**APPEARANCE OF STEADILY VIEWED LIGHTS**

**RAM L. P. VIMAL,** JOEL POKORNY† and VIVIANNE C. SMITH

The Eye Research Laboratories, The University of Chicago, 939 East 57th Street, Chicago, IL 60637, U.S.A.

(Received 2 June 1986; in revised form 23 January 1987)

Abstract—An interocular matching technique was used to investigate the variation of chromaticity and brightness following steady viewing of a chromatic test light (identical adapting and testing color). Adaptation times were of sufficient duration to ensure stable matches. Following chromatic adaptation we found changes in hue, saturation and brightness. The spectral colors appeared desaturated. The hue shift for the spectral region 546 to 570 nm was towards green and for 586 to 670 nm was towards red. The brightness decrease, independent of chromaticity, was 0.8 log unit at 150 td and 0.3 log unit at 8 td.

Data were analyzed within a two-process framework of brightness. Bezold-Brücke effect measurements showed chromaticity shifts in the same direction as for dimming caused by continuous adaptation. Changes in saturation were also observed but were usually in the opposite direction from those found for adaptation.

**INTRODUCTION**

It is well known that the appearance of visual stimuli changes with continued viewing. The resulting percept appears dimmer than for a glimpsed stimulus (Exner, 1868; Craik, 1940). Hues may be altered and colors appear less saturated (Exner, 1868; Wright, 1934, 1937; Fedorova, 1941; Yustova, 1958; McCree, 1960). The change in color appearance can be evaluated by comparison with that of the fellow (unadapted) eye. This phenomenon is quite striking in a colorimeter or anomaloscope where it is easy to switch back and forth between adapted and unadapted eyes.

The phenomenon is a form of chromatic adaptation—the change in appearance of an adapting field itself. In this work we describe changes in brightness and chromaticity as a function of continuous viewing. One interest involves the mechanism of dimming. Current analysis suggests that the psychophysically defined luminance and chromaticity channels both contribute to brightness (e.g. Guth et al., 1969; Bauer and Röhler, 1977; Burns et al., 1982; Yaguchi and Ikeda, 1983a, 1983b). The specific question we address is whether changes in brightness produced by steady viewing include both luminance and chromatic components. The paradigm we employ allows direct evaluation of the changes in the luminance and chromatic contributions to brightness produced by steady viewing.

We compared our data to measurements of the Bezold-Brücke effect (change in hue with change in luminance) for the same observers. Since the Bezold-Brücke hue shift can be produced by induced dimming of a field (van der Wildt and Bouman, 1968; Coren and Keith, 1970) as well as reduced stimulus radiance (Purdy, 1931; Wyszecki and Stiles, 1982), it is of interest to evaluate whether the chromaticity shifts are in the same direction for dimming produced by adaptation as for the other methods of producing dimming. Our instrumentation allowed matches in both hue and saturation and the current data are, to our knowledge the first Bezold-Brücke measurements to evaluate saturation as well as hue.

Relevant literature studies used congruent monocular fields (Fedorova, 1941; Yustova, 1958; McCree, 1960) or monocular adapting fields which extended over the extent of binocu-
larly presented conjugate test and comparison fields (Wright, 1934, 1937). We designed a stimulus situation which minimized the potential for induction or after-effects. We used an interocular color-matching task (Wright, 1934; Bartleson, 1978; Wyszecki and Stiles, 1982) with a $1^\circ$ separation between two hemifields. Following adaptation to a test color presented to one eye, the fellow (unadapted) eye made color matches to the resultant adapted chromaticity. Previous work delineated the time-course of adaptation (Wright, 1934), and we confirmed that our measurements were made under "steady-state" conditions.

**METHODS**

**Apparatus**

The experiments were performed with a two-channel, binocular-view, Burnham-type colorimeter (Fig. 1). Light from a 250 W tungsten halogen lamp was sampled in two directions to allow two parallel channels. In each channel, the light was collimated and passed through filter slides. For the purpose of these experiments, the left channel was used as a color mixture field and the right channel as a test field. The mixture channel contained a chromaticity filter slide (CFS) adjustable in horizontal and vertical directions. Three color filters were used for primaries. The test channel contained a horizontal slide (LS) to control luminance and a filter box to select test chromaticity. The light was then integrated and diffused uniformly, using integrating bars.

Following the integrating bars were field stops and shutters to control the spatial and temporal characteristics of the matching fields. For adaptation, the test field was a semicircle of $1.5^\circ$ radius whose vertical edge was $15^\circ$ from the center of fixation. During adaptation only the right channel test field was presented [Fig. 2(a)]. For color matching, the field stops were semicircles of $1^\circ$ radius, whose vertical edges were separated by $1^\circ$ [Fig. 2(b)]. The choice of adapting or color matching fields and stimulus timing was computer-controlled. A $1.5^\circ$ right semicircular field was used for adaptation and a $1^\circ$ field for color matching to minimize the possibility that eye movements might produce uneven adaptation at the test borders.
Steadily viewed lights

A separate source (not shown in Fig. 1) was used to provide a binocular fixation target. The fixation target was an 18' circle with clockhands for fusion. It appeared between the left and right fields. A pair of mirrors and prisms allowed alignment of the fields for the two eyes. Binocular fusion was achieved by moving the prisms toward or away from the observer. Light shielding was used to minimize stray light.

Stimuli

The color matching primaries mounted on the chromaticity filter slide (CFS) were two interference filters (670 nm and 546 nm) and a broadband filter (Kodak 47 B, 453 nm). We performed heterochromatic flicker photometry to each primary, and added neutral density to the filters to achieve equiluminance for all slide positions. The filter slide CFS could be adjusted horizontally to vary the ratio of "redness" to "greenness" and vertically to vary the "blueness".

We used three-cavity interference filters and broadband filters in the test field. Interference filters were: 670, 630, 610, 600, 586, 580, 570, 558 and 546 nm. Broadband filters were 453 nm (Kodak 47 B) and five (I to V) nonspectral stimuli, shown in Table 1. Stimulus IV was close to equal energy white and stimulus V was close to C.I.E. standard illuminant A.

Calibration

The relative light output through the chromaticity filter slide (CFS) and the luminance slide (LS) were calibrated using an EG & G model 550 radiometer/photometer with its BCD output fed to a microcomputer. The output of the CFS for horizontal variation of the slide was checked at a number of fixed vertical positions. Calibrations were stored on disc.

The spectral distributions of the color and neutral density filters were measured with a laboratory-built spectroradiometer, referenced to a standard lamp of known color temperature (Hoffman Engineering). The x, y chromaticity coordinates of the test stimuli were calculated for the Judd (1951) revised colorimetric system using standard procedures given by Pokorny, Smith, Verriest and Pinckers (1979); coordinates of the broad band stimuli 453 nm and I–V are shown in Table 1. The x, y coordinates were then transformed to r, g coordinates using WDW normalization to wavelength 580 nm and to a mixture of 490 and 670 nm.

The luminance of the mixture primaries was measured by a brightness match to the chromatically similar white light comparison field of an SE1 photometer and found to be 17 cd/m². The calibration of the SE1 photometer was referenced to the standard lamp. Natural pupils were used; the retinal illuminance was estimated (LeGrand, 1968, p. 106) to be about 150 effective trolands. We collected data at effective retinal illuminances of 150 and 8 td.

Observers

The observers (R.V.: male, 36; W.S.: male, 31; and R.P.: female, 30) were color normal as assessed with the Rayleigh and Moreland equations and showed normal color discrimination on the FM-100 Hue test. Observers R.V. and R.P. had normal stereopsis as assessed with the Titmus and TNO tests; W.S. was slightly esotropic, but was able to achieve fusion without glasses. Observers R.P. and R.V. participated in all experiments; confirmatory data were collected on W.S. Observers used a chin and forehead rest. A few practice sessions were allowed.

EXPERIMENT 1: CHROMATICITY AND BRIGHTNESS FOLLOWING CONTINUOUS VIEW

Procedure

Observers were dark adapted for 5–7 min. We used an interocular matching technique and the method of adjustment. The observer made a set of five simultaneous matches to the test field by adjusting the mixture primaries and the test luminance. The observer looked away between trials; each match took about 2 min with a 2 min intertrial interval.

Following the simultaneous matches a series of five adaptation trials was obtained. Observers again dark-adapted for 5–7 min, a time sufficient to eliminate any previous chromatic adaptation (Wright, 1934). The right eye viewed the 1.5° right semicircular test color for 10
seconds and the left eye viewed only the fixation stimulus. Then, for 1 sec both eyes viewed only the fixation stimuli. After this, for 1 sec the right eye viewed the 1° right semicircular test color and the left eye viewed the mixture primaries [Fig. 2(e)]. The observer adjusted the chromaticity of the left semicircle using the chromaticity filter slide CFS and the brightness using neutral density filters on the left side. The sequence was repeated until a perfect match was obtained. Each trial took about 10 min. By the end of this time period, adaptation had reached a steady state and color appearance was stable.

We confirmed this for a number of chromaticities by allowing 10 min of continuous viewing of the adaptation field prior to making a color match. The 15 test colors were presented in random order and only one test color was presented per day to an observer. Each session (five settings) lasted about 1 hr. The entire procedure was repeated; all data points represent an average of ten repetitions.

Unique yellow (UY) and unique white (UW) were measured for the left eye of each observer by adjusting the chromaticity filter slide (CFS). Data are the averages of five repetitions.

We also ran two additional control conditions: (1) we compared the simultaneous match made with continuous viewing, with matches made in one second intervals following 11 seconds of dark adaptation; (2) we used the 1° right semicircular field for both the adaptation and the testing period.

**Results and analysis**

The results of the simultaneous color matches for all 15 test colors are plotted in an r–g chromaticity diagram with WDW normalization (Fig. 3). A transformation of the Judd (1951) color matching functions to the primary system we used ("the Judd observer") is shown for comparison. All the simultaneous matches were close to the Judd observer indicating that our observers have representative color vision and that the apparatus, calibration and procedure were acceptable. Simultaneous matches were the same in steady-state as those made with the temporal sequencing used for adaptation.

After adapting to the test field, test colors appeared desaturated, dimmer and changed in hue. The three observers gave qualitatively similar data; chromaticity plots for two observers are shown in Fig. 4. On this figure, open circles are adapted matches; solid circles indicate simultaneous matches replotted from Fig. 3. The arrows from solid to open circle indicate the magnitude and the direction of the shift in the color match following adaptation. The intertrial and interday variations were smaller than the adaptation effect.

Color matches were qualitatively the same whether a 1 or 1.5° adaptation field was used. The smaller adaptation field required more precise continuous fixation to avoid uneven adaptation at the test borders. As a result the task appeared more difficult for the observer. Precise fixation sometimes resulted in fading (Troxler’s phenomenon). The requirement of precise fixation was somewhat relaxed with the larger adaptation field, and we therefore used the larger adapting field for the data reported here.

We found that brightness always decreased during the adaptation period and the amount of attenuation was independent of the wavelength and chromaticity of the test color (Fig. 5). The brightness attenuation for the achromatic stim-
Steadily viewed lights

Fig. 4. Changes in chromaticity following adaptation for two observers. Solid circles represent the simultaneous color matches from Fig 3. Open circles indicate the color matches after adaptation. The arrows from solid to open circle represent the shift in chromaticity following adaptation. UW and UY are unique white and unique yellow points respectively. Observers and light levels are identified on each panel.

Fig. 5. The brightness attenuation following adaptation for observers R.V. (circles), R.P. (triangles) and W.S. (squares), at 150 td (open symbols) and 8 td (solid symbols).
We wished to define the direction and magnitude of the hue shifts but could not do so with conventional metameric wavelength representation since some of the hues for long-wavelength stimuli shifted off the spectrum locus in the "purple" direction. To avoid the difficulty of complementary color notation we defined the hue-shift by a vector technique. We drew vectors from the observer's unique white point to the \( x, y \) coordinates of the color match and measured the angle from the simultaneous to the adapted color match. Clockwise rotation was defined as a positive and counter-clockwise as a negative wavelength shift. The hue shifts for all three observers are shown in Fig. 7. The data are noisy but a general trend is for hue shifts for long wavelength test colors to be toward longer wavelengths and those for mid-spectral wavelengths toward shorter wavelengths.

**EXPERIMENT 2. THE BEZOLD-BRÜCKE EFFECT**

The Bezold-Brücke effect is commonly measured by hue matches of a monochromatic stimulus of fixed wavelength and luminance and a comparison field of variable wavelength and constant luminance of a value considerably lower than the fixed field (Purdy, 1931; Wyszecki and Stiles, 1982). It also can be observed for single briefly flashed fields with no physical referent (Boynont and Gordon, 1963; Smith, Pokorny and Swartley, 1973). It is of note that the Bezold-Brücke effect is a function of brightness rather than luminance (van der Wildt and Bouman, 1968; Coren and Keith, 1970). Since we found brightness changes following adaptation, we evaluated whether the accompanying hue shifts were the same as Bezold-Brücke hue shifts. Saturation is also reported to change as a function of luminance and of induced dimming. Hunt (1953), employing a stimulus situation rather different from the present experiment, reported that interocular matches of 1° half-fields embedded in equipeluminant surrounds decreased in saturation with decreases in field illuminance. With induced dimming (inducing field higher in luminance than test field) Hunt reported that satur-

![Fig. 6](image-url)
Fig. 7. Hue shifts for observers R.V. (circles), R.P. (triangles) and W.S. (squares) measured as the rotation of the vector from unique white to the test color chromaticity at 150 td (upper panel) and 8 td (lower panel) following adaptation. A clockwise rotation is considered as a positive and a counterclockwise as a negative wavelength shift. The solid line shows the average of the three observers.

Saturation increased for retinal illuminances of the inducing field above 75 td and saturation decreased for retinal illuminances below this value. Haupt (1922) reported a similar finding (saturation was greatest for moderate photopic illumination levels) for saturation discrimination of monocularly presented bipartite fields with variation of the luminance of one half field. We know of no literature reports evaluating saturation under conditions not involving illuminated surrounds or induction. The purpose of Experiment 2 was to compare color matches made following adaptation with those made when the test color was reduced in luminance.

**Procedure**

As before, we used the interocular matching technique and method of adjustment. Measurements were made on two observers (R.V. and R.P.). Observers were dark adapted for 5–7 min. First the average simultaneous match at 150 td from the first experiment was shown to the observer who, if necessary, could make minor adjustments of the primaries to restore a perfect match. A 1.54 neutral density filter was then inserted into the right side filter box to decrease the effective retinal illuminance to 4 td. Thus the test (viewed by the right eye) was at
4 td, and the mixture field (viewed by the left eye) was 150 td. The observer adjusted the mixture primaries to obtain a match in hue and saturation. An average of 5 trials was used. Observers were dark adapted for 1–2 min between trials. Test colors were presented in random order. The entire procedure was repeated twice. The intervals between sessions were 3–48 hr.

Results and Analysis

The results for both observers are shown in Fig. 8. The solid circles indicate the simultaneous color matches at 150 td replotted from Fig. 3. The open circles represent the chromaticity matches to the 4 td test. The arrows from solid to open circles indicate the shift in chromaticity when the retinal illuminance of the test decreased from 150 to 4 td. In general, the shift in chromaticity was away from unique white.

The change in saturation was calculated as before and is shown in Fig. 9. For most test colors, the lower luminance stimulus appeared more saturated. Little change in saturation was found for 558, 570 and 580 nm.

The Bezold–Brücke hue shifts for the two observers are shown in Fig. 10 together with average data replotted from Fig. 7. Purdy's (1931) data calculated by the same graphical technique are also shown. The direction of the shifts are comparable for the three data sets. For long wavelengths (> 580 nm), the hue shift was toward longer and for mid-spectral wavelengths (between 546 and 580 nm) toward shorter wavelengths, similar to the classical results of Purdy (1931). The invariant yellow hue with luminance change was at 580 nm for R.V. and 574 nm for R.P.

DISCUSSION

We found the brightness reduction accompanying steady viewing adaptation to be independent of chromaticity (see also Fedorova, 1941). With our paradigm the brightness reduction was evaluated between the adapted and unadapted chromaticities. Such shifts in chromaticity (particularly for stimuli which appear highly saturated) would themselves be expected to cause brightness differences (Burns et al., 1982). We confirmed this for our experimental situation by having the three observers perform heterochromatic brightness matches for 453 and 670 nm to a 150 td chromatically neutral appearing stimulus (stimulus V for R.V. and R.P., stimulus IV for W.S.). A heterochromatic brightness match was first established under unadapted conditions. Following adaptation to the chromatic component, the observers reset the luminance of the neutral stimulus for a new heterochromatic match. For each of the three observers the attenuation was about 0.9 log unit for 453 nm, and 1.0 log unit for 670 nm, about 0.1–0.2 log unit more brightness attenuation than obtained for the metameric matching conditions. Our results are consistent with the hypothesis that two processes contribute to the

![Fig. 8](image-url)
Steadily viewed lights

Fig. 9. The change in the saturation correlate $S^*$ for observers R.V. (left panel) and R.P. (right panel) when the test color is 4 td. Solid circles represent $S^*$s for the simultaneous color matches replotted from Fig. 6. Open circles represent $S^*$s following luminance decrement of the test.

brightness percept (e.g. Guth et al., 1969; Bauer and Röhler, 1977; Burns et al., 1982; Yaguchi and Ikeda, 1983a, 1983b). Changes in "achromatic brightness" are characterized by a chromaticity-independent reduction in brightness with adaptation. Changes in "chromatic brightness" are exactly compensated by the change in brightness accompanying the chromaticity shift caused by adaptation. Within the precision of our measurements, the two processes appear to contribute independently to brightness.

Experiment 2 was performed to evaluate whether the dimming of the field following adaptation was responsible for the measured changes in hue and saturation. Our Bezold–Brücke measurements are consistent with literature reports of hue shifts (Purdy, 1931; Wyszecki and Stiles, 1982). The hue shifts accompanying adaptation are generally in the same direction as the Bezold–Brücke shifts. However, the decreased saturation with adaptation differs from our Bezold–Brücke measurements which indicate that the dimmer stimuli were seen as higher in saturation than the brighter stimuli. The adaptation data show the same general trend as Hunt's (1953) data, obtained for a rather different stimulus situation (comparison of fields embedded in equiluminant surrounds). If steady viewing produced a functional state equivalent to dimming by induction, then saturation would be expected to increase for the 150 td condition and decrease for the 8 td condition (Haupt, 1922; Hunt, 1953). It appears that the mechanism(s) involved in steady viewing adaptation differ from those mediating perception with changes in luminance or induction.

The hue-shift, desaturation and brightness attenuation following adaptation to a test light might be due to receptoral and/or neural adaptation. Some of our data clearly implicate a postreceptoral locus for adaptation. For spectral lights between 546 and 670 nm, short-wavelength cone stimulation is negligible (LeGrand, 1968; Smith and Pokorny, 1975). Receptor adaptation can only change the relative quanta1 catch in the long- and middle-wavelength cones and therefore only shift chromaticity along the spectrum locus (if the brightness decrement of 0.8 log unit for 150 td is assumed to be receptoral, short-wavelength cone contributions above 560 nm would be insufficient to alter a color match; at 8 td the potential contribution of the short-wavelength cones would be even less, given the 0.3 log unit reduction in brightness). The adaptation data
(as well as data of Fedorova, 1941; Yustova, 1958; and McCree, 1960) indicate significant desaturation for stimuli on the region of the spectrum locus where receptor adaptation would not predict it. This leads us to conclude that the origin of the phenomenon must be, at least in part postreceptoral.

Acknowledgements—This research was supported in part by NEI, NIH research grant EY00901 and training grant EY07010. It was presented at the Annual meeting of the Optical Society of America in San Diego in 1984. Richard Bowen and Bill Swanson provided comments on a draft of this manuscript.

REFERENCES


