Very-long-term and short-term chromatic adaptation: Are their influences cumulative?

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1. Introduction

Chromatic adaptation from viewing light of selective wavelengths causes reversible changes in color appearance. Chromatic adaptation for a few seconds or minutes (short-term adaptation) or for days or weeks (very-long-term adaptation) has been studied experimentally, but the work here is the first to study shifts in color appearance when both types of adaptation are combined.

Short-term adaptation is a well-studied phenomenon. It results from exposure of 15 min or less to a chromatic light. The adapting effect decays within seconds or minutes (Jameson, Hurvich, & Varner, 1979; Rinner & Gegenfurtner, 2000). Many studies support a two-process model of short-term chromatic adaptation (Cicerone, Krantz, & Larmier, 1975; Drum, 1981; Guth, Massof, & Benzschawel, 1980; Hayhoe & Wenderoth, 1991; Jameson & Hurvich, 1972; Larimer, 1981; Shevell, 1978; Ware & Cowan, 1982). Very-long-term (VLT) chromatic adaptation has been little studied until recently. It results from exposure to an altered chromatic environment for an hour or more each day over many days or weeks. Several adapting techniques have been used, including natural viewing with chromatically selective (typically long-wave-transmitting) lenses (Eisner & Enoch, 1982; Neitz, Carroll, Yamauchi, Neitz, & Williams, 2002; Yamauchi et al., 2002) or with a spectrally filtered illuminant that predominantly emits long wavelengths (Belmore & Shevell, 2008; Neitz et al., 2002). VLT adaptation can be induced also by viewing a long-wavelength grating on a video display for an hour each day (a technique suggested to us by Dr. J. Neitz). Different VLT-adapting methods and durations produce similar shifts in unique yellow, which are maintained for days or even weeks after the end of the adapting period (Belmore & Shevell, 2008; Neitz et al., 2002). The color shifts from VLT adaptation cannot be fully explained by a gain (von Kries) theory of adaptation (Belmore & Shevell, 2008). As with short-term chromatic adaptation, VLT adaptation causes shifts in unique yellow consistent with a two-process model.

VLT and short-term adaptation often have been distinguished by the temporal properties of the color shifts resulting from the adaptation. VLT adaptation is characterized by color changes (i) that can increase in magnitude with recurring exposure to the adapting light over several days or longer and (ii) that persist for tens of hours, days or even weeks after chromatic adaptation ends. Short-term adaptation typically is assumed to reach its asymptotic impact within an hour or less of viewing the adapting stimulus,
and any effect of adaptation is presumed (though seldom demonstrated) to dissipate within an hour. The different time courses for the influence of VLT versus short-term adaptation suggest distinct neural mechanisms, which may be isolated to a significant degree with carefully chosen adapting durations and testing periods. Both mechanisms, however, conceivably may drive a common, higher-level neural pathway that mediates the color shifts caused by either type of adaptation. Even though each type of adaptation may be initiated by a separate mechanism with distinct temporal properties, if they share a later nonlinear neural pathway then one type of adaptation may completely dominate the other. If so, VLT adaptation may not affect color perception in natural viewing when both short-term and VLT adaptation occur simultaneously.

In general, the relative strength of VLT versus short-term chromatic adaptation is not easily determined. Under some comparable conditions, for example exposure to a long-wavelength adapting light in the laboratory, short-term chromatic adaptation can produce a shift in equilibrium (neither reddish nor greenish) yellow far greater than that produced by VLT adaptation. Consider a test stimulus that is an admixture of 540 and 660 nm light. With the level of the 540 nm light fixed, the observer sets the radiance of the 660 nm component so the test appears equilibrium yellow. Introducing short-term long-wavelength chromatic adapting light can increase the required 660 nm radiance by a full log unit, but VLT adaptation may raise the 660 nm level by as little as 0.1 log unit. Laboratory measurements of VLT adaptation, however, do not extend for a sufficiently long period of time to examine VLT-adapting mechanisms that may depend on light stimulation over months or longer. Also, other color-measurement paradigms may yield a different relative contribution from short-term versus VLT adaptation. A challenge, therefore, is to assess whether color shifts from short-term and VLT adaptation are cumulative without having to determine a “baseline” state of color perception without VLT adaptation.

The aim of this study was to assess whether the color shifts found in laboratory experiments of VLT adaptation are important for natural viewing. This can be determined without knowing the absolute magnitude of the color changes that may result from VLT adaptation. The critical question is whether the color shifts induced by VLT laboratory adaptation are the same, with or without short-term adaptation that alone causes large color shifts; that is, are the color shifts from short-term and VLT adaptation cumulative even when short-term adaptation causes a much larger change in color appearance than VLT adaptation? If so, then laboratory studies of VLT adaptation reveal a neural process of color perception whose effect survives even in the presence of a far larger color shifts due to short-term adaptation, and thus they reveal an important neural process in natural viewing.

2. Methods

2.1. Overview of procedure

The experiment was divided into two contiguous time periods: a baseline period followed by VLT chromatic adaptation (Fig. 1a and b). During both periods, the observer made equilibrium-yellow measurements at approximately the same time each day. Two sets of baseline measurements were taken during the first 6 days of the experiment. One set immediately followed dark adaptation, and then another set was taken during short-term chromatic adaptation. At the end of the testing session on the sixth day, the observer began the VLT chromatic adaptation, which lasted 1 h. On the following (seventh) day, testing began at least 22 h after the end of the previous day’s VLT adaptation. This sequence of taking equilibrium-yellow measurements and then, immediately afterward, 1 h of VLT adaptation continued for 12 or 14 days.

2.2. Adapting stimulus

The stimulus for VLT chromatic adaptation was a grating pattern (Fig. 2a) presented for 1 h each day on a cathode ray tube (CRT) video display in an otherwise dark, windowless room. The screen displayed randomly located, parallel lines of some orientation; a new set of lines at a different randomly chosen orientation presented every 5 s. The width of each line was approximately 10 min of arc. The line density covered 25% of the area of the display. Judd chromaticity coordinates for the lines were \( (x = 0.60, y = 0.35) \) at 22.4 cd/m². The display, a carefully calibrated Sony Trinitron monitor (GDM-F520), was controlled by a Macintosh G4 computer. The CRT display was set via software for 1360 × 1024 pixel resolution and a refresh rate of 75 Hz noninterlaced.

Short-term chromatic adaptation took place during the testing session as part of the test-stimulus presentation, using a Maxwellian-view optical system. The short-term adapting field was a 660 nm, 2.7° diameter disk at 100 td. At this light level, the additive and gain components that account for color perception under short-term adaptation are well differentiated (Shevell, 1982). Initially, the observer viewed this adapting field for 3 min; later, it

![Fig. 1](image-url)
2.3. Test stimulus

The test field for assessing equilibrium yellow was an annulus of inner–outer diameter 0.8–1.3° presented using the Maxwellian-view system. The observer viewed the field with the right eye. The test was composed of an admixture of 540 nm and 660 nm lights. The observer adjusted the level of the 660 nm light so the test appeared equilibrium (neither reddish nor greenish) yellow. The 540 nm component was fixed in retinal illuminance on each trial; the levels of 540 nm tested within each session were 0.5, 1.0, 1.5 and 2.0 log td (a 2.5 log td level was added for the combined-adaptation measurements).

For the combined-adaptation condition, or short-term adaptation alone, short-term chromatic adaptation was maintained with a repeating 4 s cycle of stimulus presentation. The test field was presented alone for 1 s and then was presented superimposed on the adapting field for 3 s. The observer judged the color of the test during only the 1 s test-alone presentation. The stimulus presentation sequence is diagrammed in Fig. 2b.

2.4. Procedure

In testing sessions, unique yellow measurements began at the lowest 540 nm light level and ended with the highest. The observer used a game pad to adjust the radiance of the 660 nm light in the admixture to achieve a percept that was neither reddish nor greenish. There were five trials at each 540 nm level in the test; measurements from the five trials were averaged. This protocol is similar to one used by Shevell (1982) in studies of color perception with a short-term chromatic adapting field. Both observers were practiced at setting equilibrium yellow before the start of data collection.

Each set of measurements began with 5 min of dark adaptation. Then measurements were taken for VLT adaptation alone (or, during the baseline period, for dark adaptation). There was 1 min of further dark adaptation before measurements were taken at each new level of 540 nm light in the test field. An additional 3 min of dark adaptation was presented as part of the test-field presentation sequence (see Section 2.3 below), which ensured that short-term adaptation was maintained throughout those equilibrium-yellow measurements.

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Fig. 2. (a) Example of CRT display for very-long-term chromatic adaptation (see text). (b) Test-stimulus presentation sequence for conditions that included short-term chromatic adaptation (see text).

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Fig. 3. Average measurements of equilibrium yellow during the baseline and very-long-term chromatic adaptation experimental periods. Baseline measurements: dark adaptation (solid line) and short-term chromatic adaptation alone (dotted line). Shifts in unique yellow due to introducing very-long-term adaptation: VLT adaptation alone (dashed line); VLT together with short-term adaptation (dash-dot line). The amount of 660 nm test light (vertical axis) needed to establish equilibrium yellow is given as a function of the amount of 540 nm test light (horizontal axis).
dark adaptation preceded the following measurements that included short-term chromatic adaptation. An initial 3 min period of exposure to the short-term chromatic adapting field preceded short-term-adaptation measurements.

2.5. Observers

Observers were two University of Chicago undergraduate students. They were naïve about the purpose of the experiment and were paid for their participation. Both observers had normal color vision as assessed by Rayleigh matching using a Neitz anomaloscope. Consent forms were completed in accordance with the policy of the University of Chicago’s institutional review board.

3. Results

Either VLT or short-term chromatic adaptation shifted color perception. Following either type of adaptation, the amount of 660 nm light in the test field had to be increased for the percept of equilibrium yellow, compared to dark adaptation. These measurements are shown in Fig. 3 for each level of 540 nm light in the test field (horizontal axis), for dark adaptation (solid line), VLT adaptation alone (dashed line) and short-term adaptation alone (dotted line). Each plotted value is the average of measurements made on many days. Error bars show standard errors of the mean, though most of them are smaller than the plotted point so are not visible. Each panel shows results for a different observer.

The main aim of this experiment was to compare the color shifts with combined VLT and short-term chromatic adaptation to shifts with either type of adaptation alone. Measurements with combined-adaptation (dash-dot line, Fig. 3) fall above the shifts found with only short-term chromatic adaptation (dotted line); the results show that adding VLT chromatic adaptation increased the color shifts beyond those due to short-term adaptation alone (p < 0.01 for each observer by Tukey HSD test, comparing the four types of adaptation: dark, short-term alone, VLT alone and combined). VLT adaptation alone (dashed line) also caused a color shift compared to dark adaptation (solid line; p < 0.01 for each observer by Tukey HSD test). Furthermore, the magnitude of the average shift from VLT adaptation alone compared to dark adaptation (0.12 log td for Obs. G.A., 0.09 log td for M.O.) was comparable to the shift from combined-adaptation compared to short-term adaptation alone (0.08 log td for G.A., 0.09 log td for M.O.). Thus, the shifts in equilibrium yellow produced by short-term and VLT adaptation together were cumulative; this shows that VLT adaptation can significantly affect color perception in natural viewing where, of course, VLT and short-term adaptation operate simultaneously.

4. Discussion

To our knowledge, there is no previous comparison of the color shifts from VLT chromatic adaptation combined with short-term adaptation, to the color shifts from short-term adaptation alone. The results here showed that the color shifts caused by short-term and VLT chromatic adaptation together were cumulative. The incremental shift due to VLT adaptation was very similar whether or not the observer also was exposed to short-term adaptation.

While the results from short-term and VLT adaptation are additive, this additivity does not imply separate, independent neural mechanisms. Consider for example a single linear process, such that introducing adapting stimulus A results in a color shift of magnitude S, regardless of the initial adapted state (and thus of any color shift already induced) when A is introduced. This single mechanism could account for the cumulative color shifts found with combined short-term and VLT adaptation. Nonetheless, distinct short-term and VLT neural mechanisms are supported by other properties of the color shifts they induce. Color shifts from VLT adaptation, but not short-term adaptation, increase with additional adaptation over many days; and the color shifts from VLT adaptation, but not short-term adaptation, persist for days after the adaptation ends (Neitz et al., 2002). The question of independent mechanisms for each type of adaptation, however, is not the focus here, because even fully independent mechanisms at one stage of the visual system may interfere with each other. As mentioned earlier, if short-term and VLT chromatic-adaptation mechanisms converge on a later nonlinear neural mechanism or some other bottleneck, then short-term chromatic adaptation could saturate or otherwise inhibit neural responses that mediate color shifts from VLT adaptation alone.

Different processes of adaptation have been described at many levels of the visual system. A classical distinction is photochemical (pigment bleaching; Wyszecki & Stiles, 1980) versus neural processes of adaptation, and of course there is a variety of different neural mechanisms. For example, two distinct mechanisms are posited to explain color shifts that persist for a longer duration following a 10 s-on/10 s-off chromatic adapting cycle (0.05 Hz), compared to presenting the same adapting light continuously (Jameson et al., 1979). Within the realm of neural adaptation, some mechanisms depend on the space-average or time-average of the adapting stimulus (Fairchild & Lennie, 1992; Valberg & Lange-Malecki, 1990; Webster & Wilson, 2000), while other mechanisms are driven by the variation in the adapting stimulus over space (Brown & MacLeod, 1997; Monnier & Shevell, 2003; Shevell & Wei, 1998) or time (Webster & Mollon, 1991, 1994).

Additional evidence in support of multiple mechanisms comes from the observation that a given long-wavelength adapting light can shift color appearance toward either greenness or redness, depending on whether the light is presented to the same eye as the test, as is typical, or to only the contralateral eye (Shevell & Humanski, 1984); presumably, the contralateral stimulus drives only a central neural mechanism while the same-eye adapting field affects also retinal mechanisms of adaptation that influence the neural representation of the test field. In addition, separate mechanisms are revealed by their distinct time scales (Vul, Krimay, & MacLeod, 2008; Webster & Leonard, 2008). Multiple, hierarchical mechanisms of adaptation are posited even for short-term adaptation to a steadily presented adapting field in the same eye as the test (Rinner & Gegenfurtner, 2000).

Given the broad evidence for multiple mechanisms of adaptation, it may not be surprising that short-term and VLT chromatic adaptation act cumulatively. Isolating distinct mechanisms, however, does not guarantee that each one has an influence on color perception when other mechanisms are also active. The findings here show the importance of understanding VLT adaptation because the color shifts it causes persist even with strong, simultaneous short-term chromatic adaptation.

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References


