can be fit fairly well by a template curve. All of the filled symbols (representing measurements with the adapting light present) are best described by the Fig. 3 template with \( f(R) > 0 \). Most of the measurements made while the adapting field briefly was extinguished (open symbols) require the Fig. 5 template \( f(R) < 0 \), though this is not always the case\(^*\); observer J.H. requires positive \( f(R) \) values for the two shortest test intervals at \( R = 2.0 \) log td. The systematic nature of J.H.'s measurements (discussed below) indicates these positive \( f(R) \) values are not the result of random variation. Instead, there appear to be between-subject differences in the effect of test trial duration. Considering the difficulty of the experimental task, the overall correspondence between the template curves and the data is good.

**DISCUSSION**

The results from each of the above experiments can be described accurately by equation (1). This follows directly from the templates' accurate fits to the data in every condition of each experiment.

The empirical fact that the measurements follow the templates is strong support for equation (1), since each template is completely invariant in shape (the parameters \( f(R) \) and \( g(R) \) only shift the templates parallel to the logarithmic coordinate axes). A more detailed evaluation is possible by considering the plausibility of the parameter values.

*Steady adapting fields*

With steady backgrounds (Experiment 1), the pattern of parameter values was identical for each of the five observers. The contribution from the adapting field, \( f(R) \), always was positive and increased monotonically with adapting level (that is, more quanta from the adapting light resulted in a larger net contribution from the background). In addition, increasing the level of the 660 nm adapting field reduced sensitivity to 660 nm light (\( \Delta R \)) more than it reduced sensitivity to 540 nm light (\( \Delta G \)). This is indicated in Fig. 4 by the \( g(R) \) values, which decreased monotonically as \( R \) was increased. To be sure, both of these results are expected; the fact that the estimated parameters for every observer are consistent with expectation lends support to equation (1).

Confirming previous results (Shevell, 1978), \( f(R) \) is not near zero for any observer except at the dimmest background (10 td). Since measurement error for \( f(R) \) is quite small (wherever estimated—see error bars, Fig. 4) and agreement among observers is excellent, Walraven's (1976) conjecture that equation (1) may be reduced to the more simple form

\[
\frac{\Delta G}{\Delta R} = \text{constant}
\]

is rejected unequivocally.† Though related evidence has been presented elsewhere (Shevell, 1980), it is important to refute Walraven's (1979) claim that differences between observers in an earlier study (Shevell, 1978) indicated unreliable measurement. Experiment 1 of this paper demonstrated fairly large (and reliable) observer differences. Since nearly all of Walraven's data are measurements on his own eye, his data might be accounted for by (extreme) observer variability.

Values of the parameter \( f(R) \) always were far smaller than \( R \). This can be seen clearly in Fig. 7, where the \( f(R) \) values of Fig. 4 are plotted against their respective adapting levels (the line specified by \( f(R) = R \) has been drawn for reference). The \( f(R) \) values are roughly described by the equation \( f(R) = kR \) (\( k \) a constant, equal to 0.186 for the 45°

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\*As mentioned above, the values of the parameters [including the sign of \( f(R) \)] were determined by least squares. The sign of parameter \( f(R) \) specified the choice of template curve (from Fig. 3 or Fig. 5). A likelihood ratio test of hierarchical models suggests these data cannot be fit by 45° lines \((\hat{g}_0)\) values of 26.2 to 52.0, \( P < 0.001 \), though the small number of points fit \((42)\) dictates cautious interpretation. A nonparametric procedure demonstrates for observers J.D. (excluding his AG OFF data) and J.N. that the measurements are not random deviations about a 45° line: all six \( f(R) \) values (test intervals 500, 200 and 150 msec at each of two adapting levels) are less than zero \((P < 0.02)\).

†Walraven (1979) states that the viewing condition (steady fixation vs “free scanning”) is critical to whether his simpler form or equation (1) describes the steady background data. This is incorrect (Shevell, 1980).

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\*See footnote \* on p. 283.
0.186 was determined by a least squares fit to points at \( R = 1.65, 2.0, \) and \( 2.3 \) log td. This line is extrapolated (dashed portions) to \( R = 1.0 \) and \( 3.0 \) log td. The equation \( f(R) = kR \), another special case of equation (1), only coarsely describes the results. In any case, the determined value of \( k \) is certain to depend upon the spatial and temporal features of the test and adapting fields. As a crude approximation, however, the results of Experiment 1 indicate that the counter-balancing signal reduces the additive contribution from a steady adapting field (of fixed wavelength) in rough proportion to the field's retinal illuminance.

**Briefly extinguished adapting fields**

For color perception judgments made with the adapting field physically absent during the brief test interval, all \( f(R) \) values were negative with the exception of three conditions for observer J.H. With 1 sec test intervals, the negative \( f(R) \) values tended to increase in magnitude with adapting field radiance for observers D.N. and J.D. (see Fig. 8); for observer J.H., the magnitude of \( f(R) \) clearly is not monotonically related to the level of the adapting light. There is no suggestion for any observer that the log \( f(R) \) values in Fig. 8 fall along a 45 line: thus for 1 sec test trials the equation \( f(R) = -kR \) has no empirical support. Also shown in Fig. 8 is relative 660 to 540 nm sensitivity. \( g(R) \); for every observer, it decreased monotonically as \( R \) was increased from 1.0 to 3.0 log td. The log \( g(R) \) values with 1 sec test trials were different from the values found with steady backgrounds. Arrows in Fig. 8 point to each observer's analogous log \( g(R) \) value from Experiment 1 (steady adapting fields).

The reduced effect of the adapting field with steady backgrounds (i.e. \( f(R) < R \) - see Fig. 7) and the negative \( f(R) \) values found with briefly extinguished adapting lights both can be accounted for by a counter-balancing signal (resulting from adaptation) that partially negates the effect of the adapting light quantas. This signal will be denoted \( s(R) \); and is assumed to depend on adapting intensity \( R \) as well as the spatial and temporal features of the test and adapting fields.

*Estimation of \( k \) was based only upon measurements with \( R = 1.65, 2.0, \) or \( 2.3 \) log td since only for these adapting levels were finite log \( f(R) \) values found for every observer (at \( R = 1.0, \) log \( f(R) \) was negative infinity for observer J.H.; at \( R = 3.0, f(R) \) could not be estimated for J.D. [see footnote * on p. 283]). At \( R = 1.0 \) and \( 3.0 \) the value of log \( f(R) \) can depend upon very small deviations from a (slope 1 or slope 0, respectively) straight line. Thus small measurement errors for the different annulus (at \( R = 1.0 \) or the brightest annulus (at \( R = 3.0 \)) can have a large effect on the estimated value of log \( f(R) \).

In most cases, log \( g(R) \) values with no arrows in Fig. 8 indicate the steady adapting field value was within the plotted point. Two exceptions are the point for observer J.D. at \( R = 3.0 \) log td for which no log \( g(R) \) value for a steady background could be determined [see footnote * on p. 283] and the R OFF points (for which temporal features of the adapting field are meaningless).

**Fig. 8. Values for three observers of log \( f(R) \) [open symbols] and log \( g(R) \) [filled symbols] determined from the data in Fig. 5 (1 sec briefly extinguished adapting field). Arrows point to each observer's analogous log \( g(R) \) value for his steady background (Experiment 1) data (see text).**

Thus the general form of (1) is

\[
\Delta G [\Delta R + R - s(R)] = \vartheta(R). \tag{2}
\]

It already has been shown that the steady background data are described by (2); the parameter \( f(R) \) simply has been redefined as \( R - s(R) \). Figure 7 shows that approx. \( f(R) = 0.186 \); equivalently, \( s(R) = 0.814 \).

Direct qualitative evidence for the presence of \( s(R) \) is observer J.D.'s observations with extinguished adapting lights and test light \( \Delta G \) off (bottom points, Fig. 5). Since he was able to adjust the 660 nm test light (\( \Delta R \)) so that it appeared equilibrium yellow when viewed on an adapted patch of retina, there must exist an adapting signal that cancels the redness from \( \Delta R \) (sensitivity changes cannot explain these data, since varying the radiance of \( \Delta R \) changed the percept from greenish to yellow to reddish as described earlier).

With the state of adaptation well established, briefly removing the adapting light specifies equation (2) reduces to

\[
\Delta G [\Delta R - s(R)] = g(R).
\]

Since \( R = 0 \). This equation is a form of (1) where \( f(R) = -s(R) \); thus negative \( f(R) \) values are expected with briefly extinguished adapting lights. Since neural signals do not follow the crisp waveform of the stimuli, any signal resulting from the adapting field
quanta may decay gradually during the test interval. Specifically, the adapting effects \( s(R) \) and \( g(R) \) and the neural signal due to quantum absorptions each will decay with unknown (and in all likelihood, different) time-courses. Thus it cannot be expected that the negative \( f(R) \) values found with extinguished adapting lights will equal the analogous \( s(R) \) values found with steady backgrounds. If the various neural signals decay at different (and intensity-dependent) rates, this can account for the negative \( f(R) \) values' large deviations from the relationship \( f(R) = -kR \) (Fig. 8).

More direct evidence concerning decay is available from the observations for various test trial lengths. Values of \( f(R) \) and \( g(R) \) from Experiment 3 are shown in Fig. 9 (note \( f(R) \) is plotted on a linear scale). There are very clear differences between observers, but each subject has a consistent pattern of results. For observer J.D., the effects of the 660 nm adapting light decay rapidly. The \( f(R) \) values, all negative for measurements made with \( R \) briefly off, declined in magnitude as test interval length was increased. For J.D., \( g(R) \) also decayed toward its dark adapted value.
as test interval length was increased. Turning to observer D.N., there is at best a weak tendency for \( f(R) \) to decrease in absolute value with longer test intervals. Sensitivity \( g(R) \) is nearly constant, and there is no indication that \( g(R) \) is decaying toward its dark adapted value. Despite these differences, for both of these observers the absolute value of \( f(R) \) at any given interval length always was larger with \( R = 2.0 \) than with \( R = 1.65 \) log td. This strongly suggests their negative \( f(R) \) values in Fig. 9 are revealing signal \( s(R) \), since a greater adapting field radiance always displaced \( f(R) \) farther (negatively) from its dark adapted value.

Observer J.H. has quite a different pattern. At \( R = 1.65 \) log td, the negative \( f(R) \) values increased in absolute value as test trial length was increased. At the higher adapting level (2.0 log td), the \( f(R) \) values were positive at short intervals. It appears that the quantum absorption signal (from the 660 nm adapting light) decays more slowly for J.H. This declining signal is the primary factor affecting her measurements, since for every test interval the higher adapting light (2.0 log td) always resulted in a less negative \( f(R) \) value than the dimmer background (1.65 log td). The antagonism between the decreasing quantum catch neutral signal and decaying signal \( s(R) \) also provides an account for J.H.'s nonmonotonic \( f(R) \) values for 1-sec test trials (Fig. 8), including the positive \( f(R) \) value at \( R = 3.0 \) log td where the quantum catch signal seems not to have decayed sufficiently for signal \( s(R) \) to be revealed.

The effect of adaptation on sensitivity, as expressed by \( g(R) \), is consistent with the signal decay interpretation. According to equation (2), instantaneous (decaying) levels of the quantum catch signal and the adapting effect \( s(R) \) antagonistically interact with each other, but they should not affect sensitivity (regardless of their time courses). Thus increasing the adapting level at any test interval might result in more negative observers D.N. and J.D.) or more positive (observer J.H.) \( f(R) \) values, but sensitivity \( g(R) \) always should be lower for a higher adapting level (given that other experimental conditions, including test interval, are the same). This expectation is observed for all three subjects: at any given test interval the sensitivity \( g(R) \) always was smaller (less relative 660 nm sensitivity) for the brighter adapting field (open symbols, Fig. 9). Thus there is no evidence that the differences between observers represent general differences in the processes of adaptation. The empirical observations can be accounted for by individual variation in the time courses of the adapting signal \( s(R) \) and the neural signal from the adapting quanta. The steady background measurements further support this view, since these data were similar for every observer.

At the right of Fig. 9 (symbols connected with dashed lines) are parameter values for measurements with the adapting light on. The leftmost symbol of each connected pair is from the 1-sec-test-interval paradigm but with the observer instructed to make his setting while the adapting light was present. For observers D.N. and J.H., who showed little or no variation in sensitivity \( g(R) \) with length of test trial, the absence or presence of the briefly extinguished adapting light had no systematic effect on sensitivity. On the other hand, \( f(R) \) was greatly affected, as would be expected, the presence of the adapting quanta changed \( f(R) \) from a negative value to a positive one. This is consistent with equation (2), since with the adapting light off \( f(R) = -s(R) \) while with it on \( f(R) = R - s(R) \). For observer J.D., the expected result for \( f(R) \) was observed: his \( g(R) \) values were slightly higher (greater relative 660 nm sensitivity) for measurements made while the adapting light was on.

Comparing sensitivity for the two conditions with the adapting light present during the measurements, for each observer the relative 660 nm sensitivity was lower with steady backgrounds (see \( g(R) \) values connected by dashed lines in Fig. 9). Observers D.N. and J.D. also showed smaller \( f(R) \) values (i.e. larger \( s(R) \) values with steady backgrounds), thus consistently revealing larger effects of adaptation with steady adapting fields. For J.H., the positive \( f(R) \) value increased with the steady background. This is opposite to the finding for the other observers, but consistent for this subject (i.e. higher [time-averaged] adapting level resulting in a more positive \( f(R) \) value, as discussed above). This again may reflect J.H.'s more sluggish quantum catch signal.

Differences among observers, particularly when the adapting field is extinguished and effects may begin to decay, place a constraint on the specificity of any model of chromatic adaptation. Theoretical formulations must be sufficiently flexible to allow a moderate amount of observer variability. On the other hand, subject differences can provide important tests for proposed models. Can the model account for each subject's data? Observer variability implicitly is included in equations (1) and (2). Since each set of measurements is well described by an appropriate template curve (and for each subject the parameter estimates across conditions are reasonably consistent), subject differences lend added support to the model.

**The two-process theories**

The discussion to this point has been in terms of a descriptive relationship (equation (1) or (2)) and its parameters. The constraints for a theoretical framework are obvious: the model must imply equation (2).

A number of "two-process" theories all implicitly specify (2). These models are extensions or refinements of the Hurvich and Jameson (1958) two-process proposal, which specified that both sensitivity changes and an incremental effect result from chromatic adaptation. The details of some of these models are described elsewhere (Shevell, 1978); each model assumes that

1. the red-green chromatic response is a weighted
Equilibrium yellow and long-wavelength adaptation

sum of the three receptor-types' spectral sensitivities.

(2) chromatic adaptation affects the sensitivities of the three receptor-types [expressed by altered weights in the linear combination of assumption (1)], and

(3) a second effect of chromatic adaptation is some kind of incremental (or decremental) modification to the "red-green signal".

The models differ in the assumption concerning what "red-green signal" is increased (or decremented) by adaptation. For example, the Jameson and Hurvich (1977) model has the incremental effect entering after the linear chromatic response has undergone a nonlinear transformation, while another model (Shevell, 1978) proposes the increment is applied to the linear red-green chromatic response. Both of these models, as well as some more complicated veiling formulations, imply equation (2). The essential feature of each model is that the red-green chromatic response is a linear combination of the receptor-types' spectral sensitivities.

The various models specify different interpretations for the parameter $\alpha(R)$ in equation (2), but each model implies that

$$g(R) = \frac{a_1(R)x_600 - a_2(R)b_600 + a_3(R)}{-[a_1(R)x_{540} - a_2(R)b_{540} + a_3(R)]}$$

where $x_i$, $b_i$, and $s_i$ are the receptor-types' spectral sensitivities and weights $a_i(R)$ are functions of the adapting field $R$. Thus values of $g(R)$ may be interpreted as the sensitivity ratio for the presented wavelengths (540 nm and 660 nm) for the r-g chromatic response (by convention, greenness is assigned negative values so the bracketed part of the denominator is negative, resulting in a positive $g(R)$ value).

CONCLUSIONS

The two-process theories can account for the data from all three experiments. Variability among observers is fairly large; however, the two-process model can account quantitatively for each observer's data. Further, the least squares parameter estimates are sensible; where differences between observers are present, the parameter estimates provide a consistent set of values for each individual subject. The model also is consistent with results from many other experiments, including paradigms where the test is briefly flashed (Shevell, 1978), the adapting field is greenish (Larimer, 1981), the observer freely scans (instead of steadily fixates) the test annulus (Shevell, 1980), or the subject's criterion is neither reddish nor greenish blue (rather than yellow; Larimer, 1981).

The notation of equation (2) emphasizes the actual visual process. The adapting light quanta absorbed in the test area are not qualitatively different from those delivered by the superimposed test, since all experiments here reported caused negligible photopigment bleaching, the adapting field's effect must be reduced at a stage that follows quantum absorption. With steady adapting fields (and for the particular spatial features of the stimuli used here), the signal represented by $s(R)$ is quite large ($s(R)$ estimated to exceed 80% of the adapting light's retinal illumination). Measurements made with the adapting field momentarily extinguished demonstrate that the counterbalancing signal can decay rapidly and that the decay rate may vary widely across observers. Following Augenstien and Pugh (1977), the quantity $s(R)$ may be called the restoring effect, since the general nature of the signal reflected by $s(R)$ is the visual process they describe: "when the 'potential' at the opponent site is displaced from its equilibrium or neutral position, a restoring force slowly builds up which tends to drive it back toward equilibrium (p. 278)."

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