

Color Constancy of Red-Green Dichromats and Anomalous Trichromats

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PURPOSE. Color-vision deficiency is associated with abnormalities in color matching and color discrimination, but its impact on the ability of people to judge the constancy of surface colors under different lights (color constancy) is less clear. This work had two aims: first, to quantify the degree of color constancy in subjects with congenital red-green color deficiency; second, to test whether the degree of color constancy in anomalous trichromats can be predicted from their Rayleigh anomaloscope matches.

METHODS. Color constancy of red-green color-deficient subjects was tested in a task requiring the discrimination of illuminant changes from surface-reflectance changes. Mondrian-like colored patterns, generated on the screen of a computer monitor, were used as stimuli to avoid the spatial cues provided by natural objects and scenes. Spectral reflectances were taken from the *Munsell Book of Color* and from natural scenes. Illuminants were taken from the daylight locus.

RESULTS. Protanopes and deuteranopes performed more poorly than normal trichromats with Munsell spectral reflectances but were less impaired with natural spectral reflectances. Protanomalous and deuteranomalous trichromats performed as well as, or almost as well as, normal trichromats, independent of the type of reflectance. Individual differences were not correlated with Rayleigh anomaloscope matches.

CONCLUSIONS. Despite the evidence of clinical color-vision tests, red-green color-deficient persons are less disadvantaged than might be expected in their judgments of surface colors under different lights. (*Invest Ophthalmol Vis Sci.* 2010;51:2286–2293) DOI:10.1167/iops.09-4576

Color vision allows us to judge the colors of objects and surfaces largely independently of the accidental conditions of viewing, whether under the blue light of the sky or the yellow-orange light of the setting sun. The constant appearance of surface colors under different lights (color constancy) is an important feature of color vision and central to the use of color as a biological signaling device.¹ Despite the relevance of color constancy to everyday visual tasks, little has been published on how it is affected by the common inherited color-vision deficiencies.^{2,3}

It might be expected that color deficiency would severely limit the ability of affected persons to make judgments about surface color, the perceptual correlate of spectral reflectance. In fact, the traditional characterizations of inherited color-vision deficiency,^{4–6} used for classification purposes, provide little guide to the extent of color constancy. Although measures linked to particular occupations might seem more promising indicators, they have several practical disadvantages that effectively exclude them.⁷

The principal method of classification of the common inherited color deficiencies is based on matching colored lights. Red-green dichromats, who form approximately 2% of the male population, can match any test color with only two mixture stimuli in proportions that depend on whether they are protanopes, who lack the long-wavelength-sensitive pigment, or deuteranopes, who lack the medium-wavelength-sensitive pigment. Protanopes also have reduced sensitivity to long-wavelength light. Red-green anomalous trichromats, who form approximately 6% to 7% of the male population, generally need a mixture of three stimuli to match a test color, but in proportions different from those chosen by normal trichromats. These abnormal proportions may be quantified by a Rayleigh anomaloscope match in which a monochromatic yellow light is matched against a mixture of monochromatic red and green lights. Protanomalous trichromats require more red light, and deuteranomalous trichromats require more green light.

Red-green dichromats and anomalous trichromats show characteristic losses in their ability to discriminate colors, whether derived from monochromatic or broad-band sources. Thus, the range of acceptable mixtures in a Rayleigh match (the matching range) is often used as a measure of the severity of the color deficit (for a review, see Ref. 5), and the discriminability of printed colors forms the basis for clinical tests such as the Ishihara pseudoisochromatic plates.⁸ Although the Rayleigh match itself (the match midpoint) might be expected to correlate with color-discrimination ability, it has been long known that it is a poor predictor,⁹ and it is inherently difficult to recover cone-pigment properties from match data alone.¹⁰

A more fundamental way of classifying the common inherited color-vision deficiencies is to appeal to genetic data,¹¹ but the relationship between genotype and phenotype is not always obvious.¹²

Although a loss in color-discrimination ability over a portion of the spectrum implies a commensurate difficulty in distinguishing and identifying colored surfaces under a fixed light,^{13,14} this task is not the same as that of judging whether the color of a particular object or region of a scene is constant under different lights. For these judgments, a different measure is needed.

In the laboratory, color constancy may be assessed in several ways (for review, see Smithson¹⁵). No one method is perfect. Simply assigning color names to samples under different lights generally provides insufficient chromatic resolution (many more colors can be discriminated than named). Matching a variable reference sample under one light to a test sample

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under another (asymmetric color matching¹⁶) depends critically on the instructions given to the subject,¹⁷ and adjusting a test surface in a scene so that it appears white (achromatic setting¹⁸) provides information only about the estimated illuminant, to which observers, in other circumstances, can be remarkably insensitive.^{19,20}

An alternative approach to measuring color constancy, which avoids difficult subjective judgments about color appearance,¹⁷ is to use an operational method, requiring discriminations between changes in the illumination on a scene and changes in the reflecting properties of the surfaces comprising it.²¹ With geometric Mondrian-like patterns made up of reflectance spectra drawn from the *Munsell Book of Color*,²² normal trichromats can discriminate between illuminant and reflectance changes rapidly, effortlessly, and with little or no training. Such discriminations can be related to traditional asymmetric color matching with a “paper match” criterion,¹⁶ and levels of recorded color constancy in normal trichromats are closely similar in the two kinds of tasks.¹⁷

This operational approach has been used to measure color constancy in anomalous trichromacy, but with simulations of natural scenes rather than geometric patterns.²³ Natural scenes contain familiar objects with familiar colors, illuminated by light that is partially directional and partially diffuse and that usually produces shadows across surfaces. Object familiarity—shape, texture, and shading—can all influence subjects’ performance through cues that do not depend directly on color-vision function.²⁴ Mondrian patterns lack these cues and so provide a more stringent test of color constancy. The color gamut of natural scenes, however, is constrained: it contains predominantly greens (foliage), browns (earth and dried vegetation), and blues (water and sky),^{13,25} whereas the gamut of the *Munsell Book of Color* is, by construction, larger and more uniformly distributed.^{26,27} The results of an earlier study,²⁸ included for completeness, suggest that the type of spectral reflectances—natural or Munsell—may be important for protanopes’ surface-color judgments, but it is unknown whether this distinction applies to everyone with red-green color deficiency.

The work reported here had two aims. The first was to measure, operationally, how well red-green dichromats and anomalous trichromats judge—in the absence of spatial cues—surface colors under different illuminants. Reflectance spectra were drawn separately from the *Munsell Book of Color* and from the spectra of natural scenes. The second aim was to test whether the degree of color constancy in anomalous trichromats could be predicted from their Rayleigh anomaloscope matches.

It was found that deuteranopes as well as protanopes discriminated illuminant changes from reflectance changes more poorly than normal trichromats with Munsell spectral reflectances but less so with natural spectral reflectances. Protanomalous and deuteranomalous trichromats performed as well as, or almost as well as, normal trichromats with both Munsell and natural spectra, and, critically, individual differences were uncorrelated with their Rayleigh matches.

METHODS

Stimuli

Figure 1 shows images of differently illuminated Mondrian patterns used in the experiment. The patterns consisted of 49 (7 × 7) abutting, 1°-visual-angle square, uniform, simulated Lambertian surfaces with spectral reflectances drawn at random from either the 1269 samples in the *Munsell Book of Color*^{22,29} (Fig. 1, top row) or from 5,379,200 (=820 × 820 × 8) samples in eight hyperspectral images of four urban natural scenes and of four rural natural scenes (Fig. 1, bottom row),

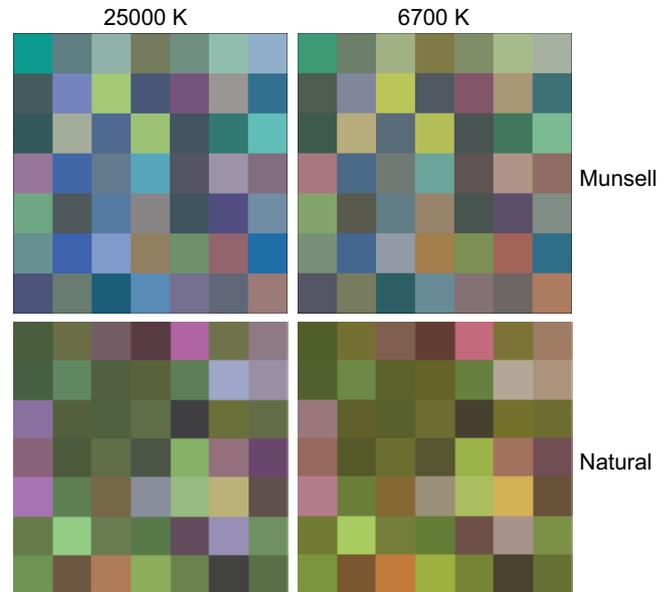


FIGURE 1. Images of Mondrian patterns under different daylight illuminants with correlated color temperatures 25,000 K (*left*) and 6700 K (*right*). The two rows of panels are for the different types of spectral reflectances, Munsell (*top*) and natural (*bottom*).

each measuring 820 × 820 pixels.³⁰ Because reflectances were sampled uniformly, the distribution of colors in the patterns of natural spectra reproduced their natural relative abundances.

The images were generated on the screen of a computer-controlled color monitor (for normal trichromats, the degree of color constancy depends little on whether simulated or real surfaces are used as stimuli). The monitor RGB calculations were based on the appropriate color-matching functions for each group of subjects. For the dichromats and normal trichromats, the Smith and Pokorny³¹ normal cone fundamentals were used. For the protanomalous and deuteranomalous trichromats, Rayleigh match midpoints fell largely into separate groups, and the DeMarco et al.³² calculations for average pigments in anomalous trichromacy were therefore used. Spectra were sampled at 10-nm intervals, and integrations were performed over 400 to 720 nm.³⁰

In each trial, two images of a single pattern were presented in successive 1-second intervals, with no intervening gap, to avoid involving memory.³³ In the first interval, the pattern appeared illuminated by the first global illuminant, a fixed, spatially uniform daylight that was either bluish, of correlated color temperature 25,000 K (Fig. 1, left column), or yellowish, of correlated color temperature 4000 K (not shown). In the second interval, the pattern made from the same reflecting surfaces appeared illuminated by the second global illuminant, a fixed, spatially uniform, whitish daylight of correlated color temperature 6700 K (Fig. 1, right column), except for the center surface, in which 6700 K daylight was replaced by a spatially uniform local illuminant constructed from a linear combination of the daylight spectral basis functions.³⁴ The effect of the local illuminant was to simulate a reflectance change in the center surface. That it was based on a linear approximation was only for computational convenience and had no theoretical relevance. The chromaticity of the local illuminant was sampled randomly in each trial from a large convex gamut in the CIE 1976 (u' , v') diagram consisting of 65 locations, shown by the small solid points in Figures 2 and 3. Further details of the experimental stimuli, apparatus, and calibration have been published elsewhere.²⁸

Task

The task of the subject was to decide whether the reflecting properties of the center surface in the successive images of the Mondrian patterns

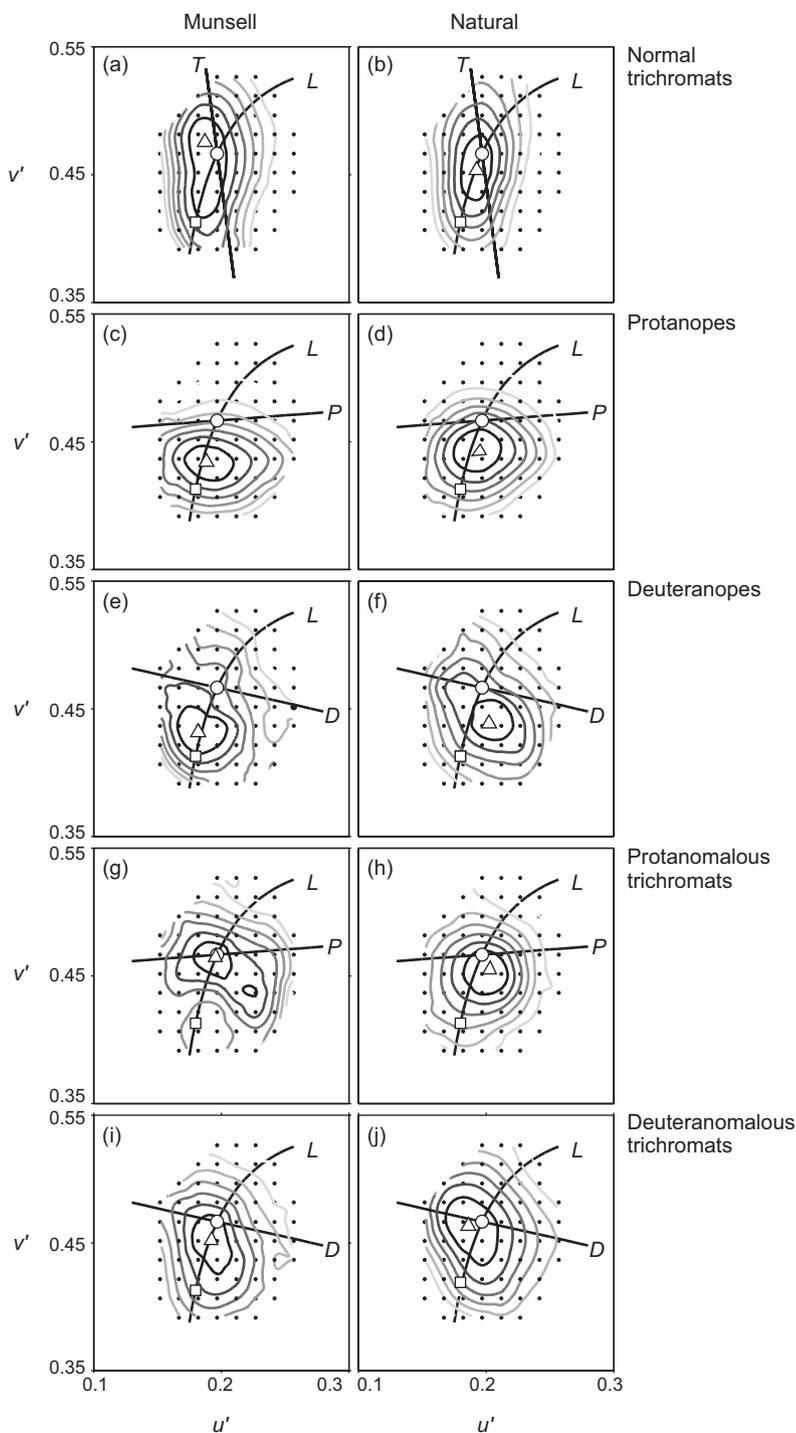


FIGURE 2. Detectability of changes in surface color of Mondrian patterns under changes in illuminant from a daylight of correlated color temperature of 25,000 K (*squares*) to 6700 K (*circles*). Each contour represents a constant frequency of illuminant-change responses in the CIE 1976 (u' , v') chromaticity diagram, with increasing frequencies shown by increasingly dark contours. The two columns of panels are for Munsell and natural spectra, and the five rows of panels are for the different subject groups, (a, b) nine normal trichromats, (c, d) five protanopes, (e, f) five deuteranopes, (g, h) five protanomalous trichromats, and (i, j) nine deuteranomalous trichromats. The daylight locus (L) and the protanopic (P), deuteranopic (D), and tritanopic (T) confusion lines are indicated. If subjects' judgments were perfectly color constant, then the distributions of illuminant-change responses shown in the contour plots would have maxima (*triangles*) coincident with the second global illuminant (*circles*).

were the same or different, that is, whether the change in the image was due to a pure illuminant change or to an illuminant change accompanied by a surface-reflectance (material) change.²¹ Responses indicating illuminant change or material change were made with a push-button switch box connected to the computer. Each subject performed 10 to 40 trials, with most subjects performing 20 trials, for each of the 65 local illuminants, but in random order. Thus, in each trial, the chromaticity of the local illuminant was drawn randomly without replacement from at least 650 ($=10 \times 65$) values, in one to four blocks. Patterns comprising Munsell or natural (rural and urban) spectra were tested with the two different global illuminant changes in separate experimental sessions.

Subjects

In all, 33 subjects, aged 19 to 38 years, took part in the experiments. There were 5 protanomalous and 9 deuteranomalous trichromats, 5 deuteranopes, 5 protanopes (all male), and 9 normal trichromats (3 female, 6 male), the last acting as controls. Subjects were classified with a battery of clinical color-vision tests: the Farnsworth-Munsell 100-Hue Test; Ishihara pseudoisochromatic plates (24-plates edition, 1964); Rayleigh and Moreland anomaloscopy and luminance matching (Interzeag Color Vision meter 712, Schlieren, Switzerland); and the Cambridge Color test.³⁵ Additionally, the two-color threshold method was used to test whether subjects had functioning Π_4 and Π_5 mechanisms.³⁶ All subjects had normal or corrected-to-normal visual acuity.

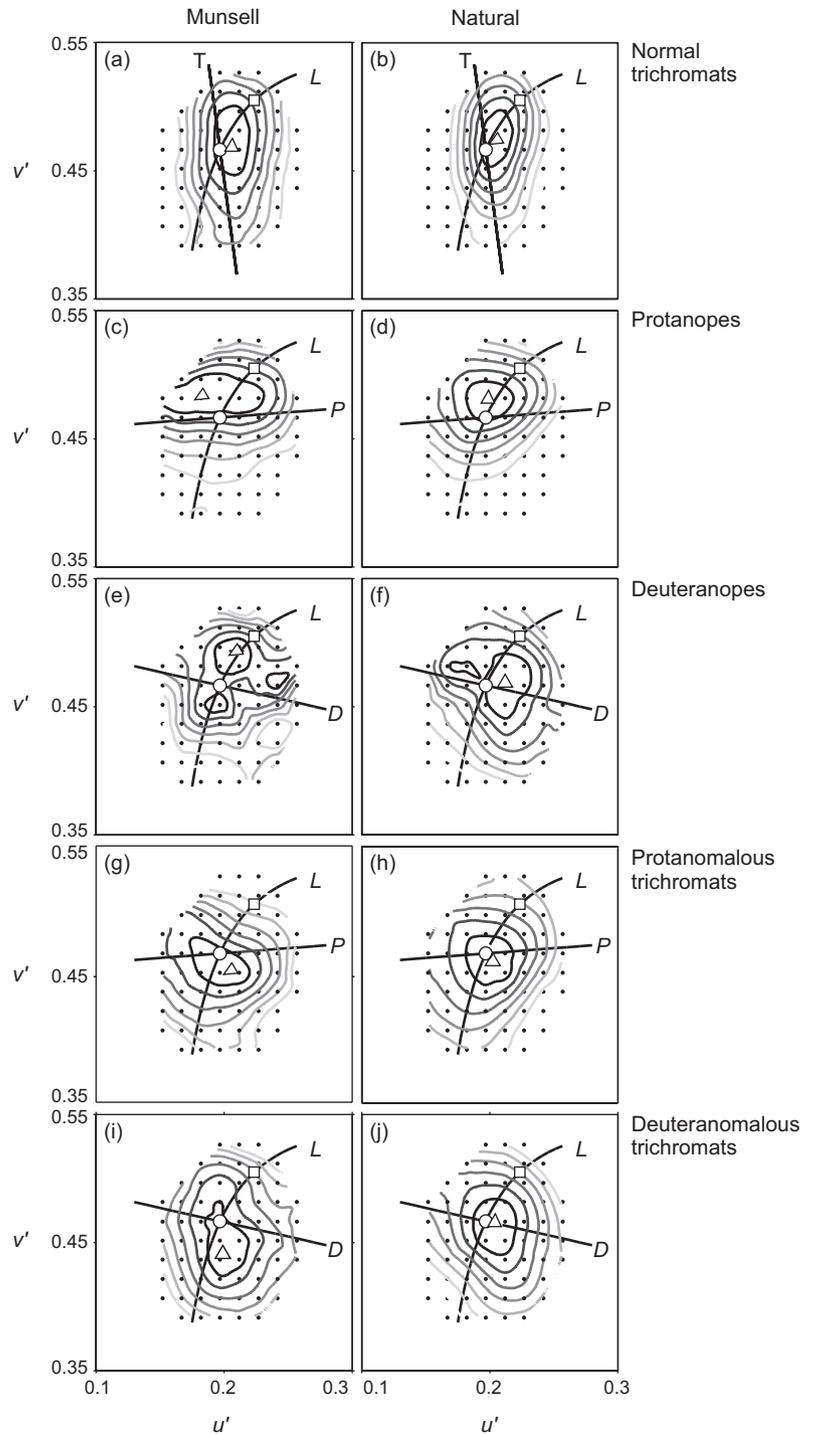


FIGURE 3. Detectability of changes in surface color of Mondrian patterns under changes in illuminant from a daylight of correlated color temperature of 4000 K (*squares*) to 6700 K (*circles*). (a–j) Other details are as for Figure 2.

The experiments were conducted in accordance with the principles embodied in the Declaration of Helsinki (Code of Ethics of the World Medical Association). All subjects were unaware of the purpose of the experiment.

Statistical Analysis

Formally, the task was a performance one²¹ in that each response by a subject was either correct or not correct.³⁷ The relevant measure, however, was the distribution of illuminant-change responses over different shifts in the chromaticity of the center surface in the Mondrian pattern induced by changes in the local illuminant. In chromaticity space, if responses were concentrated around the location of the

second illuminant, color constancy was good; if they were concentrated around the location of the first illuminant, constancy was poor.

The concentration of responses was measured in the following way. The frequency of illuminant-change responses was first pooled within each subject group for each experimental condition and, in the CIE 1976 (u' , v') chromaticity diagram, plotted against the chromaticity of the local illuminant defining the change in reflectance of the test surface.^{38,39} The frequency plots were then smoothed by a two-dimensional, nonparametric, locally weighted quadratic regression (loess^{40,41}) rather than assuming a particular functional form for the response distribution.³⁸ A common fractional bandwidth for the loess smoothing was estimated by leave-one-out

TABLE 1. Mean Color-Constancy Indices

Correlated Color Temperature	Spectral Reflectance	Normal Trichromats	Protanopes	Deuteranopes	Protanomalous Trichromats	Deuteranomalous Trichromats
25,000–6700 K	Munsell	0.77 (0.19)	0.41 (0.05)	0.32 (0.10)	0.96 (0.24)	0.73 (0.15)
	Natural	0.76 (0.06)	0.57 (0.11)	0.49 (0.07)	0.76 (0.07)	0.80 (0.07)
4000–6700 K	Munsell	0.79 (0.11)	0.53 (0.09)	0.36 (0.25)	0.67 (0.12)	0.46 (0.16)
	Natural	0.75 (0.05)	0.69 (0.13)	0.68 (0.09)	0.83 (0.14)	0.84 (0.06)
Mean	Munsell	0.78 (0.11)	0.47 (0.05)	0.34 (0.13)	0.81 (0.13)	0.59 (0.11)
	Natural	0.76 (0.04)	0.63 (0.08)	0.58 (0.06)	0.80 (0.08)	0.82 (0.04)

Values are color-constancy indices (SE).

cross-validation.⁴¹ This produced a bandwidth of 0.24, which was reduced to 0.20 for consistency with previously published data but with little effect on the subsequently defined color-constancy indices (root-mean-square difference in values was 0.03).

Contour plots were then derived and plotted in the corresponding chromaticity diagrams. To anticipate the results, in Figures 2 and 3, each contour represents a constant relative frequency of illuminant-change responses, with differences between contours of approximately 0.10 to 0.15. The location of the maximum of each distribution was obtained numerically from the loess analysis and is indicated in Figures 2 and 3 by a triangle.

To summarize the correctness of the surface-color judgments, a color-constancy index¹⁶ was calculated. In Figures 2 and 3, if a is the distance between the locations of the maximum (triangle) and the 6700 K illuminant (circle) and b is the distance between the locations of the 25,000 K or 4000 K illuminant (square) and 6700 K illuminant (circle), then the constancy index is $1 - a/b$. Perfect constancy corresponds to an index of 1, and perfect inconstancy corresponds to an index of 0. The SE of this index was estimated with a bootstrap procedure,⁴² based on 1000 replications, resampling with replacement over subjects (Ref. 43 contains an informal introduction to the bootstrap method). Thus, although the responses of subjects in each group were pooled, their consistency, or lack of it, in each experimental condition could be assessed by the size of the SE.

In general, tests of differences between the effects of stimuli and between subject groups were based on bootstrap planned comparisons, again with resampling over subjects to reflect their consistency. Normal-theory estimates were performed as a control (for example, see Ref. 44). Tests were one or two tailed, as determined by the context.

Previous computational modeling of normal trichromatic function has shown that spatial ratios of cone excitations provide an effective explanatory variable in making discriminations between illuminant and reflectance changes (for example, see Ref. 30). To test its relevance here, the logarithm of the mean relative deviation (MRD) in spatial cone-excitation ratios was calculated for each of the subject groups and types of reflectance. Means were calculated over the patterns as a whole.³⁰

RESULTS

Figure 2 shows subjects' performance in the CIE 1976 (u' , v') chromaticity diagram for Mondrian patterns undergoing a global daylight illuminant change from a correlated color temperature of 25,000 K to 6700 K. Figure 3 shows the corresponding performance for 4000 K to 6700 K. In each figure, the two columns of panels correspond to surface reflectances drawn from Munsell and natural spectra, and the five rows of panels correspond to the different subject groups: (a) and (b) normal trichromats, (c) and (d) protanopes, (e) and (f) deuteranopes, (g) and (h) protanomalous trichromats, and (i) and (j) deuteranomalous trichromats. As explained earlier (see Statistical Analysis), the contours represent constant relative frequencies of illuminant-change responses, with increasing fre-

quencies shown by increasingly dark contours. The first and second global illuminants are represented in each figure by a square and a circle, respectively, the daylight locus by a curve L , and the protanopic and deuteranopic confusion lines, along which these dichromats cannot discriminate chromaticities, by the straight lines P and D , through the position of the second global illuminant (for later reference, the tritanopic confusion line is also shown by a straight line T).

If subjects' judgments were perfectly color constant, then the distributions of illuminant-change responses shown in the contour plots would have their maxima where the local and global illuminants coincide—that is, the position of the maximum response frequency (triangles) would coincide with the position of the second global illuminant (circles) (see Statistical Analysis).

For normal trichromats, the response distributions had maxima close to the position of the second global illuminant (Figs. 2a, 2b, 3a, 3b), but the distributions were anisotropic, with the long axis of the distribution between the tritanopic confusion line (T) and the daylight locus (L).³⁹ The response distributions for color-deficient subjects showed less anisotropy, except for Figure 3c for protanopes viewing Munsell reflectances. The contour plots in Figures 2g and 3e would have been less uneven if the loess bandwidth had been larger.

For protanopes and deuteranopes, the absence of a more general elongation in the response distribution in the direction of the corresponding confusion lines is not unexpected. The angle between the confusion lines is small, and each dichromat had, in principle, either long- or medium-wavelength-sensitive cones available to make the required discriminations. This contrasts with tritanopes,³⁹ whose confusion lines are oriented closer to the daylight locus.

Group Differences

Table 1 shows mean color-constancy indices for each subject group in each experimental condition, with estimated SEs in parentheses. In summary, for protanomalous and deuteranomalous trichromats, indices were generally similar to those for normal trichromats, but for protanopes and deuteranopes, they were poorer, more so for Munsell spectral reflectances than for natural spectral reflectances.

There was no significant difference in the effects of the two types of illuminant change, that is, from a correlated color temperature of 25,000 K to 6700 K and from 4000 K to 6700 K ($\chi^2(10) = 7.5$; $P > 0.5$). With performance averaged over the two directions (Table 1, bottom two rows), the mean indices for normal trichromats with Munsell and natural reflectances were 0.78 and 0.76, respectively, and fall into the range previously reported for these kinds of judgments. The mean indices for dichromats with Munsell reflectances were 0.47 for protanopes and 0.34 for deuteranopes, and each was significantly lower than for normal trichromats ($z \geq 2.5$; $P < 0.01$),

though performance was still much better than chance ($P < 0.001$). With natural reflectances, the indices were 0.63 for protanopes and 0.58 for deuteranopes, and each was significantly higher than with Munsell reflectances ($z \geq 1.7$; $P < 0.05$), though not at the level for normal trichromats ($z = 1.4$; $P = 0.08$; $z = 2.5$; $P < 0.01$, respectively).

The performance of anomalous trichromats was not significantly different from that of normal trichromats for both types of reflectances ($z \leq 1.2$; $P > 0.1$). With Munsell reflectances, the mean indices were 0.81 and 0.59 for protanomalous and deuteranomalous trichromats, respectively, and with natural reflectances they were 0.80 and 0.82, respectively.

The consistency of color-deficient subjects, as indicated by the SEs in Table 1, was almost the same as that of normal trichromats (an average of 0.12 vs. 0.11).

Type of Spectra

For normal trichromats, there was no significant difference in mean color-constancy indices with natural and Munsell reflectances ($z < 0.0$; $P > 0.5$). For protanopes and deuteranopes, there was a significant difference, with higher indices with natural reflectances ($z = 1.7$; $P < 0.05$). For protanomalous trichromats, there was no significant difference ($z < 0.0$; $P > 0.5$), but there was for deuteranomalous trichromats ($z = 1.9$; $P < 0.05$). The effect of reflectance type was evident only at lower mean levels of performance.

MRDs in spatial cone-excitation ratios differed with the two types of reflectances. Averaged over Munsell reflectances, the mean log MRD was -1.44 and over natural reflectances it was -1.75 ; given the very large number of samples, the difference in log values of 0.30 was highly significant ($P < 0.0001$).

Individual Rayleigh Matches

Figure 4 shows approximate color-constancy indices from individual anomalous trichromats and normal trichromats plotted against their match midpoints (left panel) and matching ranges (right panel). Indices have been averaged over the two types of reflectances and the two types of illuminant change. Because these indices were based on far fewer trials than in the

group data of Figures 2 and 3, they are less reliable than the estimates summarized in Table 1 and may be biased downward. Nevertheless, though regression lines have been added for anomalous trichromats, there are clearly no reliable trends. Pearson's correlation coefficient for regression on the match midpoint was -0.21 for protanomalous trichromats and 0.07 for deuteranomalous trichromats. For regression on the matching range, it was 0.32 for protanomalous trichromats and 0.24 for deuteranomalous trichromats. None of these correlations was significant ($P > 0.3$).

DISCUSSION

Of necessity, color constancy depends on the number and type of cone pigments available. A single cone pigment samples a relatively broad portion of the reflected spectrum (60–110 nm at 50% maximum sensitivity), and a pair of surfaces with different spectral reflectances may therefore fail to be discriminated under one light (and therefore seen as the same) but may succeed in being discriminated under another (and therefore seen as different). Whatever the percept generated, color constancy cannot hold for both members of the pair. But given more cone pigments, more of the spectrum can be sampled, with the result that more discriminations (and identifications) made under one light can be preserved under another light. Even so, the number of cone pigments is not the sole determinant of performance. The spectral locations of the pigments and the interactions between cone signals are also important, as are the particular combinations of the illuminants and spectral reflectances producing the stimuli.

With Mondrian patterns and daylight illuminants, all the red-green color-deficient subjects examined here were able to discriminate illuminant and surface-reflectance changes. In fact, with natural spectral reflectances, protanomalous and deuteranomalous trichromats performed as well as normal trichromats, obtaining color-constancy indices of 0.80 and 0.82, respectively, averaged over changes in a daylight illuminant from a correlated color temperature of 25,000 K to 6700 K and from 4000 K to 6700 K. These values fall at the top of the

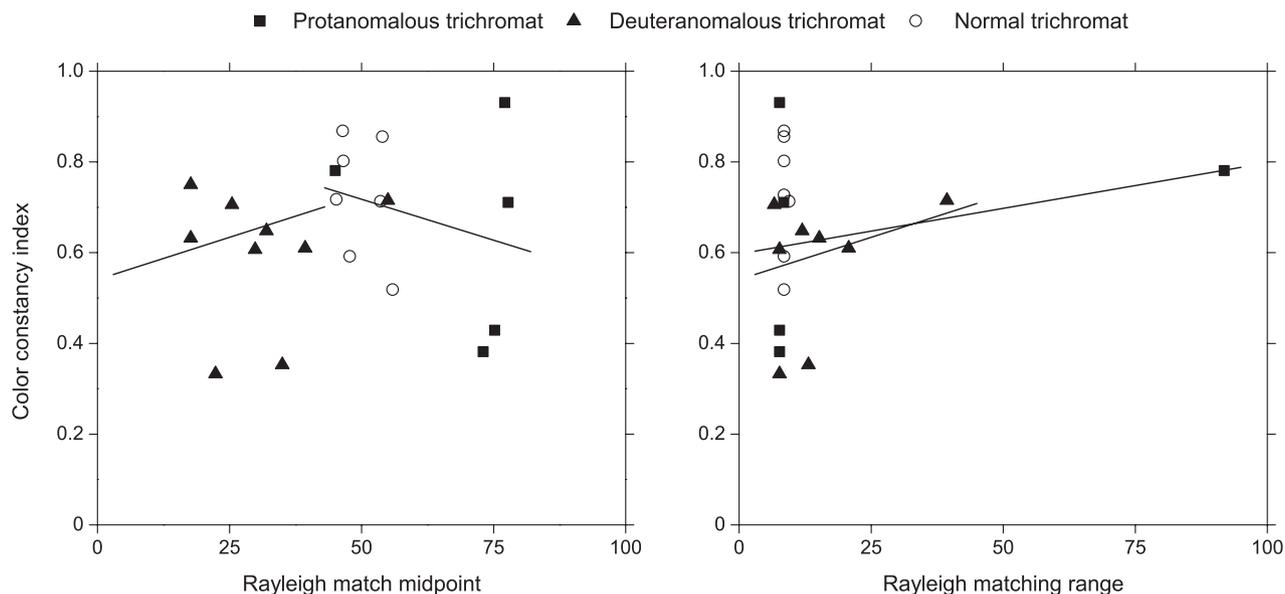


FIGURE 4. Color-constancy indices for individual subjects as a function of Rayleigh anomaloscope match midpoint (*left*) and matching range (*right*) for protanomalous trichromats (*filled squares*), deuteranomalous trichromats (*filled triangles*), and normal trichromats (*open circles*). Four overlapping symbols have been slightly displaced for clarity. Individual indices could not be calculated for two normal trichromats because there were too few data points. The *straight lines* are linear regressions.

range of previously reported values for normal trichromats making surface-color judgments with simple geometric patterns.^{16,45–47} Higher indices have been recorded in particular conditions,^{30,37,48} but the upper value of 0.82 may represent a natural ceiling on performance with these types of stimuli. Although protanopes and deuteranopes performed less well than normal trichromats and anomalous trichromats, their average indices with natural spectral reflectances of 0.63 and 0.58, respectively, were only a little lower than the normal range of published values.

Previous measurements based on the same experimental task but with images of natural vegetated and nonvegetated scenes rather than Mondrian patterns produced an almost identical mean color-constancy index of 0.81 for deuteranomalous trichromats, although a lower mean index of 0.63 for protanomalous trichromats.²³ Why protanomalous trichromats should have performed better with Mondrian patterns of natural spectra than with natural scenes is unclear. The degree of deficiency in the two groups of subjects, at least as indicated by their Rayleigh matches, was almost the same, with mean match midpoints of 75.3 and 76.5 and mean matching ranges of 8.43 and 7.72.

How might these discriminations between illuminant and reflectance changes be made? One possibility, discussed in detail elsewhere,^{49,50} is that subjects exploit the constancy of perceived color relations under illuminant changes (relational color constancy) and the failures of this constancy under spectral-reflectance changes. A physical basis for relational color constancy could be the spatial ratios of cone excitations⁵⁰ or of opponent and nonopponent combinations of cone excitations,⁵¹ under changes in daylight illuminant. These ratios, defined between one surface and another, are known to be stable for both Munsell and natural spectral reflectances.^{49–51} For the Mondrian patterns used in this study, the mean relative deviation in spatial cone-excitation ratios was 2% for natural spectra and 4% for Munsell spectra.

Thus, in each trial containing a pure illuminant change, the deviation in cone-excitation ratios between the center and other surfaces in the Mondrian pattern would have been small but would have increased with the size of any change in the center surface reflectance simulated by a change in local illuminant. This particular deviation signal would have been detected—or not—against a background of deviation “noise” arising from other surfaces, even though their reflectances were constant.³⁰ The smaller deviation noise with natural reflectances might have accounted for the corresponding better performance by protanopes, deuteranopes, and deuteranomalous trichromats. The ceiling on performance mentioned earlier might have masked a similar improvement in performance by normal trichromats and protanomalous trichromats with natural reflectances, but other mechanisms might also have been involved.

To develop this analysis further and to provide quantitative predictions about the performance of red-green color-deficient subjects, it would be necessary to make specific assumptions about the stage, receptor or postreceptor, at which signals are compared, the relative weighting of these signals, and the role of any perceptual correlates.⁵¹ These assumptions would need the support of independent data to reduce the ensuing degrees of freedom of the model (see Ref. 39 for tritanopic subjects).

It seems unlikely that the recorded levels of performance were the result of the operational method of measurement. As noted earlier, asymmetric color matching yields closely similar levels of color constancy in normal trichromats.¹⁷ Moreover, Rüttiger et al.³ used a different method to measure color constancy in red-green color-deficient subjects but came to the same conclusion about their ability. In that work, four protanopes,

three deuteranopes, and three deuteranomalous trichromats made achromatic settings of a gray test surface in a Mondrian pattern undergoing illuminant shifts along the red-green and blue-yellow cardinal axes.⁵² The degree of color constancy for these subjects was similar to that for normal trichromats, although settings by color-deficient subjects were more variable along the red-green illuminant axis than along the blue-yellow illuminant axis.

The Rayleigh match is often accepted as a point of reference for other clinical tests: persons who fail the Ishihara test will in some instances be allowed to enter a profession otherwise closed to those with red-green color deficiency if they have a narrow-enough anomaloscope matching range.⁵³ But the power of the anomaloscope—with its small stimulus field and spectrally purer stimulus colors—to predict performance in more general color judgments is limited.⁹ As shown here, the degree of color constancy in anomalous trichromats was unrelated either to their Rayleigh match midpoint or to their matching range. Other studies of color discrimination,⁵⁴ color naming⁵⁵ and surface-color judgments with natural scenes,²³ have also identified the limitations of anomaloscopy.

These considerations do not lessen the relevance of anomaloscopy in classifying color deficiency. Indeed, given knowledge of cone-pigment optical density, it is possible to relate Rayleigh matches to the spectral differences revealed in genotyping.⁵⁴ It is, however, important to distinguish between classification and competence. In normal viewing conditions, color-deficient persons can exploit a range of cues to infer surface-reflectance properties. In addition to the presence of familiar objects in natural scenes and illumination by light from multiple sources, objects can be manipulated and viewed from different angles. Even when all these cues are removed, red-green color-deficient persons can still achieve normal or nearly normal levels of color constancy with the same kinds of spectra as those encountered naturally.

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