Simultaneous color constancy: papers with diverse Munsell values

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Arend and Reeves [J. Opt. Soc. Am. A 3, 1743 (1986)] described measurements of color constancy in computer simulations of arrays of colored papers of equal Munsell value under 4000-, 6500-, and 10,000-K daylight illuminants. We report an extension of those experiments to chromatic arrays spanning a wide range of Munsell values. The computer-simulated scene included a standard array of Munsell papers under 6500-K illumination and a test array, an identical array of the same papers under 4000 or 10,000 K. Observers adjusted a patch in the test array in order to match the corresponding patch in the standard array by one of two criteria. They either matched hue and saturation or they made surface-color matches, in which the test patch was made to “look as if it were cut from the same piece of paper as the standard patch.” The test and the standard patches were surrounded by a single color (annulus display) or by many colors (Mondrian display). The data agreed with those of our previous equal-value experiment. The paper matches were often approximately color constant. The hue-saturation matches were in the correct direction for constancy but were always closer to a chromaticity match (no constancy) than to the chromaticity required for hue–saturation constancy.

INTRODUCTION

Color constancy refers to invariance of perceived surface colors under changes of illuminant color. In recent years there has been renewed interest in color constancy. Most of this new research has been theoretical: analyses of theoretical limits of color constancy and proposals for computational strategies. Empirical studies of simultaneous color contrast and chromatic adaptation are not directly interpretable in terms of surface-color constancy for several reasons discussed below.

We have recently begun a series of experiments specifically designed for directly examining human color-constancy capabilities in complex images. Our observers viewed a computer-simulated scene consisting of two identical arrays of patches of Munsell papers. The standard array was illuminated with a constant source. The test illuminant varied from trial to trial. Observers adjusted one patch in the test array in order to match the corresponding patch in the standard array.

Our experiments improved on previous studies in several ways:

(1) We made a clear procedural distinction between two kinds of judgment. The first is judgment of the hue, saturation, and brightness of the light that is coming to the eye from a point in the scene. We will refer to this variable as unasserted color, short for perceptually unasserted color. Our observers were instructed to match the hue, saturation, and brightness of the test patch to those of the standard patch, disregarding all other areas as much as possible. The second kind of judgment is judgment of surface color, a property of the surface at a point in the scene. The observers were instructed to make the test patch look as if it were cut from the same piece of paper as the standard patch.

Color constancy refers to perception of surface color rather than to sensory appearance. Under some viewing conditions there may be a close correspondence between perceived surface color and unasserted color. Under other conditions there may be a discrepancy. Indeed, one can imagine two kinds of visual system, both having perfect color constancy but producing two different appearances: A surface might produce identical hues, saturations, and brightnesses under different illuminations, with no direct sensory representation of the illumination difference. Alternatively, the surface might produce different unasserted colors but be recognized as the same surface under perceptibly varying illumination. For example, consider a yellow surface in the greenish illumination under a tree. In the first kind of visual system it would produce the same hue as a yellow...
surface under full sunlight. In the second visual system it would have a yellowish-green hue (easily distinguished from the full-sunlight hue) that is correctly perceived to be a yellow surface in greenish illumination.  

(2) We limited chromatic adaptation to rapid processes, with time constants less than 1 sec. When integrated over time intervals of the order of minutes, exposure was constant, preventing changes in slow adaptation processes. The distinction between rapid and slow adaptive processes has a long history in vision research.11,12  

Rapid constancy mechanisms are needed in natural vision. Shading and indirect illumination make uniformly illuminated scenes rare, and eye and head movements change focal scenes rapidly. Slow adaptation cannot be appropriate for all regions in a single scene and alters sensitivity too slowly to compensate for natural environmental scanning. Chromatic illumination varies from surface to surface within scenes because of variation in surface orientation with respect to various light sources. The illumination variation can be as large as chromatic reflectance differences. For example, Maximov13 has shown that a yellow dandelion blossom in north skylight has the same chromaticity as grass in direct sunlight. Even larger chromatic illumination changes can occur when an object is partially illuminated by light that has been reflected from nearby colored objects.

(3) We used identical reflectances in the test and standard arrays. By providing the same reflectance context for the test and standard patches, we limit the experimental independent variable to illuminant color.  

In our first experiment9 we studied simultaneous lightness constancy and brightness in simple and complex achromatic patterns. We found that matches of the brightness of a gray test patch varied substantially as the illumination level changed, but matches of its surface color, i.e., lightness matches, were remarkably invariant over our 19:1 illumination range. The need to distinguish lightness from brightness has often been noted but has also often been neglected in discussions of constancy. The consistency of our observers' data further confirms the multidimensionality of achromatic color perception.  

In a second experiment we studied simultaneous constancy in simulations of chromatic papers and illuminants. Our illuminants spanned the chromatic range of normal daylight. We wished to examine the effect of chromatic interactions independent of any effect of luminance variation. We therefore kept the luminance range small by simulating only Munsell papers of Value 5.

The observers' unasserted color matches were slightly shifted in chromaticity from the chromaticities of the standard patches. While the shifts were mostly in the correct direction for constancy of unasserted color, in all cases they were small relative to the shifts required for invariance of unasserted color. On the other hand, our subjects' surface-color matches did approximate constancy of perceived surface color, though not nearly so precisely as in the achromatic case. Nevertheless, the data qualitatively agreed with the achromatic data: Our observers had approximate constancy of perceived surface colors in spite of substantial differences of unasserted colors.  

Various studies of simultaneous color contrast in simple patterns differ regarding the effects of luminance differences. Some early investigators found maximum induced hue and saturation when the luminances of the test field and inducing fields were equal,15 while more recent researchers have reported either larger effects when the test-field luminance was below that of the inducing field16-18 or no effect of luminance.19 It is therefore possible that unasserted color might be closer to constancy if there were larger luminance differences among the color patches.

We report here extensions of our experiments to simulated patterns of colored papers spanning a wide range of luminous reflectances. As in the earlier experiments we used both simple and complex patterns, and we asked for separate matches of unasserted color and perceived surface color. We also report a control experiment in which we presented the patterns in brief flashes. A comparison with the previous experiments provides a measure of the effectiveness of the voluntary-eye-movement control of adaptation used in those experiments.  

METHODS  

Equipment  

The equipment was that used in the previous two experiments. Details of the equipment are reported elsewhere.13 All patterns were presented on a carefully calibrated Tektronix 690SR high-resolution color monitor under the control of an Adage 3000 image processor and a VAX 11/750 minicomputer. Chromaticities were based on measurements of the spectral radiances of the phosphors. Chromaticity and luminance did not vary appreciably over the effective viewing area. Nonlinearity of the relationship between digital data and luminance was measured in each color channel individually and linearized by means of 10-bit lookup tables.

Subjects controlled the color of the test patch with a high-resolution graphics tablet. The position of the bit-pad pointer was interpreted by the computer as a position within an RGB color triangle, and the test-patch chromaticity was set accordingly. Vertical cursor movement controlled yellow-blue content and horizontal movement controlled red-green content. The luminance of the test patch increased at a constant logarithmic rate when the subject held down one of two buttons on the bit-pad pointer and decreased when another was depressed. Between trials the computer randomly offset the luminance and the horizontal and vertical positions of the color mapping on the bit pad within a range of ±10% in order to prevent position cues from influencing the matches. The spatial resolution of the bit pad exceeded the 10-bit resolution of the image processor's digital-to-analog convertors.  

Stimuli  

The stimuli were simulations of arrays of uniformly illuminated, flat, matte Munsell papers; i.e., there were no highlights or shadows, and the stimulus appeared flat. Chromaticities and luminances of the 32 papers used, under three daylight illuminants (4000-, 6500-, and 10,000-K correlated color temperatures), were based on the published tables of Kelly et al.20 The 4000- and 10,000-K illuminants represent the reddish and bluish extremes of daylight, and 6500 K represents average sunlight.
Since the tables did not include entries for the desired daylight simulations, we obtained the required chromaticities by means of an interpolation algorithm. The logic of the simulation is based on superposition of lights: Conceptually, the 4000- and 6500-K correlated color temperature white lights were obtained by mixing appropriate amounts of illuminants A and C used by Kelly et al. and the 10,000-K light by mixing their sources S and D. The light reflected from each of the 32 papers under, for example, the 4000-K light is just the sum of the reflected lights from the A and C illuminant components of the 4000-K source. In practice, tristimulus values for the simulated paper-illuminant combinations were obtained by linear interpolation between the tabulated tristimulus values for illuminants A, C, D, and S. The required ratios for the mixtures of the sources were obtained by using correlated color temperature lines. The resulting chromaticities were produced on our monitor and will hereafter be referred to by the names of the simulated papers (Munsell notation\textsuperscript{22}) and daylight illuminants.

The disk-annulus stimuli are illustrated in Fig. 1(a) and the Mondrian stimuli in Fig. 1(b). The left-hand display (standard) was given a simulated illumination of 6500 K on all trials, the right-hand display (test) either 4000 or 10,000 K. The papers were chosen to provide as large and as uniform coverage of the Munsell set as possible, given the constraint that the color gamut of our monitor must simulate all the selected papers under all illuminants. The size and chroma composition of the patterns [Fig. 2(a)] was the same as in our constant-value experiment,\textsuperscript{1} with the exception of a few patches that were made black in order to span the entire range of physical luminous reflectances.

Figure 2(b) gives the pattern luminances. Two luminance-contrast conditions were run for each pattern complexity, one in which the test-patch luminance exceeded the...
pattern mean luminance and one in which it was less than the mean luminance. In the disk–annulus condition the annulus luminance was either a factor of 4.4 greater or a factor of 4.4 less than the test-disk luminance. In the Mondrian condition two arrangements of test-patch luminances were used. In one condition (luminance arrangement 1) the red- and yellow-test-patch luminances were greater than the Mondrian mean luminance and the blue- and green-patch luminances were less than the mean luminance. In the other (luminance arrangement 2) the luminance relations were reversed, with the blue and green patches above the mean luminance, the red and yellow below the mean luminance. All other patch luminances were the same in the two conditions. In the second condition the yellow test patch had the expected yellow-brown appearance.

Our three illuminants were simulated at the same illuminance. Thus the only effect on test-patch luminance of changing the illuminant was that resulting from interaction of the illuminant spectral distribution and the paper spectral reflectance distribution. As can be seen from the values in Fig. 2(b), these were small because of the broad spectral distributions of the papers and lights simulated.

Procedure
At the beginning of the first session the method of controlling chromaticity and luminance was explained to the observers, who were then given approximately 1 min of practice with the controls and asked whether they understood how they were used.

Observers initially adapted to a spatially uniform field, 6500 K, 20-cd/m² white, for 3 min. They then viewed the continuously presented test and standard arrays and varied the chromaticity and luminance of the test patch in order to match the corresponding standard patch. Observers were requested to spend approximately the same amount of time looking at each display and to alternate between the displays approximately once per second. Trials for the five different test patches, red (Munsell R 5/8), yellow (Y 5/4), green (G 5/4), blue (B 5/4), and gray (N 5/), occurred in pseudorandom order, once under 4000 K and once under 10,000 K, in each of the five blocks of trials.

Task
In the unasserted-color condition, observers were instructed to match the hue, saturation, and brightness of the test patch to those of the standard patch. They were told to disregard, as much as possible, other areas of the screen.

In the perceived-surface-color condition, observers were told that the two displays were a simulation of identical paper arrays illuminated by different lights. They were instructed to make the test patch "look as if it were cut from the same piece of paper" as the corresponding patch in the standard array. It was pointed out that other patches in the Mondrians had similar colors (there were no patches identical to the test patch) and that the relations among such groups might be useful. Hence, they could (for example) match the standard red at 6500 K with the corresponding test patch at 10,000 K by comparing the standard patch with other reds (or oranges or violets) within the 6500-K standard and then transposing the relevant relations to the 10,000-K display.

Since three of our four observers (LA, AR, JS) were the authors, they were familiar with the tasks. For them, the instructions merely served as reminders for the fixation procedures and use of relations among patches. The fourth observer (DA) was unaware of the hypotheses and had no prior experience with chromatic adjustments (he had experience as a subject in achromatic matching experiments). A fifth subject, also naïve, was run in one session each of the unasserted-color and apparent-surface-color tasks. Her data are not reported here as they were not complete and closely resembled the data of three of the other subjects. Both of the naïve subjects found the instructions sufficient for performing the tasks. With no prior training they both produced data with differences between tasks comparable with those of the most experienced observers, LA and AR.

Data Analysis
Plotting Method
Before presenting the data, let us consider our plotting method and the meaning of various data patterns. Figure 3
task would be roughly equivalent to color matching two patches on a dark surround. The subject would set the test patch to approximately the chromaticity of the standard patch, i.e., R 5/8 under 6500 K, in both illuminant conditions [Fig. 3(a)]. In doing so, he would not be setting the patch in the test illuminant to the R 5/8 reflectance of the standard patch which gives the chromaticity indicated by the open triangle. Instead he would set the test patch to the reflectance that, under the test illuminant, gives the same chromaticity as R 5/8 under the 6500-K standard illuminant. In other words, there would be no constancy of surface color.

If the subject had perfect surface-color constancy, on the other hand, he would set the test-patch chromaticity to that of R 5/8 under the 4000-K test illuminant, the open triangle, or, for the 10,000-K test illuminant, to the open square [Fig. 2(b)].

**Constancy Index**

In achromatic surface-color constancy there are several widely accepted, unidimensional indices of constancy, for example, the Brunswik ratio. We have attempted to develop a comparable index of chromatic constancy in order to facilitate comparisons across different experimental conditions. We decided to restrict the index to (primarily) chromatic dimensions and ignore, for the moment, the luminance dimension. Our achromatic constancy experiments indicated that there should be no complications due to lightness variation. Nevertheless we decided to analyze lightness separately in order to eliminate any possibility of luminance matches influencing our chromatic index. Our index is not, therefore, closely related to color difference formulas developed for other purposes. We emphasize that this index is for comparative purposes and is not necessarily optimal from a theoretical standpoint. It is difficult to justify any single scalar index as it requires collapsing a two-dimensional quantity into a single number. Under these conditions we decided in favor of simplicity.

We employed the 1976 CIE $u', v'$ color space, which provides a crude approximation to equal, just-noticeable differences in the region of our primaries. The deviation from color constancy can be represented by the Euclidean distance $b$ from the match point $P_0$ to the chromaticity $P_2$, at which color constancy would be perfect [Fig. 3(c)]. That is,

$$b = [(u'_0 - u'_2)^2 + (v'_0 - v'_2)^2]^{1/2}.$$  

(1)

The different test patches may be made comparable by dividing each $b$ by the Euclidean distance $a$ between the chromaticity $P_1$ of the test patch when illuminated by the 6500-K standard and the chromaticity $P_2$ of the same patch under the comparison illuminant:

$$a = [(u'_1 - u'_2)^2 + (v'_1 - v'_2)^2]^{1/2}.$$  

(2)

Our chromatic constancy index is then

$$I = 1 - b/a,$$  

(3)

the distance from constancy relative to the colorimetric shift of the test patch, averaged over the five test patches. Perfect constancy is indicated by $I = 1$, and a chromaticity match between test and standard patches (no constancy) is indicated by $I = 0$.  

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### Fig. 3. Diagram of logic of data graphs: (a) appearance of data in case of almost no color constancy, (b) appearance of data in case of nearly perfect color constancy, (c) distances used in calculation of constancy index ($= 1 - b/a$).
Fig. 4. Mean-chromaticity settings for Mondrian patterns, first luminance arrangement: open symbols, theoretical chromaticities; closed symbols, mean-chromaticity data. The left-hand column shows unasserted-color matches; the right-hand column shows surface-color matches. The rows present data by observer. Error bars represent ±1 standard error.

RESULTS

Five-trial mean-chromaticity settings for the Mondrian patterns (luminance arrangement 1) are plotted in Fig. 4. The matches in the unasserted-color condition (left-hand panels) were closer to the 6500-K theoretical points than to the test-illuminant theoretical points. Thus, when the test patch was at the correct simulated chromaticity under the test illuminant (open squares or triangles), its unasserted color did not match that of the standard patch. To produce a match, the observer required a chromaticity closer to that of the standard patch. Moreover, the illumination difference between the two displays was always quite visible.

On the other hand, for three of our four subjects the apparent surface-color matches (right-hand panels) were significantly closer to surface-color constancy. Even though the patches in the test displays had different unasserted colors from their counterparts in the standard display, the subjects knew approximately what sensory appearance the standard paper would have under the test illuminant and could set the test patch chromaticity in order to produce it.

This qualitative description is supported by our constancy index (Fig. 5). The unasserted-color matches were closer to a chromaticity match \( I = 0 \) than to constancy \( I = 1 \). By comparison, the surface color matches were closer to constancy. Indices calculated by using data from our equal-value experiments\(^1\) are plotted for comparison.

Means from luminance arrangement 2 Mondrians are plotted in Fig. 6. The pattern of the data is much the same as for luminance arrangement 1, even for the yellow patch with its different appearances in the two conditions (yellow in 1, brown in 2). The constancy indices are similar for the two luminance arrangements (Fig. 7).

Means from both luminance ratios of the disk-annulus patterns are shown in Fig. 8. For all but observer JS's surface-color matches, the constancy index was higher when
Fig. 5. Mean-constancy index for first-luminance-arrangement Mondrians (1st Arr Mond) versus equal-value Mondrians (Equal V Mond): unasserted, unasserted-color matches; surface color, apparent-surface-color matches. Error bars represent ±1 standard error. Equal-value data were previously published.¹

Fig. 6. Mean-chromaticity settings for Mondrian patterns, second luminance arrangement. Symbols, rows, and columns are as in Fig. 4. Error bars represent ±1 standard error.

the annulus luminance was greater than that of the disk (Fig. 9). On the other hand, the effect of the task was inconsistent from subject to subject. For observer AR the difference between the unasserted-color matches and the apparent-surface-color matches was smaller for disk-annulus patterns than that for Mondrian patterns. For LA there was little difference between the two stimulus conditions, and the Mondrian data from our equal-value experiment were no more constant than the disk-annulus data. We tentatively conclude that pattern complexity had little effect on either task.

6500-K–6500-K MATCHES

For analysis of the perceptual meaning of our data the theoretical points described above are the correct reference points; they describe the physical reality. The vectors from the data to the 6500-K point might be slightly misleading as empirical descriptions, however. Matches of a 6500-K illu-
minated test field to the 6500-K illuminated standard field might not fall exactly on the theoretical 6500-K point. Subjects often introduce biases into matches, based on spatial position or based on which field is fixed and which variable.

To examine this issue, we reran the unasserted-color-match condition, using test Mondrian illuminants of 4000, 6500, and 10,000 K. Trials with the three test illuminants appeared once each, in random sequence, in each of five blocks of trials. All other procedures were the same as in the above experiment.

Mean-chromaticity settings are shown in Fig. 10. The matches for the 4000- and 10,000-K illuminants were similar to those in Fig. 4. For all four subjects there were some biases present in the 6500-K–6500-K matches but not for all colors. The R, G, and N matches for all four subjects were close to the chromaticity matches. Two of the subjects' Y matches also showed little bias, but LA and AR both showed biases toward higher purity (relative to the N 6500-K theo-

Fig. 7. Mean-constancy index for first-luminance-arrangement Mondrians (1st Arr Mond) versus equal-value Mondrians (2nd Arr Mond): unasserted, unasserted-color matches; surface color, apparent-surface-color matches. Error bars represent ±1 standard error.
Fig. 9. Mean-constancy index for disk luminance greater than annulus luminance (Disk L > Ann L) versus disk luminance less than annulus luminance (Disk L < Ann L): unasserted, unasserted-color matches; surface color, apparent-surface-color matches. Error bars represent ±1 standard error.

The tendency to set the patch to higher purity makes sense in terms of the observers' introspections. The observers had to be reminded each session to resist the urge to match the hue precisely, at the expense of accurate saturation matching. This bias probably explains a portion of the vectors in Figs. 4 and 5. The problem is clearest in AR's Y point. His vectors to the 6500-K point are misleadingly long with respect to differences among the appearances of the test illuminants. Had we always included the 6500-K test illuminant, we might have often gotten this configuration. Nevertheless, the longer vectors are perceptually correct in the sense that he was actually selecting surface colors that were discrepant from identical surface color.

**FLASHED MONDRIAN EXPERIMENT**

The above experiment and our previous constancy experiments all involved continuously presented displays. In
5-sec 6500 K

1-sec test stimulus

3-min adaption, uniform 6500 K

Fig. 11. Timing sequence in flashed-exposure experiment.

Results and Conclusions
Mean chromaticities from five trials are plotted in Fig. 12. The data closely resemble those from the continuous-presentation experiments. Figure 13 shows the constancy indices for these flashed data compared with the unasserted-color-match instructions.

Methods
The spatial patterns were the Mondrians of our equal-value experiment. All the papers were simulated at Munsell value 5/7, making their luminances approximately equal (=20 cd/m²).

The subjects were preadapted for 3 min to a 6500-K white, spatially uniform field. The test and the standard patterns were then simultaneously presented in 1-sec exposures, in alternation with 5-sec exposures of the 6500-K homogeneous field (Fig. 11). This sequence was continued until the subjects were satisfied with their adjustment of the test patch. A new trial then began with a different test patch.

The subjects adjusted the test patches as in the above experiments, according to the unasserted-color-match instructions.

Fig. 12. Mean-chromaticity settings of flashed Mondrian test patches, unasserted color criterion. Symbols and rows as in Fig. 4. Error bars represent ±1 standard error.
color-match data from the equal-value Mondrian experiment. We conclude that the observers' voluntary eye movements in the previous experiments were sufficient to prevent important slow-adaptation effects.

DISCUSSION

The Mondrian data from the current experiment are substantially the same as those from our previous equal-value experiments, and we conclude that relations among apparent surface colors and unasserted colors in complex patterns are largely independent of the luminance contrast of the scene.

For both experiments our data show that rapid processes alone (e.g., simultaneous color contrast) are insufficient to produce invariance of unasserted color over the range of daylight illuminants. Accordingly, our overall conclusion is that there is little constancy of unasserted color from one illuminant to another within the same scene, provided that the observer scans the scene sufficiently rapidly that slow adaptation is uniform over the retina.

The paper-match data, on the other hand, show that the unasserted-color differences perceived between test and standard Mondrians are systematic. The illumination difference is always visible as a pattern of correlated shifts of unasserted-color. Our subjects' attempts to produce the standard Mondrians no doubt contribute to the stability of this percept, but random rearrangement of the chromaticities in the test Mondrian does not destroy the perception of two illuminants. With the disk-annulus pattern, on the other hand, it was only our instruction, that observers consider the test annulus to be the same gray surface-color under a different illuminant, that permitted the apparent-surface-color-data to resemble those from the Mondrians. Had we described it as a bluish-gray paper under the same 6500-K illumination as the standard annulus, the apparent-surface-color-data would presumably have been much closer to chromaticity matches to the standard disks.

There remain at least two conditions for which there might be large, rapid unasserted-color shifts: single illuminant scenes and scenes with gradual spatial changes of illuminant. None of our experiments would have revealed a simultaneous mechanism normalizing unasserted color over the entire visual field.

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REFERENCES AND NOTES


10. A number of terms have been previously used for similar concepts. To our knowledge, all carry unwanted additional meanings. One will not go far wrong replacing our term with "sensory color," but only the definition here is intended. In particular, we wish to avoid unproductive arguments concerning the meanings of "sensation" and "perception."


13. V. V. Maximov, Transformation of Colors by Illuminant Change (Nauka, Moscow, 1984).


15. This result was stated as Kirschmann’s third law of color contrast: A. Kirschmann, “Uber die quantitativen Verhältnisse des simultanen Helligkeits- und Farben-Contrastes,” Philos. Stud. (Wundt) 6, 417-491 (1890).


22. Data from Kelly et al. refer to the original Munsell notation, and our simulated papers are described in those same terms. Both hue and chroma are somewhat different in the two systems. Our test stimuli, R, G, Y, B, and N, correspond closely to renotation hues 5R, 5G, 5Y, 5B, and N, respectively. The renotation chromas closest to the chromas of our test patches are approximately 2 chroma steps greater than our reported values, e.g., 5R 5/10 for our R 5/8.