Induction from a below-threshold chromatic pattern

Patrick Monnier
Department of Psychology, Colorado State University, Fort Collins, CO, USA

Steven K. Shevell
Departments of Psychology and Ophthalmology and Visual Science, University of Chicago, Chicago, IL, USA

Patterned backgrounds can induce large shifts in color appearance, even with patterns of only 10% S-cone contrast (S. K. Shevell & P. Monnier, 2005). The present study tested whether a background pattern could induce color shifts even at a below-threshold contrast. In the first experiment, S-cone contrast threshold for discriminating a pattern from a homogenous background was measured by a 2AFC procedure. Next, a test ring was inserted within the patterned background. With the test ring present, six of eight observers reliably distinguished trials with a patterned background from trials with a homogeneous field, even though the S-cone contrast in the pattern was too low to be discriminated from a homogeneous background. This suggested that a below-threshold S-cone pattern shifted the color appearance of the test ring; that is, the appearance of the test was used to discriminate whether the background was patterned or homogeneous. This was corroborated by asymmetric color matches, which revealed a color shift caused by subthreshold S-cone contrast within the patterned background.

Keywords: color appearance, chromatic induction, chromatic contrast, S-cones

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Introduction

Classical demonstrations of chromatic induction can be disappointing (Kaiser & Boynton, 1996) but induction from a chromatic pattern can cause a conspicuous color shift that is much larger than that from a uniform background at any chromaticity in the pattern (Gindy, 1963; Monnier & Shevell, 2003). For example, large color shifts are caused by an inducing pattern that selectively stimulates the S-cones. Previous measurements show that these shifts depend on the spatial frequency of the pattern and are accounted for by receptive-field organization with a spatially antagonistic center and surround, both driven by S-cones (Monnier & Shevell, 2004; Shevell & Monnier, 2005). When nearby and more distal inducing light differs in S-cone stimulation (e.g., lights that appear purple and lime), the response of this type of cell is large; on the other hand, the response is weak with a uniform chromatic surround because the center and surround of the receptive field are almost equally excited and therefore counterbalancing.

In general, larger color shifts are expected with more saturated inducing chromaticities. According to Kirschmann's 5th law (cited in Graham, 1965) the magnitude of the color shift is positively correlated with the saturation of the inducing surround. Also, chromatic induction increases monotically with the chromatic contrast between the test and its inducing regions in a wide range of stimulus configurations (Barnes, Wei, & Shevell, 1999). Further, the magnitude of induced contrast is linearly related to the chromatic contrast within an inducing region (Singer & D'Zmura, 1995).

The magnitude of induced color shift from an S-cone isolating pattern increases linearly with the chromatic contrast within the pattern (Shevell & Monnier, 2005), with a noticeable induced shift with as little as 10% Michelson S-cone contrast. An open question is whether a subthreshold S-cone contrast-inducing pattern still can induce a color shift. Perhaps a neural response to a pattern too weak to reach contrast threshold can cause a color change in nearby regions. The aim of this study was to test whether a color shift induced by a patterned background occurs even when the pattern is below threshold.

Several studies demonstrate that stimuli either too fast (Shady, MacLeod, & Fisher, 2004) or too small (Shady & MacLeod, 2002) to be consciously perceived can nonetheless affect perception. A tentative conceptualization is that conscious perception is restricted to relatively late stages of neural processing (Carmel, Lavie & Rees, 2006). According to this view, the contextual interaction occurs in pre-conscious stages of neural representation and only the end product of the interaction, not the stimulus configuration in its entirety, is consciously perceived. Perhaps induction from a subthreshold chromatic-contrast pattern occurs at a pre-conscious stage of neural representation with only the color shift it induces experienced consciously.

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Methods

Observers

Eight observers participated in the study (five in Experiments 2 and 3). All had normal or corrected acuity (20/20) and normal color vision as assessed with the Ishihara plates. The observers completed practice sessions before data collection was initiated. All were naive as to the purpose of the study except for P.M. who is one of the authors. Each observer gave informed consent. This research protocol was approved by Institutional Review Boards at Florida Atlantic University and at Colorado State University.

Apparatus and calibration

Stimuli were presented on a 17-in. CRT monitor (Eizo FlexScan T566, 1152 by 870 pixels, 75 Hz). A Macintosh G4 computer equipped with an ATI Radeon 7000 video card (10 bits per gun) was used to present the stimuli. The spectral power distribution of each of the three guns was measured using a spectroradiometer (Photo Research PR-650). The 1,024 light levels for each gun were linearized with a radiometer (International Light IL-1700) and stored in a look-up table. Calibration was checked regularly with the spectroradiometer and was found to be stable during the course of the study.

All chromaticities were specified in a cone-based color space with two dimensions (MacLeod & Boynton, 1979): $l = L / (L + M)$ and $s = S / (L + M)$. The unit of s is arbitrary and normalized here to 1.0 for a light metameric to equal-energy white (EEW). Equiluminance was measured separately for each observer using the method of minimum motion photometry (Anstis & Cavanagh, 1983); S-cone isolation was confirmed for each observer using the minimally distinct-border technique (Tansley & Boynton, 1978).

Experiment 1: Discrimination thresholds for S-cone patterns with and without a test ring

Stimuli and Procedure

In this experiment, S-cone contrast threshold was measured for discriminating an S-cone pattern from a uniform background at the pattern's space average chromaticity and luminance. In the pattern-only condition, a non-signal interval contained two identical uniform achromatic backgrounds (l, s, Y: 0.665, 1.0, 15 cd/m^2) presented side by side (Figure 1a); a signal interval contained one uniform achromatic background and one patterned background (Figure 1b). The patterned background was composed of 13 circles alternating between higher S-cone (purple in appearance) and lower S-cone (lime in appearance) stimulation. The areas inside and outside the patterns were achromatic (l, s, Y: 0.665, 1.0, 15 cd/m^2) in order to eliminate a chromatic-edge difference between the patterned and uniform backgrounds at their inner and

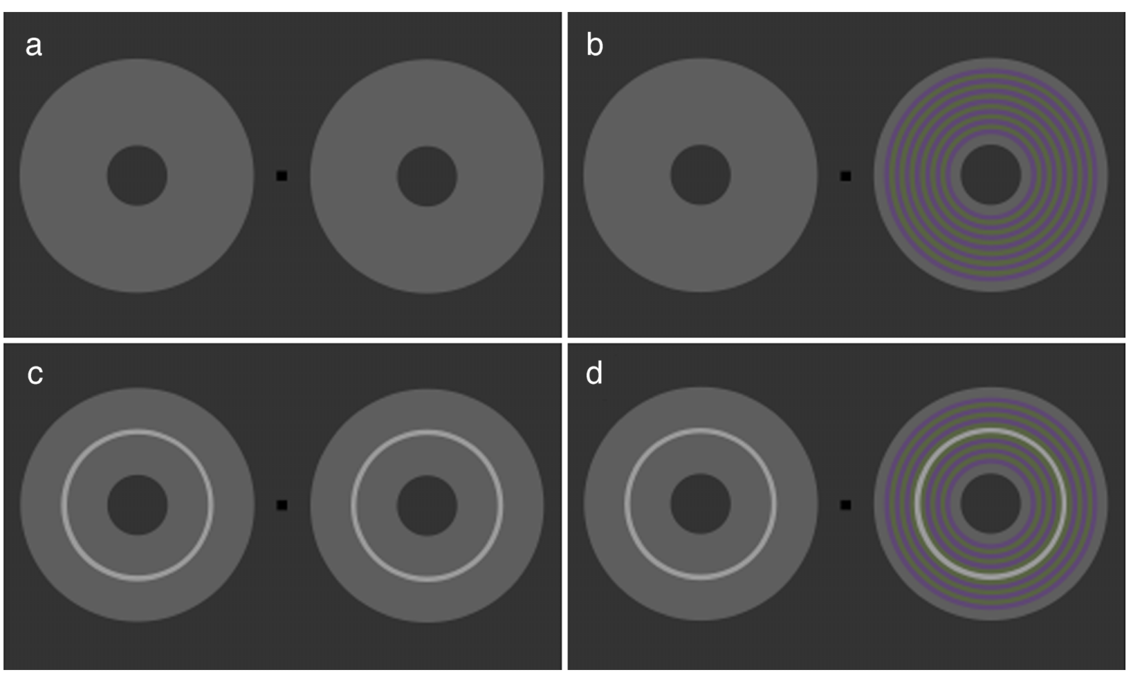

Figure 1. (a–b) Pattern-only condition. Panel a shows a non-signal interval and b a signal interval. (c–d) Pattern-with-test-ring condition. Panel c shows a non-signal interval and d a signal interval. The S-cone patterns were composed of 13 purple/lime rings (12 in the pattern-with-test-ring condition) at spatial frequency 3 cycles per degree.

outer boundaries (see Figure 1b, right). The *l*-chromaticity of the chromatic circles was fixed at $l = 0.665$.

The spatial frequency of the patterned background was three cycles per degree at the viewing distance of one meter. Both uniform and patterned backgrounds were presented on an achromatic field (*l, s, Y*: 0.665, 1.0, 10 cd/m^2). A dark fixation point between the two backgrounds was presented for the duration of a block of trials. The inner and outer diameter of each background was 1.3 deg and 5.2 deg, respectively. The two backgrounds were separated by 6.2 deg, center to center.

In the pattern-with-test-ring condition, a test ring was inserted in otherwise identical backgrounds (Figures 1c and 1d). Three chromaticities of test ring were used; they were selected based on previous results showing large color shifts (Monnier & Shevell, 2003). The chromaticities (*l, s, Y*) were 0.62, 1.0, 20 cd/m^2; 0.665, 1.0, 20 cd/m^2; and 0.70, 1.0, 20 cd/m^2. Additionally, in different runs, the phase of the alternating purple and lime circles was reversed so that the test ring was immediately flanked by either purple or lime inducing circles.

In all conditions, observers dark adapted for two minutes and then adapted to the large achromatic field for one minute. Within a run, two interleaved staircases were run simultaneously. A pair of signal/non-signal intervals from one or the other staircase was randomly presented for 200 msec, with an inter-stimulus interval of one second. The task was to choose the interval that contained non-identical backgrounds. Within a trial, the side on which the patterned background was presented was selected randomly. The S-cone contrast within the patterned background was adjusted following a three-up/one-down staircase procedure and converged to a 79% S-cone contrast-discrimination threshold. Each staircase ran for twelve reversals; the last ten were averaged to estimate threshold. Each condition was repeated three times on separate days to determine the threshold so the final threshold was the mean of three daily thresholds, each one determined from the mean of 10 staircase reversals.

Results

The design included two main factors: phase (purple or lime circles flanking the test) and test chromaticity (3 test-ring chromaticities, plus the no-test-ring condition). A separate analysis of variance was completed for each observer.

The main effect of test ring was significant for six of eight observers. Differences between the various test-ring conditions were investigated with post hoc comparisons (Tukey's protected HSD test, $p < 0.05$). Three comparisons were of primary interest: the pattern-only condition vs each of the three test-ring chromaticities. All three comparisons were significant for three observers, two comparisons were significant for two observers, and one comparison was significant for one observer. Overall, six of eight observers showed lower threshold when a test ring was included within the patterned background.

For two out of eight observers, the main effect of phase was significant (although the phase differences for these two observers were in opposite directions). For three observers, the interaction was significant. A significant interaction indicated that the effect of test-ring chromaticity (or absence of the test) varied with the phase. Inspection of the significant interactions did not reveal systematic differences across observers. Small differences between test-ring chromaticities and between phases of the inducing pattern are not uncommon (Monnier & Shevell, 2003; Shevell & Monnier, 2005). With respect to our previously proposed model of induction based on a pure S-cone center-surround antagonistic receptive field, differences among test-ring chromaticities may indicate a small influence from L or M cones. Phase differences may indicate a small imbalance between the center and surround responses. Again, these differences were small and not systematic across observers.

The ratio of the pattern-only (no test ring) threshold divided by the test-ring threshold (vertical axis) as a function of the test ring chromaticity is shown in Figure 2. Each line shows results for a different observer. A ratio of 1.0 indicated that threshold for the pattern-only and a test-ring condition were equal. A ratio greater (smaller) than 1.0 indicated that contrast threshold for the pattern-only

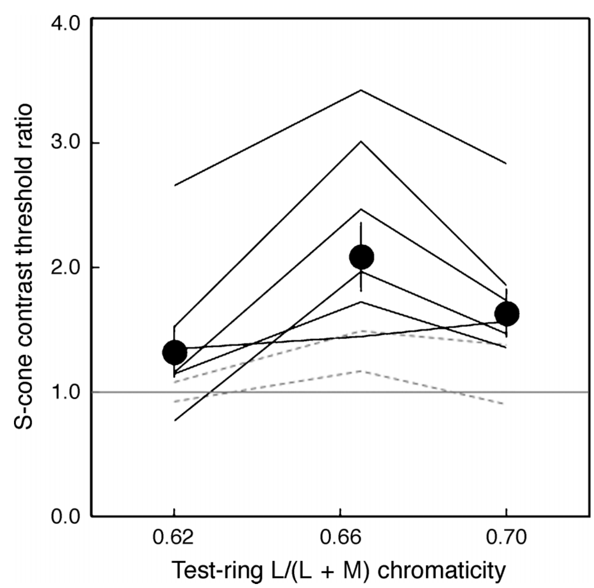

Figure 2. Ratios of threshold for pattern-only and pattern-with-test-ring conditions. Threshold S-cone contrast ratio (vertical axis) is plotted as a function of the test-ring chromaticity (horizontal axis). Ratios greater than 1.0 indicate superior discrimination in the pattern-with-test-ring condition compared to the pattern-only condition. Each line shows measurements for a different observer. Symbols show the means and standard errors for the eight observers. The dashed lines denote the two observers with a non-significant effect of introducing a test ring.

condition was higher (lower) than for a test-ring condition. Symbols show the means and standard errors over the 8 observers. To summarize, introducing the test ring reduced threshold for discriminating a patterned-background stimulus from a uniform-background stimulus for six of eight observers (solid lines, Figure 2).

The average threshold ratio for each observer is shown in Figure 3. All ratios were greater than 1.0 ($p < 0.01$ by sign test), though only marginally so for one observer. Asterisks denote observers with a statistically significant change in threshold due to adding a test ring. The median value was 1.43. This indicated contrast threshold for the pattern-only condition typically was about 1.43 times greater than for the pattern-with-test-ring conditions.

Experiment 2: Asymmetric matching with very low S-cone contrast patterns

Stimuli and procedure

A possible explanation for the results of Experiment 1 is that the subthreshold S-cone contrast in the patterned backgrounds caused a color shift within the test area. This induced color shift, then, was used to discriminate the patterned-background stimulus from the uniform-background stimulus. This hypothesis was tested by measuring the color shifts in the test with the stimuli used in Experiment 1. Comparison and test backgrounds, identical in size to the stimuli in Experiment 1, were presented side by side. The comparison background was uniform and metameric to EEW (*l, s, Y*: 0.665, 1.00, 15 cd/m^2). The patterned background of the test was composed of

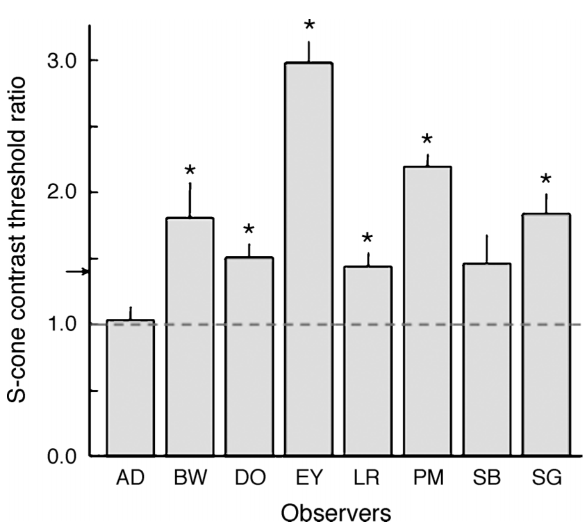

Figure 3. Ratios of the pattern-only to pattern-with-test-ring S-cone contrast thresholds, averaged across the three test-ring chromaticities. The asterisks denote observers with a statistically significant change in threshold due to adding a test ring. The median S-cone contrast ratio for the eight observers was 1.43 (arrow on vertical axis).

chromatic concentric inducing circles alternating between two chromaticities selected from a tritanopic confusion line (as in Experiment 1). The S-cone Michelson contrast of the patterned background was set for each observer to be roughly half the S-cone discrimination threshold for the pattern-only condition measured in Experiment 1 (observers AD 4%; BW 5%; PM 5%; SB 3%; SG 2.5%; original S-cone contrast thresholds in Experiment 1: observers AD 8.6%; BW 10.1%; PM 9.5%; SB 6.9%; SG 4.9%). Observers adjusted the hue, saturation, and brightness of the comparison ring to match the appearance of the test ring using buttons on a Gravis gamepad. Steady fixation was not enforced. Induction was measured for the same three test-ring chromaticities as in Experiment 1 (*l, s, Y*: 0.62, 1.00, 20 cd/m^2; 0.665, 1.00, 20 cd/m^2; and 0.70, 1.00, 20 cd/m^2), and the other chromaticities and luminances were identical to those in Experiment 1. Matches in each condition were considered relative to an isomeric match in which both the comparison and test backgrounds were set to a uniform chromaticity metameric to equal-energy white (*l, s, Y*: 0.665, 1.00, 15 cd/m^2).

Each session began with two minutes of dark adaptation. A session was composed of five matches to each of the three test-ring chromaticities, for a total of 15 matches per session. Each condition was repeated three times on separate days. Five of the eight observers from Experiment 1 completed Experiment 2.

Results

A reliable color shift was measured for all five observers, even with the subthreshold level of S-cone contrast in the patterned backgrounds. The color shifts (relative to the isomeric match) are shown in Figure 4 along the S / (L + M) chromatic direction as a function of the test-ring L / (L + M) chromaticity (horizontal axis). Each line represents measurements for a single observer; symbols show means and standard errors for the five observers. Measurements above and below zero were for patterned backgrounds in which the test ring was immediately flanked by either purple or lime inducing circles, respectively (the equivalent of the phase manipulation in Experiment 1). The direction of the color shift mirrored previous results (Monnier & Shevell, 2003) and demonstrated that a below-threshold pattern within a background induced color shifts ($p < 0.001$ by sign test).

Note that the color shifts from subthreshold patterns always were toward the chromaticity of the light contiguous with the test, not away from it as in typical simultaneous color contrast. This shows that the pattern within the surround, not the chromatic contrast at the edge of the test area, caused the color shifts shown in Figure 4. A small set of measurements verified that uniform surrounds at a chromaticity taken from a subthreshold pattern caused a color shift away from, not toward, the uniform surround's chromaticity. The subthreshold patterns, therefore, not only induced a significant color shift but also reversed the direction of the shift, compared to a uniform surround at the chromaticity of the part of the pattern contiguous with the test area.

Experiment 3: Equiluminant control

An alternative possible explanation for the higher thresholds in the pattern-only condition is that the luminance contrast between the test ring and patterned background enhanced the visibility of the patterned background (recall that the test ring was set to 20 cd/m^2 while the patterned background was 15 cd/m^2). To rule out this explanation, an additional equiluminant condition was run in which the luminance of both the test ring and the patterned background was 15 cd/m^2. Only one test-ring chromaticity was used (l, s, Y: 0.665, 1.00, 15 cd/m^2). As in Experiment 1, each phase of the alternating purple and lime circles was tested (in different runs) so that the test ring was immediately flanked by either purple or lime inducing circles.

Results

The design included two main factors: phase (purple or lime circles flanking the test) and test ring (one test-ring chromaticity and the no-test-ring condition). A separate analysis of variance was completed for each observer. The main effect of test ring was significant for all observers; neither the main effect of phase nor the interaction was significant for any of the observers. Figure 5 shows the threshold ratio for the pattern-only condition compared to the condition with the equiluminant test ring within a patterned background. Thresholds for both phase conditions were averaged. Asterisks denote observers with a significant main effect of test ring. Superior discrimination with the test ring present again was observed, now with no luminance contrast between the test ring and patterned background.

In fact, the two observers with non-significant threshold changes in Experiment 1 showed significantly better discrimination with these equiluminant stimuli. It may be that the luminance contrast between the test ring and patterned background actually reduced the color shift induced by a very low S-cone contrast patterned background.

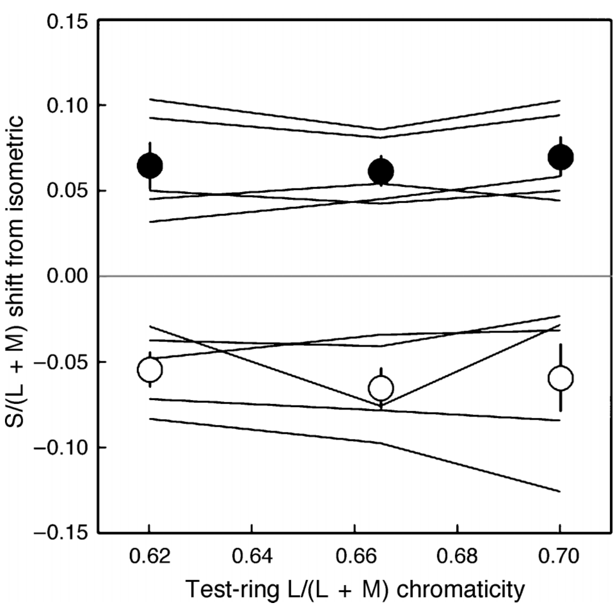

Figure 4. Color appearance measurements expressed as shifts form the isomeric match along the S / (L + M) chromatic direction. Each line represents measurements from a single observer; symbols show means and standard errors for the five observers. Measurements above (below) zero were for patterns with the test ring flanked by purple (lime) inducing circles.

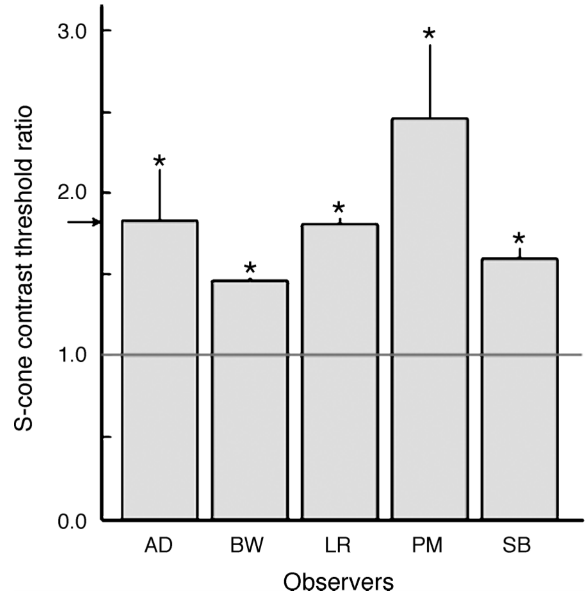

Figure 5. Ratios of the pattern-only to pattern-with-test-ring S-cone contrast threshold with equiluminant stimuli. The asterisks denote observers with a statistically significant change in threshold due to adding an equiluminant test ring. The median S-cone contrast ratio for the five observers was 1.83 (arrow on vertical axis).

Discussion

The human sensory system is limited in its ability to encode information. For example, human spectral sensitivity covers approximately 400 to 700 nm and visible flicker for an achromatic flickering grating extends to about 50 Hz while a chromatic flickering grating can be seen to flicker up to only about 15–20 Hz (Kelly, 1975). Some of these limits can be explained by a relatively small sensitivity range of the sensory transducer (e.g., spectral sensitivity reflects the spectral tuning of the cone photopigments). Energy outside these sensory windows is not encoded so it cannot affect perception. Other limits are not as easily explained because the stimulus is encoded faithfully by peripheral (or sometimes even central) neural processes but does not result in conscious perception. For example, neurons in area V1 respond to temporal variations higher than the critical flicker frequency (CFF; Gur & Snodderly, 1997). Additionally, adaptation to a uniform disk flickering above the CFF, which appears as a steady field, can significantly reduce contrast sensitivity (Shady et al., 2004). A monochromatic grating too high in spatial frequency to be resolved can alter color appearance (Shady & MacLeod, 2002), and the orientation of a central patch can be altered by a surrounding grating even when the surround is not seen due to masking (Clifford & Harris, 2005).

One conceptualization of these phenomena is that conscious perception is restricted only to relatively late stages of neural processing. Indeed, a recent fMRI study shows differential brain activity for psychologically distinct percepts (flickering vs. fused) of a light pulsed at a fixed frequency near the CFF. When the physically pulsed light is perceived as steady, brain activity is greater in relatively early brain regions (mainly in occipital extrastriate cortex) compared to later brain areas (frontal and parietal regions). When the identical pulsed light is perceived as flickering, brain activity is greater in later brain areas compared to early brain regions, suggesting conscious perception of flicker invokes frontal and parietal cortex (Carmel et al., 2006). Of course, it remains to be determined whether all pre-conscious/conscious phenomena conform to such a conceptualization. In the present study, a patterned background composed of S-cone inducing circles so low in chromatic contrast that they were below contrast threshold caused a shift in color appearance. This would be consistent with chromatic induction taking place within pre-conscious neural stages with only the color shift represented at a later neural stage.

A previously proposed neural model of induction for S-cone patterns invokes a receptive field with S-cone center-surround antagonism (Monnier & Shevell, 2004; Shevell & Monnier, 2006). Psychophysical evidence from a pure S-cone mechanism shows band-pass spatial-frequency sensitivity (Humanski & Wilson, 1992), which is consistent with the type of model proposed to account for the color shifts (Shevell & Monnier, 2005). Physiological measurements reveal such neurons in visual cortex (Conway, 2001; Solomon, Peirce, & Lennie, 2004), consistent with the idea that induction from a very low S-cone contrast pattern could occur at an early level of visual representation. The response from this type of receptive-field may be passed to higher stages that mediate a perceived color shift, even though a neural representation of the pattern driving this response is not.

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Corresponding author: Patrick Monnier.
Email: patrick.monnier@colostate.edu.
Address: Department of Psychology, Colorado State University, Fort Collins, CO 80523-1876, USA.

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