Partial color constancy of isolated surface colors examined by a color-naming method

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Abstract. Color samples selected from the OSA Uniform Color Scales set were viewed without any surround. Separate light sources were used to illuminate the samples and to control the state of adaptation of the subject, thereby separating two factors that are normally confounded. A color-naming procedure was used to assess shifts in color appearance produced by altering the spectral distributions of one or both light sources. The results confirm that chromatic adaptation, when it is the only factor operating, can mediate partial color constancy.

1 Introduction

Mechanisms of color constancy, in which there has been a recent revival of interest, can be divided broadly into two categories: (i) von Kries's chromatic adaptation, and (ii) computational mechanisms dependent upon the spatial complexity of the stimulus. (See MacAdam 1970, pages 101-126, for translations of relevant passages from a selection of work published by von Kries between 1878 and 1910.) Although von Kries himself considered various possible complications, the basic idea is very simple. For example, when unbalanced in the long-wavelength direction, the power spectrum of an illuminant produces two effects that tend to cancel each other. One of these is the alteration, in favor of long wavelengths, of the spectral distribution of light reflected from the surface of an object, thereby making the surface seem redder than before. The other is the adaptation of the eye to the same unbalanced spectrum, thereby resulting in a selective reduction in the sensitivity of L-cones, making the object seem less red than it otherwise would. Thus the increase in long-wave input to the eye tends to be compensated by the selective reduction of L-cone sensitivity. In this paper we are concerned with chromatic adaptation more generally, including that which occurs at receptor level and at subsequent stages of visual processing. We do not attempt to distinguish between these stages.

Current opinions differ rather widely on the importance of chromatic adaptation as a mechanism of color constancy. It is considered the major mechanism of color constancy by some authors, as revealed for example by the following statement by Werner and Walraven (1982):

> "The significance of the von Kries type of sensitivity control is self-evident ... since it provides a mechanism for maintaining the approximate color constancy of the visual system ... ." (page 942).

On the other hand, color constancy mechanisms that do not depend upon chromatic adaptation have been stressed by computational vision theorists, starting with Land and McCann (1971). For example, Maloney and Wandell (1986) play down the possible role of chromatic adaptation, and consider instead how the distribution of light reflected

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¶ Address at which the research was carried out.

from surrounding surfaces in the visual field could serve to aid color constancy for a test object, even for an eye in a constant adaptive state. Brill and West (1986) explicitly question the relevance of chromatic adaptation as an important mechanism of color constancy.

In the experiment reported here, we have isolated reflecting color samples which, when illuminated by hidden projectors, appear self-luminous against a dark background. In this situation, color constancy must fail completely for the dark-adapted eye, because no basis exists for disentangling the relative contributions of surface and illuminant to the spectral power distribution of light reaching the retina by reflection from the isolated color sample.

Ordinarily, a change in illumination alters the spectral distribution of reflected light both from the surface being judged and from surrounding surfaces. Light reflected from these surrounds primarily determines the adaptive state of the eye, but it also produces a context of surrounding colors that could provide a basis for partial color constancy, even for an eye in a constant adaptive state. These two classes of effects are normally confounded and difficult to separate. Our experiment allowed the independent manipulation of illuminant and adaptational state required to study the effects of chromatic adaptation in pure form, without contextual complications.

2 Rationale

If color constancy were perfect, then by definition the colors of reflecting surfaces would appear identical when seen under different sources of illumination. Because time is required for adaptation to occur, the comparison of colors seen under two different conditions of illumination cannot be made simultaneously. Therefore, as the illumination is changed, for example when going from sunlight to artificial light, one's impression of the extent to which the colors of things appear either to change or not to change depends upon memory for color. In an evaluation of completely isolated stimuli, the use of a comparison field, which otherwise might be used to eliminate the need for memory, would itself provide context that must be avoided.

We have chosen to evaluate color appearance by means of a color-naming procedure that requires the examination of real surface colors seen without surround colors or comparison fields. The method is derived from the discovery by Berlin and Kay (1969) of eleven basic color terms that are used to refer to eleven basic color sensations that seem to be common to all humans with normal color vision (Ratliff 1976). In English, the basic color terms are: white, gray, black, red, green, yellow, blue, orange, purple, pink, and brown. In previous publications, it has been shown with groups of American and Japanese subjects that all the basic color terms are used more quickly, more consistently, and with greater consensus than any other color terms (Boynton and Olson 1987; Uchikawa and Boynton 1987). Using the method described below, the centroids of regions of color space occupied by each color have been determined in these studies. In the present experiment we have examined the shifts in centroid location that occur as a function of changes in the spectral character of two sources of illumination. One of these, the 'outside' source, illuminates the surface colors seen by the subject. The other, the 'inside' source, is used to control independently the state of chromatic adaptation of the subject.

3 Method

3.1 *Subjects*

Two individuals with normal color vision served as observers. One was American and the other Japanese (the first and third authors, respectively).

3.2 *Stimulus materials*

The Uniform Color Scales set of color samples, available from the Optical Society of America (OSA),(1) was developed in an attempt to sample three-dimensional subjective color space uniformly (Nickerson 1981). The colors are organized around a central gray specimen which plots at the origin of the system, where $L = j = g = 0$. The lightness dimension, L, is plotted vertically and the sampling of colors is made at thirteen levels, labeled from -7 to $+5$. Colors located at level -7 appear dark and are sometimes called black; those at level $+5$ are very light and are sometimes called white. At each level of L, colors are arranged in two dimensions, orthogonal to each other and to the L-dimension, called j (roughly yellow-blue) and g (roughly red-green). Each of these dimensions varies from the origin either positively (toward yellow or green) or negatively (toward blue or red). Each sample is intended to be equidistant from its twelve nearest neighbors. We have shown (Boynton and Olson 1987) that the centroid locations of basic colors are arranged within this space in a regular and reasonable way when the samples are viewed against a neutral gray background of 20% reflectance illuminated by a tungsten light source of 3000 K equivalent color temperature.

In the present experiment, the colors were limited to the two hundred and fifteen samples that occupy the even-numbered OSA lightness levels ($L = -6$ to $+4$). In other experiments (Olson 1988) it has been shown that this so-called 'half set' of two hundred and fifteen colors is sufficient to yield results that differ in no important way from those obtained with the full set of four hundred and twenty four colors.

3.3 *Apparatus*

Figure 1 illustrates the apparatus that we constructed for the present experiments. A test sample, placed by hand on a vertical floor-mounted pipe, was illuminated by two slide projectors. The projectors flanked the color sample, with beams of 90° to the subject's line of sight, and aimed downward toward the sample at an angle of about 45°. This will be referred to as 'outside' light, because it illuminates the color sample located outside the viewing booth. The specular component of reflection from the sample was at right angles to the subject's line of sight, and therefore invisible to the subject. The

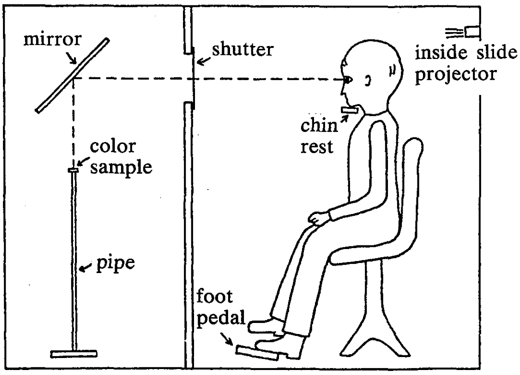

Figure 1. Schematic view of the experimental arrangement. Except for calibration purposes, the color sample was mounted directly on top of the pipe and there was no surround. The projectors used to illuminate the color sample are not shown. The 'outside' lights were furnished by two slide projectors flanking the color sample, with beams at 90° to the subject's line of sight, each aimed downward toward the color sample at an angle of about 45°. The 'inside' (adapting) light was provided by the inside slide projector.

(1) The OSA Uniform Color Scales samples, including a supplemental set of one hundred and thirty-four intermediate samples which cover the near-neutral region of colors of middle lightness (not used in this study), are available from The Optical Society of America, 1816 Jefferson Place, Washington DC 20036, USA.

test sample, which from the subject's vantage obscured the view of its support, was viewed binocularly at a distance of 133 cm, where it subtended 130 min visual angle. The presence of suitably shaped apertures in the slide planes of the projectors meant that the beams from the outside projectors escaped beyond a sample only to the extent necessary to ensure that it was fully and uniformly illuminated. Where necessary, black felt was used to absorb this light, as well as the specular component of reflection from the surface of the color sample.

A mirror was placed at an angle of 45° above the test sample so that the square patch of color was seen in a vertical orientation in a completely dark space, directly in front of the subject, and without any visible means of support—a circumstance so unlikely for a real reflecting surface that several visitors, when placed in the experimental situation, have been convinced that they were seeing self-luminous colors, produced in some unknown way. Even for the three of us who knew otherwise, this illusion was difficult to escape.

Sitting in a lightproof booth and positioned by means of a chin rest, the subject saw the test sample binocularly through a 17 cm by 15 cm opening in a gray panel located 60 cm in front of his head. A large shutter, when held in its upper position, filled the viewing aperture. The front section of the booth, and the shutter, were painted with several coats of flat gray paint (PPG 4752 'Gray Velvet') of almost perfectly uniform reflectance (20%) at all visible wavelengths. The 'inside' light, used to control the subject's state of adaptation, was provided by a third projector which illuminated the front panel (including the shutter area) to provide an adapting field.

Some of the color chips used as samples exhibited tiny defects at their edges that exposed their white substrate; these bright white specks were eliminated by careful application of black paint so that, when illuminated, only the appropriately colored surfaces of the samples were perceptible.

3.4 *Procedure*

The observer was adapted to the illumination inside the booth for 5 min at the beginning of each session. On each trial, the experimenter placed the test sample in position and signaled to the subject, who then released a foot pedal to allow the shutter to drop. This action also operated a switch to extinguish simultaneously the booth light. The observer responded with any single-word color term that came to mind. No modifiers or hyphenated terms were allowed. After responding (there was no time limit, but the response seldom took more than 2 or 3 s) the observer depressed the foot pedal to close the shutter and restore illumination inside the booth. The experimenter recorded the response on the keyboard of a microcomputer programmed to display the random stimulus order and to allow subsequent analysis of the data entered on each trial (Boynton 1988). After recording a response, the experimenter replaced the color sample in preparation for the next trial.

As shown in table 1, four conditions were studied. For the inside-white, outside-white (IWOW) condition, light from the tungsten-halogen lamps of the Kodak Carousel projectors was attenuated by means of neutral density filters. The chromaticity coordinates of the light reflected from the gray surfaces of the booth (adapting light) were $x = 0.404$, $y = 0.422$, corresponding to a correlated color temperature of about 3600 K. A gray board of 20% reflectance was temporarily placed for calibration purposes in the location normally occupied by the color samples; the outside chromaticity coordinates of this gray board, indicative of the sample illumination, were essentially the same as the gray surfaces inside the booth ($x = 0.407$, $y = 0.417$). For the inside-red, outside-red (IROR) condition, three layers of Kodak Wratten color-compensating filters were placed in front of all three projectors. 'Inside-red' therefore refers to the adapting illuminant, inside the booth, and 'outside red' refers to the illumination falling upon the isolated color sample outside the booth. With the red filters in place, the chromaticities were $x = 0.502$, $y = 0.384$, and $x = 0.503$, $y = 0.382$ for inside and outside measurements, respectively. For the inside-white, outside-red (IWOR) condition, the color-compensating filters were placed in front of the outside projectors only, and for the inside-red, outside-white (IROW) condition, they were placed in front on the inside projector only.

The illumination provided by the projectors was adjusted with neutral density filters so that the gray board placed outside the subject's enclosure appeared equal in brightness to the gray panel inside. For white light, the luminance of the gray boards was 25 cd m^{-2}.

The samples were presented in a random order and, in a later replication, in the reverse of that order. The full rationale for the use of this color-naming procedure is given in Boynton and Olson (1987).

Because of the correspondence between basic color terms in fully-developed languages (recently confirmed for Japanese and English by Uchikawa and Boynton 1987), the basic color names of the two languages can be unambiguously interchanged. The English terms equivalent to the Japanese words used by subject KU are red (aka), green (midori), yellow (ki), blue (ao), orange (daidai), purple (murasaki), pink (momo), brown (cha), white (shiro), gray (hai), and black (kuro). A variety of nonbasic color terms were also used; for analysis these were grouped into a single category called NB.

Table 1. The four conditions used in the study.

Condition	Illumination	
	adaptation (inside)	excitation (outside)
IWOW	white[a]	white[b]
IWOR	white	red[c]
IROW	red[d]	white
IROR	red	red

[a,b] White light comes from the projectors (neutral filters only). The 1931 CIE chromaticity coordinates of the light are: (a) $x = 0.404$, $y = 0.422$; (b) $x = 0.407$, $y = 0.417$.
[c,d] Reddish light obtained using Kodak Wratten color-compensating filters. The CIE chromaticity coordinates of the light are: (c) $x = 0.503$, $y = 0.382$; (d) $x = 0.502$, $y = 0.384$.

4 Results

4.1 *Number of responses*

Figure 2 shows the distribution of response names recorded under the four conditions of the experiment. Consider the color term red for subject RMB as an example, and scan the appropriate collection of four-bar graphs from left to right. The white bar indicates that the term red was used seventeen times under the reference condition (IWOW), where both the illumination of the sample and the state of adaptation of the subject were maintained with white light. Changing the outside light, which illuminated the color sample, to red (IWOR, black bar) increased the number of red responses from seventeen to fifty-eight. Changing the inside light, which affected the subject's state of adaptation, to red while illuminating the sample with white light (IROW, stippled bar), eliminated all but three of the original seventeen responses to red. With red light used both inside and outside (IROR, hatched bar), forty red responses were recorded, a partial shift back toward the original seventeen responses of the reference condition IWOW. Although the absolute values vary, this response pattern is the same for orange and pink. Illuminating samples with red light decreases the numbers of white, green, and blue responses. Adaptation to red light increases the frequency of their use, but again does not restore the values to those of the reference IWOW condition.

The terms brown and black were almost never used. The frequency of responses of yellow, purple, and gray were not much affected by the experimental operations.

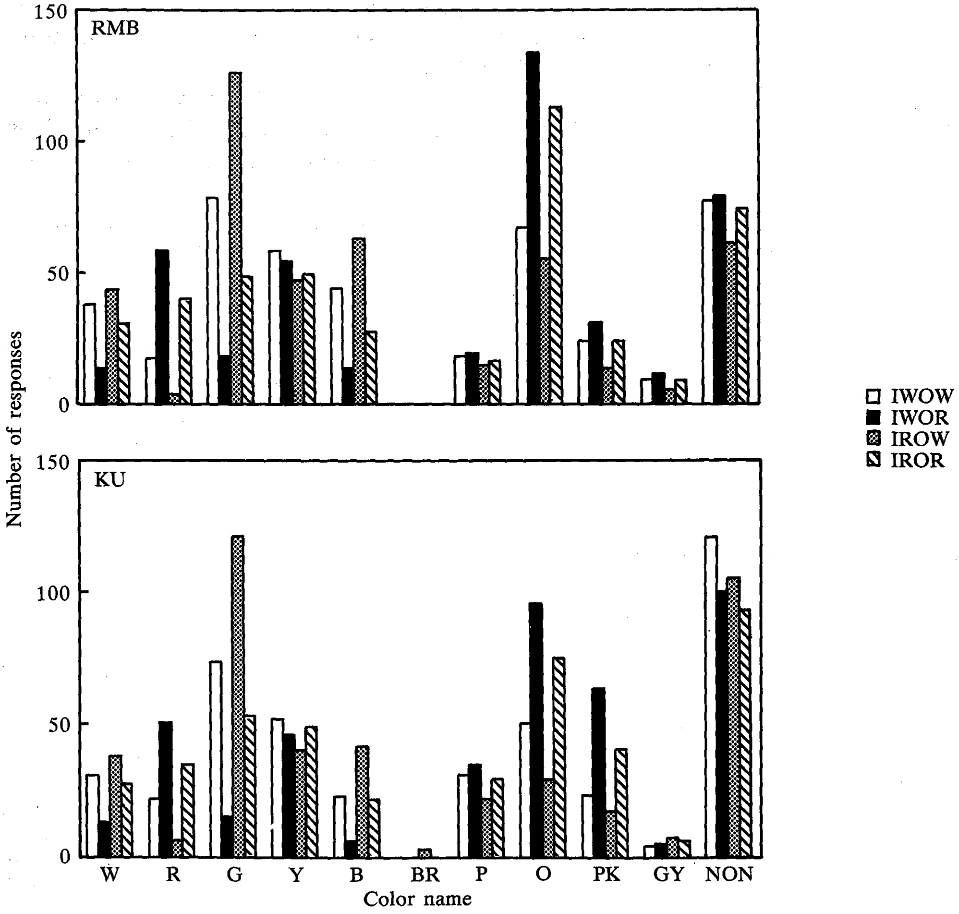

Figure 2. Distribution of color-name usage for the four conditions of the experiment, shown individually for the two subjects. Condition IWOW means that the inside adapting light and the outside light that illuminated the color samples were both white; IROR that both lights were reddish, as modified by color-compensating filters; IWOR and IROW that one of the lights was white, the other reddish. W, white; R, red; G, green; Y, yellow; B, blue; BR, brown; P, purple; O, orange; PK, pink; GY, gray; NON, nonbasic color terms.

4.2 *Centroids*

The distributions of response frequency tell only part of the story, as they do not show specifically the pattern of category shifts in the use of basic color terms. The centroid statistic is useful for this purpose. It is computed by summing individually the L, j, and g values of all samples named by the basic term being analyzed, weighted according to frequency of use (once or twice). The centroids for the two subjects are plotted in figure 3. As an example, consider the effects of the various experimental conditions on the yellow centroids for subject RMB. The filled square, indicated by an arrow, shows the centroid for the reference condition IWOW, plotted in the j, g plane of the top panel. (The lightness level L is plotted as a function of j in the lower panel.) Centroid values for L do not change much with conditions, but those in the $j-g$ plane shift considerably. Illuminating the samples with red light (IWOR, black diamond) shifts the centroid in the $+g$ direction. Adapting the subject to red light (IROW, open diamond) produces a shift in the opposite direction. Combining these (IROR, open square) brings the displaced centroid of the IWOR condition back toward the reference position, but only part of the way. This pattern repeats in much the same way for all the color categories, with good agreement between subjects.

Comparison of figures 2 and 3 indicates that the shifts of the yellow centroids occur without a significant change in the number of yellow responses. This implies that the set of samples called yellow tends to shift as a group in the direction of *g*. On the other hand, large increases and decreases in the numbers of red responses are correlated with only modest centroid shifts. This indicates that many of the added red responses are recruited from samples that are located in flanking regions parallel to the *g*-axis.

In sum, changes in response frequency and centroid location are both useful for gauging the effects of changes in illuminant or adaptation. In all cases, where one of these statistics is not very sensitive to the effects of such changes, the other one is.

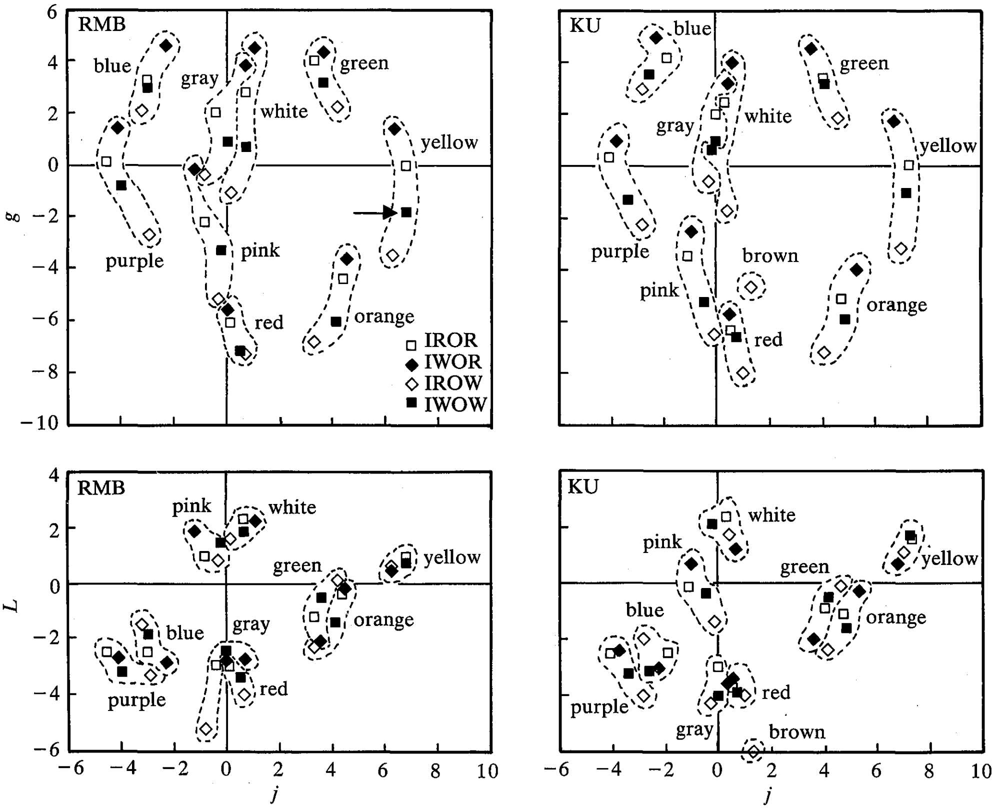

Figure 3. Centroid locations of the basic colors for the four conditions of the experiment, shown individually for the two subjects. Conditions are explained in the text and in the legend to figure 1. The centroid indicated by an arrow (for the reference condition IWOW for subject RMB's responses of yellow) is discussed in the text.

5 Discussion

The data presented here show that most isolated samples of surface colors, except brown and black, which disappear, can be 'correctly' identified when they are illuminated with white light. In the present study we changed the perceived colors of the samples in two ways, either of which should have altered the balance of L- and M-cone excitations elicited by the retinal images of the color samples. One procedure was to change the adaptation of the subject by altering the 'inside' light; the other was to change the illumination of the samples by altering the 'outside' light. In both cases we did this by using color-compensating filters that shift the spectral power distribution toward long wavelengths. As expected, more samples were then called red, and fewer were called green. Centroids shifted in the green direction (toward $+g$), showing that samples that would appear relatively greener in white light were now required to define the middle of the region within which a color name is applied. For example, because a color chip that appears pure yellow in white light will appear orange-yellow in the reddish light, to regain pure yellow a color chip that would appear greenish yellow in white light must be displayed.

The key question related to color constancy concerns what happens when the reddish illumination of the samples is compensated by appropriate reddish adaptation of the eye. If color constancy were complete, the results for this condition (IROR) would be the same as for the reference condition (IWOW), where white light is used both for illuminating the color sample and to adapt the subject. By the criterion of either color-name frequency or centroid shift, and sometimes according to both, the actual result is intermediate for all color names used. Chromatic adaptation is therefore demonstrated to be a mechanism for producing partial color constancy.

The centroid shifts in the j, g plane are apparently reliable, because all eighteen centroid shifts (nine colors for two subjects) are of the same type: toward green with a switch from white to reddish illuminant, part of the way back toward red ($-g$) if red adaptation is added, and toward red if reddish adaptation alone is used. Colors whose initial centroid values plot at negative g values show an increase in response frequency as more greenish samples are recruited. Red, orange, and pink behave in this way. For colors whose centroid values plot at positive g values, the centroid shifts toward green require a decrease in response frequency because there are no samples with even more positive g values to recruit, while samples nearest to $g = 0$ no longer appear greenish and therefore tend to drop out. Blue, which also plots at a positive g value, shows this result along with green. For white and gray, which initially plot near the origin, the data show a pattern similar to that for blue and green.

Purple and yellow are the colors whose centroids normally plot nearest the g-axis. For purple, as already described for yellow, there is little change in response frequency. Instead, the entire region in the j, g plane within which these names are used shifts in the green ($+g$) direction.

There exist several possibilities for extending this work. For example, the extinction of the adapting light prior to presentation of the color samples must have allowed part of the adaptive effect of that light to dissipate. Therefore our results will tend to underestimate the extent to which chromatic adaptation can help to maintain color constancy. A systematic examination of the effects of varying intensity levels of preadaptation, and of time between extinction of the inside light and presentation of a target for judgement, could help evaluate the extent of this effect. As noted in section 1, there are other factors that could maintain some degree of constancy, given the presence of many reflecting samples in the environment. Adding such samples to the display, while maintaining selective control over excitation and adaptation, could be another step in our research program. And, of course, we have examined only one modification of the spectral distribution of white light; others need to be tested also.

Finally, it should be pointed out that all aspects of this experiment could, in principle, be simulated by means of an emissive (eg color TV) display. Indeed, when the present experiment was reported at ARVO (Boynton et al 1988) the presentation followed three others in the same session in which color constancy has been studied using emissive displays to simulate surface colors (Blackwell and Buchsbaum 1988; Brainard and Wandell 1988; Reeves et al 1988). It is perhaps ironic that, whereas our presentation was about surface colors that looked like emissive ones, the others were about emissive displays designed to simulate surface colors. Simulations of surface colors in emissive displays require expensive equipment and involve extensive calculations. There may yet be something to be said for studying the perception of surface colors by actually using them.

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