

# Chromatic Variation: A Fundamental Property of Images

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## Abstract

An isolated light has a color appearance specified reasonably well by its wavelength, but the same light within a complex image can appear a quite different hue. How does the context of an image affect the appearance of an embedded light? A classical approach is to aggregate light from throughout the image to determine an equivalent uniform background that has the same effect as the complex stimulus. Several models have been proposed to determine this 'equivalent background', including simple averaging of light, spatial weighting, and nonlinear neural responses. The main point of this paper is that none of these models can succeed because *variation* within a complex image is a fundamental property of it. Studies show that color perception depends on a chromatic-contrast gain-control mechanism, which is regulated by chromatic variation over a large area. Any uniform field has no variation, of course, so cannot mimic the color shifts caused by a complex image.

## Introduction

Color perception is a fundamental aspect of vision. Natural objects have a perceived size, shape, location, brightness and color. Color is not in the light reflected from the objects. The hues that we perceive result from neural coding of light by the eye and brain. For example, a 580 nm light viewed alone appears yellow, but the same light appears reddish after extended viewing of a shorter wavelength background (say, one that appears green), or greenish after a longer-wavelength background (one that appears red). Further, at very low luminance a 580 nm light can appear achromatic (the photochromatic interval; Graham & Hsia, 1969). The point is that the neural representation of a light determines its appearance, not the physical properties of the light itself.

What are the neural mechanisms mediating color perception of a 'complex' scene? A series of experiments shows that cortical mechanisms, not just retinal ones, affect the neural representation of a given light caused by other lights also in view. The term 'complex' is a relative one; it distinguishes this research from studies with uniform adapting fields, such as the classical test on a background field. The focus is on neural mechanisms, so stimulus

complexity is modest and carefully controlled to eliminate potentially artifactual or confounding interpretations of results.

In order to integrate this work in context, consider the 'equivalent background' principle, which holds that the state of visual adaptation from viewing a complex chromatic scene is equivalent to the adapted state that would result from some uniform, homogeneous 'equivalent' adapting light. The equivalent-background concept has a long history in vision, and successfully accounts for some aspects of visual performance (Hood & Finkelstein, 1986). The equivalent background principle, however, cannot explain color perception (Bäumli, 1994; Jenness & Shevell, 1995; Brown & MacLeod, 1997; Zaidi, 1999). Weaknesses of the equivalent background principle are well known, but what new theoretical approaches can replace it?

The theory proposed here is based on contrast coding at boundaries, followed by a chromatic-contrast gain-control mechanism. A chromatic-contrast gain-control mechanism is defined as a mechanism that controls and is controlled by chromatic contrast. Several experiments reported here demonstrate changes in color perception that follow from this theory. Additional work reveals a cortical locus for the gain-control mechanism.

## Neural Coding of Differences and Adaptation to Chromatic Variation

Chromatic induction is the change in the perceived color of one light caused by introducing another light nearby. The classical example is a small central test patch of one chromaticity within a surrounding field of another. Consider a central  $0.5^\circ$  wide patch which appears yellow in the dark, but which appears greenish when viewed within a  $1.5^\circ$  long-wavelength surround. What is the neural mechanism that mediates this change in hue?

This was investigated by introducing a third region, called the *remote region*, outside the uniform long-wavelength surround (a schematic stimulus is in the left panel of Fig. 1). In the main experiment, the remote region was a checkerboard,  $4^\circ$  wide and composed of checks at two different chromaticities (one that appeared red and one that appeared green). In other experiments, the remote region was a uniform field or dark. A chromatic-contrast

gain-control mechanism, regulated by chromatic variation over the whole stimulus, would attenuate contrast more strongly with the checkerboard, which has chromatic variation, than with a uniform or dark remote region, which does not. Therefore, if chromatic induction is mediated by contrast coding of the edge between the test and surround, and by subsequent regulation of this signal by a chromatic-contrast gain-control mechanism, then introducing the remote chromatic checkerboard should reduce chromatic induction.

The measurements confirmed this prediction (Shevell & Wei, 1998; results for one of the observers are shown in the middle of Fig 1). The observer adjusted a mixture of the R and G phosphors of a CRT in the  $0.5^\circ$  central test field, so it appeared neither reddish nor greenish (that is, equilibrium yellow). First, as baseline values, the plot shows the luminance of the G phosphor (vertical axis) required to cancel the redness in various amounts of the R phosphor (horizontal axis), when (i) only the  $0.5^\circ$  test was presented ('test alone', open circles) or (ii) the test was presented with only the  $1.5^\circ$  uniform long-wavelength surround (filled circles). As expected, the long-wavelength surround induced greenness so less of the G phosphor was needed to cancel the redness in the R phosphor (filled circles below open circles). The critical question is the change in color appearance caused by introducing the chromatic checkerboard outside the surround. The checks appeared red and green (the same chromaticity of the surround and the G phosphor, respectively), and were equal in luminance. The measurements showed the checkerboard strongly attenuated chromatic induction from the long-wavelength surround (squares-with-plus above filled circles). For this observer, the remote chromatic variation nearly eliminated the induction of greenness.

The far right panel in Fig. 1 shows a control condition that demonstrates the remote chromatic checkerboard does *not* act by directly affecting the color of the  $0.5^\circ$  test.

When the  $1.5^\circ$  surround was changed in chromaticity to appear yellowish (but still clearly discriminable from the central patch) and no remote checkerboard was presented, there was little chromatic induction as expected (compare open and filled circles in right panel). Now, introducing the remote chromatic checkerboard caused almost no change in hue (compare squares-with-plus to filled circles), which shows the chromatic variation in the remote region acts on the neural process mediating induction from the  $1.5^\circ$  long-wavelength surround, not by directly shifting the hue of the  $0.5^\circ$  test toward redness.

Other experiments verified that chromatic *variation* within the remote region was the critical factor affecting the color the central test. A *uniform* remote region at the same space-averaged chromaticity as the checkerboard had little effect on the color of the  $0.5^\circ$  patch presented within the  $1.5^\circ$  long-wavelength surround. Further, a uniform remote region at the chromaticity of the 'green' checks caused a smaller change in color than the checkerboard (Shevell & Wei, 1998). Thus, a remote region with chromatic variation (that is, the checkerboard) altered color perception more than a uniform remote region at either chromaticity composing the checkerboard. This confirms that chromatic variation is the critical factor, as expected for a chromatic-contrast gain-control mechanism.

### A Gain-control Mechanism Controlled by Contrast

A contrast gain-control mechanism was defined as a mechanism controlled by and controlling contrast. This implies that varying chromatic contrast within the remote region should vary the change in color of the central test. This was confirmed by varying the chromatic contrast in the remote region while keeping constant its average chromaticity and luminance.

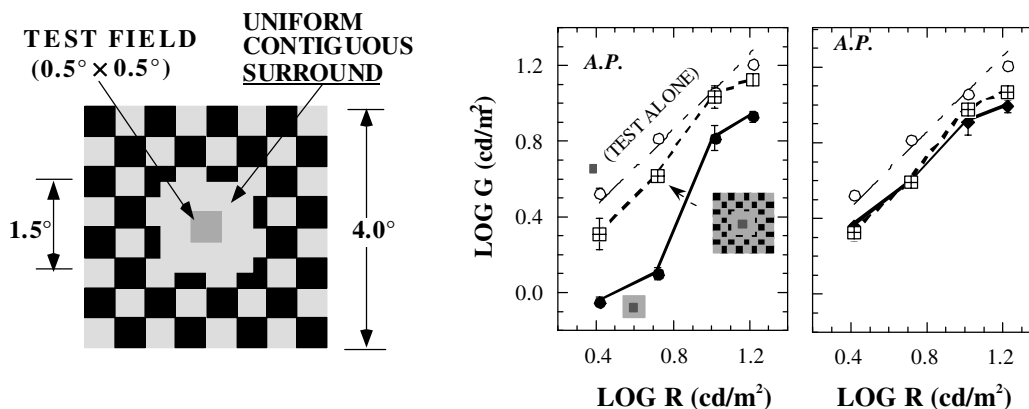


Figure 1. Left: Schematic of stimulus: a central test field within a uniform surround, presented with a remote region containing chromatic contrast (the 'checkerboard'). Middle: Measurements of the G and R phosphors in the test that appeared neither reddish nor greenish, with the test alone (open circles), the test within a uniform long-wavelength surround (filled circles), or the test-within-surround presented with remote chromatic contrast (squares-with-plus). Right: As in the middle panel but with the  $1.5^\circ$  uniform surround at a chromaticity that appeared yellowish.

A summary of measurements for 3 observers is shown in Fig. 2 (raw data and further details are in Barnes, Wei & Shevell, 1999). The vertical axis is the average change in the measurements caused by introducing a checkerboard, with 1.0 defined as the change found with the chromatic checkerboard used in the experiment described above (this checkerboard contrast level is defined as 100% contrast). The chromatic contrast within the checkerboard, shown on the horizontal axis, was varied in 20% steps. The results show that increasing the magnitude of chromatic contrast within the remote region increases the change in color appearance that it causes, in accord with the definition of a contrast gain-control mechanism.

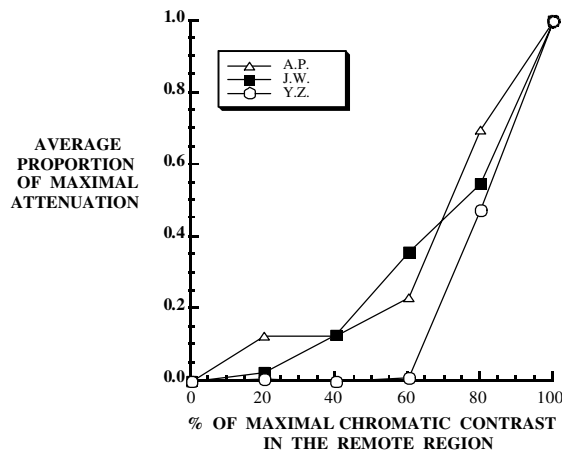


Figure 2. Relative change in color appearance measurements caused by varying the chromatic contrast within the remote region, for 3 observers.

### Spatial Frequency Selectivity

A simple gain-control that aggregates chromatic contrast over the scene implies a stronger influence of remote chromatic variation as check size decreases (and thus contrast-edge total length increases). Eventually, very small checks would not be well resolved so would approach a uniform surround, but the 0.5° wide checks used above can be substantially smaller before approaching this limit. On the other hand, a cortically mediated gain-control could be spatial-frequency selective, in which case changing the size of the remote checks, either smaller or larger, would reduce the change in color appearance they cause, compared to the results presented above with test and remote checks of the same size (schematic stimuli are shown in Fig. 3).

The measurements show spatial frequency selectivity. The plot in Fig. 3 summarizes results for 3 observers (raw data are in Barnes, Wei & Shevell, 1999). The average reduction in chromatic induction caused by introducing the remote chromatic checkerboard (vertical axis) is shown as a function of check size (horizontal axis). Remote chromatic variation has the strongest effect when the remote checks are the same size as the central test (dashed vertical line).

Figure 3 shows spatial frequency selectivity for remote contrast but does not prove conclusively that the greatest change in induction occurs with checks that correspond to the size of the central test. This was shown in an additional experiment that used a larger central test size, for which the peak change in chromatic induction did, indeed, occur with checks at this larger size (Barnes, Wei & Shevell, 1999).

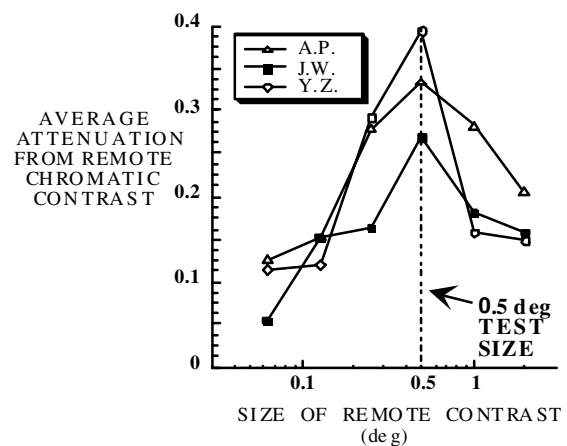
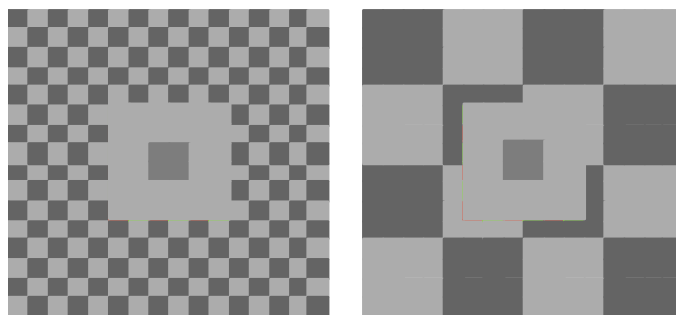


Figure 3. Left: Schematics of stimuli with checks smaller or larger than the test field. Right: Change in color appearance measurements caused by varying the size of the chromatic checks within the remote region, for 3 observers. The size of the central test is indicated by the dashed vertical line.

### Locus of Neural Mechanism

Chromatic variation in the remote checkerboard was found to act at a cortical locus, by demonstrating interocular transfer and an effect of binocular retinal disparity. The stimuli used to test for interocular transfer are shown schematically in Fig. 4. Conceptually, the question is whether remote contrast, presented to one eye, affects the color of a test-within-surround, presented to the other eye. The actual stimuli, however, are slightly more complicated in order to achieve rigid binocular fusion of the different lights presented to each eye. As shown in the top pair of Fig. 4, the left-eye stimulus is the usual test-within-surround, now with a remote checkerboard at 10% contrast. A thin dark gap between them avoids rivalry. The right-eye stimulus is only the remote checkerboard with 10% contrast. The bottom pair is the same in the left (test) eye but now the checkerboard in the right eye is at 100% chromatic contrast. How does raising remote chromatic contrast in one eye affect the appearance of the test-within-surround in the other eye?

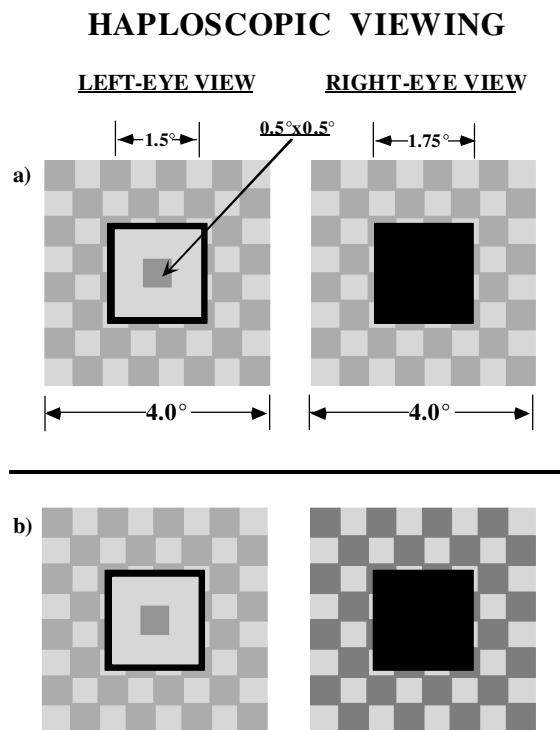


Figure 4. Schematic of stimulus used to test for interocular transfer. The test, uniform long-wavelength surround, and remote region with 10% contrast were presented to the left eye. Only the remote region was presented to the right eye, at either 10% contrast (above) or 100% contrast (below). The fused percept was the test and surround within a single fused checkerboard.

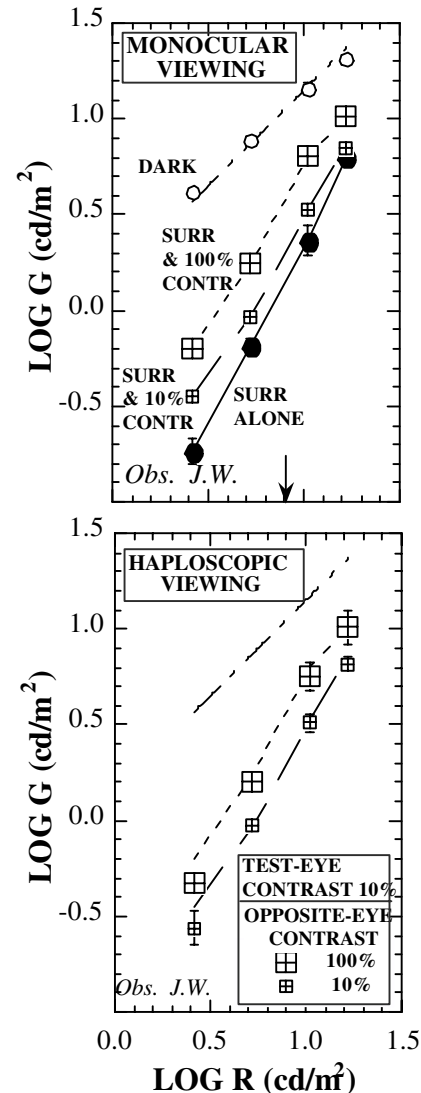


Figure 5. Above: Monocular measurements of the G and R phosphors in the test that appeared neither reddish nor greenish, with the test alone (open circles), the test within a uniform long-wavelength surround (filled circles), or the test-within-surround presented with 10% (small squares-with-plus) or 100% (large squares-with-plus) remote chromatic contrast. Below: As above but with remote chromatic contrast in the left (test) eye fixed at 10%. Remote contrast in the contralateral eye was either 10% (small squares-with-plus) or 100% (large squares-with-plus). The lines are replotted from the monocular results above (they are not fit to the measurements).

The answer is remarkably simple: raising remote contrast has the same effect, whether presented to the same eye as the test or the contralateral eye. The top panel of Fig. 5 shows monocular measurements for one observer (for additional observers and more detail, see Shevell & Wei, 2000), (i) under dark adaptation (test alone), (ii) with the test-within-surround (no remote contrast), (iii) with

remote contrast at 10% and (iv) with remote contrast at 100%. As before, raising remote contrast monocularly from 10% to 100% reduced chromatic induction from the long-wavelength surround (larger squares-with-plus above smaller squares-with-plus). The critical measurements are in the bottom panel of Fig. 5, where the lines from the monocular measurements for 10% and 100% remote contrast are redrawn from the top panel. The data points in the bottom panel are measurements with contralateral remote contrast at 10% or 100%, and fall on the lines for the monocular measurements (in the bottom panel, the lines are *not* fit to the data points). Raising remote contrast from 10% to 100% in either eye has the same effect.

## Conclusions

The experiments presented here are explained by early contrast coding at boundaries within a scene, followed by a central chromatic-contrast gain control regulated by chromatic variation over a relatively large area. The measurements demonstrate for visual processing the fundamental nature of chromatic variation within an image. One reason the equivalent background principle cannot explain color perception in complex scenes is that any uniform background, regardless of luminance and chromaticity, has no variation within it. A contrast gain-control mechanism, regulated by contrast, responds differently to a complex field containing chromatic variation than to a uniform field without variation.

The emphasis on contrast is not meant to exclude other mechanisms of visual adaptation. For example, receptor sensitivity change and optical light spread within the eye can affect the appearance of one light presented in the context of others. In the natural world, the visual system must adapt over a luminance range of more than 1,000,000:1. A typical image, on the other hand, has a dynamic range on the order of 100:1, and this is where adaptation to contrast is an important factor affecting color perception.

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## Biography

Steven Shevell is chair of the Perception Program and a professor in Psychology and Ophthalmology & Visual Science at the University of Chicago. He studies human color perception, ranging from the genetics of abnormal color vision to neural processes of eye and brain. He received an A.B. in psychology and an M.S. in engineering from Stanford University in 1973, and a Ph.D. in mathematical psychology from the University of Michigan in 1977. He is a fellow of the Optical Society of America and editor of the OSA's new edition of *The Science of Color*, to be published next year.