Anomaloscopic settings with added chromatic fields: The use of red light to reproduce protan function

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Rayleigh equations and brightness matches of spectral yellow to mixtures of spectral red and green were determined for four normal trichromats and one protanomalous trichromat. A Nagel anomaloscope, modified to allow the superposition of a chromatic field on the bipartite Nagel field, was used. The effect of adding a 650 nm. field to the Nagel field was to widen the match range toward the red end for all observers. When matching the brightness of spectral yellow to mixtures of spectral red and green, with the added 650 nm. field present, the observer required very low luminances of yellow to match reddish mixtures, behavior similar to that of protan observers. Similar results were obtained with a 620 nm. added field, but not with 2,700 K white, 490 nm., 550 nm., or 590 nm. added fields.

Key words: protanomaly, color vision, spectral sensitivity tests, trichromatic vision, anomaloscope, wavelength, luminance, humans.

Narrow-band red light has a selective effect on the red-absorbing visual pigment when used as a preadaptation light or a superimposed field. Visual functions, including wavelength discrimination, spectral sensitivity, and color matching obtained under such conditions often resemble the protan visual function.

Wavelength discriminations similar to those shown by Wright for protan observers have been reported following long-wave adaptation and when a 650 nm. light is superimposed on a discrimination field. A relative sensitivity loss for long-wave test lights similar to the protan spectral sensitivity loss has been shown following long-wave adaptation, when using a continuously present long-wave adapting field, and during rapid chromatic adaptation to long-wave stimuli. A number of investigators have reported that following intense red preadaptation, increased red is necessary in the mixture of red and green matched to yellow. Of these studies, only Alpern and Torii measured the match range. They found that although the matches required more red following the red preadaptation, the match range also included the preadaptation match for 2 out of 3 observers.

Hurvich has emphasized the distinc-
tion between "performance" and "perception," noting that the percepts of an observer are often of fundamental importance in understanding the subserving mechanisms. It is important to point out that although protan function may be reproduced by the methods specified above, the visual world of the protan is not. The percepts occurring after an intense bleach (unsaturated blue-green for wavelengths between 540 and 620 nm, according to Brindley) are in fact complementary to those observed in the presence of a superimposed field. The resultant loss in sensitivity of the red mechanism is, however, the same.

When a chromatic field is superimposed on a discrimination field in order to simulate protan function, the observer is presented with a steady-state task. With low luminances of chromatic field, the discriminations are reasonably easy to make. The present report describes the effect of superimposing a narrow-band spectral field on the bipartite anomaloscope field in which the Rayleigh equation is being determined.

The Rayleigh equation is a statement of the relative amounts of red and green that need to be mixed to match a given yellow. Three important parameters of the equation are the midpoint and range of equation and the brightness of yellow required to match the chosen red-green mixture. Franceschetti and Pickford have classified three types of protan response, based on the anomaloscope settings: The protanope, a dichromat, will accept matches over the whole range of possible mixtures, including pure red and pure green. The protanomalous or simple protanomalous has an equation which requires more red than normal but may have a narrow range of acceptance. He typically requires about 4 times the amount of red (and one quarter of the green) used by the normal observer. The extreme protanomalous has a wide range of equation which may extend from mixtures appearing green to the normal trichromat to those appearing red. All three types of protans show loss of luminosity in the red end when they match reds to yellow.

Method

The apparatus consisted of a modified Nagel anomaloscope. The Nagel anomaloscope allows presentation of a 2.5 degree bipartite field, one half of which consists of a yellow (589 nm.) variable in luminance, and the other half consists of a mixture of red (670 nm.) and green (546 nm.) in which the ratio of red to green may be varied, whereas the total luminance is unchanged. This instrument has been described in detail by Linksz. Modification consisted of placing a small cube beam splitter and 2 mm. artificial pupil at the eyepiece to allow the superposition of a second light equal in extent to the Nagel field. The added field was produced by the output of a Sylvania tungsten-halogen bulb (color temperature, 2,700 K), opal glass, field stop, neutral density, and Schott PIL interference filters.

The luminance of the added field was calibrated directly at the eyepiece with a SEI exposure photometer, whose accuracy was established by comparison with a Macbeth Illuminometer. The luminance of the Nagel field, both for the yellow half (589 nm.) and for various red-green mixtures, was calibrated by direct matching to the added field using a series of Schott interference filters in the added channel. For this procedure, either the top or the bottom half of the added channel was occluded and luminance matches were made between the Nagel fields and the output of an appropriate interference filter placed in the added channel. Calibrations for the interference filters were performed by heterochromatic flicker photometry in other equipment using a tungsten lamp of equal color temperature to that of the halogen lamp. These calibrations showed that the luminance of the red-green mixture was 0.2 log FL for all values of mixture tested, at the time observers M. S., R. P., and W. R. were used, and 0.4 log FL a year later when observers B. F. and J. P. were used.

A procedure similar to that suggested by Linksz was followed. The experimenter set a given red-green mixture and allowed the observer to adjust the yellow luminance. The observer was instructed to match the fields in

[Note: The wide match range of the extreme protanomalous is often elicited by requiring the subject to stare at his matches (fatigue). Neither the normal observer nor the simple protanomalous show a significantly wider match range after continuous viewing of the anomaloscope field. Some extreme protanomalous observers, however, can be brought step by step to accept a very wide range of matches.]
brightness and then report whether or not they matched in hue. The subject then made brightness matches between the yellow and 9 mixtures of red-green, ranging from all green (546 nm.) to all red (670 nm.). The various mixtures were presented in random permutations. After each setting the subject looked at a 25 degree, 400 FL, 2,600 K adaptation field for 25 seconds.

Data were obtained for 4 to 5 added field luminances and with no added field. One or two luminance levels were tested in each session. The session lasted about one hour and 5 to 12 sessions were required for each subject. Initially, the effect of a 650 nm. added field was investigated for all observers. Subsequently a white (2,700 K) and 4 other chromatic fields (490 nm., 550 nm., 590 nm. and 620 nm.) were investigated using one observer.

Only male observers were used. All subjects were initially screened on the Nagel anomaloscope, the AO HRR plates, and the Farnsworth-Munsell 100-hue test. The normal trichromats used in this study made fewer than 12 errors on the Farnsworth-Munsell 100-hue test.

Results and discussion

Fig. 1 shows brightness-matching behavior of normal subjects, a protanope, and a deuteranope obtained on the modified Nagel anomaloscope with no added light. In this figure, the matching luminance of the yellow field is shown in footlamberts (FL), and the red-green mixtures are designated by the arbitrary Nagel scale which ranges from all green (546 nm.) at 0, to all red (670 nm.) at 73. For the normal, the color match occurs within a narrow reproducible range which (for our instrument) centers at 50 on the red-green scale. The normal tends to overestimate the luminance of the red-green mixture when there is a large color difference. He gives a U-shaped brightness-matching function, requiring large amounts of yellow to match a pure red or pure green. The deuteranope approximately follows the calibration curve for the instrument. The protanope shows reduced luminosity in the long wave-end of the spectrum and requires very small amounts of yellow when matching yellow to the reddish mixtures.

Fig. 2 shows the brightness-matching data and match ranges for 4 normal trichromats when a 650 nm. field is added to the Nagel field. The data with

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**Fig. 1.** The luminance of spectral yellow when matched in brightness to mixtures of spectral red and green for normal observers, protanopes, and deuteranopes.
no added field (solid circles) are shown for comparison. With an added field equal in luminance to the red-green mixture field, the match is unchanged. As the added field luminance is increased, the match range first tends to widen. When the added field luminance is 10 times the field luminance (subjects M. S. and R. P.), the match range includes the red end and extends into the green; the brightness-matching data show a drop at the red end. This behavior resembles that of the extreme protanomal. Additional measurements on observer J. P. demonstrated that when the added field luminance is 16 times the field luminance, a color match could be made for all red-green ratios for which a brightness match could be made. The observers did not accept a color match for the extreme red setting (70) because they were unable to set the yellow luminance to a sufficiently low value.

The effect is not due to long-term chromatic adaptation. If the normal trichromat is looking at the Nagel field with the highest luminance of added 650 nm., and then the added field is removed, the observer will immediately accept only his original equation. Of course, the color appearance is changed and the field appears green to him.

To check that this result is specific to the use of a long-wave added field, the experiment was repeated on one observer using a 2,700 K white and four chromatic fields of dominant wavelength 490 nm., 550 nm., 590 nm., and 620 nm. Fig. 3 shows the color-match range and brightness-matching data for these added fields. The 650 nm. added field data are repro-

![Graph 1](image1.png)

**Fig. 2.** The luminance of a spectral yellow matched in brightness to mixtures of spectral red and green when a 650 nm. field is superimposed on both halves of the discrimination field.
Anomaloscopic settings with added chromatic fields 547

Fig. 3. The luminance of a spectral yellow matched in brightness to mixtures of spectral red and green when chromatic fields are superimposed on both halves of the discrimination field.
duced for comparison. Only the 620 nm added field gives results similar to those obtained with a 650 nm added field.

With the added 2,700 K white, 490 nm, 550 nm, or 590 nm added fields the brightness matching data never resemble those of the protanope. However, with sufficient amounts of these added fields the match range does tend to widen without shifting. With 1.9 to 2.0 log FL of added 2,700 K white or 550 nm, the border washed out and it was impossible to obtain a reliable match range. This effect did not occur for the 590 nm field. With 1.9 log FL of added 590 nm, the observer has a reproducible match which does not extend into the deep red.

The 2,700 K white and the 490 nm added fields tend to render the brightness-matching functions closer to the calibrated luminance matches. This result probably occurs due to the desaturating effect of these white and blue added fields.

The fifth observer was classified as simple protanomalous. He made a few R-G errors on the AO HRR test plates and showed a protan axis on the Farnsworth-Munsell 100-hue test. Fig. 4 shows the distribution of errors on the FM 100-hue test for this observer. The Rayleigh equation measured on the Nagel was 62-63 with a protan brightness-matching function. His wavelength discrimination, measured on apparatus described previously, showed a

Fig. 4. Distribution of errors on the Farnsworth-Munsell 100-hue test for protanomalous observer W. R.

Fig. 5. Wavelength discrimination and color matching data for protanomalous observer W. R. when a 650 nm field is added to the discrimination field.
minimum at 500 nm., and relative maxima and minima at 550 nm. and 590 nm., respectively. With the exception of the region at 500 nm., all the delta lambdas were elevated compared with the normal function. The protanomalous observer had no wavelength discrimination for wavelengths above 610 nm. He showed a relative luminosity loss of 0.5 log unit at 650 nm. compared with normal trichromats.

Fig. 5 shows wavelength discrimination data and match ranges when a 650 nm. field is added to the discrimination field. As the 650 nm. field is increased in luminance, wavelength discrimination deteriorates and the function becomes U-shaped, with a minimum at 450 nm. The match range widens to include the whole red end of the instrument. The brightness-matching function measured on the Nagel is unchanged by the added 650 nm. field. Similar sets of wavelength discrimination functions with added red light were obtained from 3 other observers classified as simple protanomals.

Our results may be compared with those reported by Baker12 and Alpern and Torii14 for anomaloscope matches made following an intense long-wave spectral bleach. Their experiments were designed to test the self-screening hypothesis: that the protanomalous red-absorbing pigment is dilute normal red-absorbing pigment. According to this hypothesis, normal subjects should make protanomalous matches during recovery from an intense red bleach. Baker13 found that the anomaloscope free matches following a 605 nm. bleach required more red than normal, recovering within 30 seconds. The additional red required during recovery was not in the range required by a protanomalous control observer. Baker12 therefore rejected the self-screening hypothesis. Alpern and Torii14 noting that the matches following a bleach are erratic, repeated the experiment using a 625 nm. bleach and investigated the range of acceptable settings. Immediately following the bleach the range was increased into the red end and recovered after about 3 minutes following a time course similar to that shown by Brindley,16 but still faster than would be predicted by Rushton’s10 measurements of the regeneration rate of the red-absorbing pigment. Alpern and Torii14 felt that this discrepancy in time course was not sufficient to reject the self-screening hypothesis. Following the bleach, the matching range for 2 of their 3 normal subjects included their no-bleach midpoints. The third had a displaced range (toward the red) for the first minute following the bleach. The free matches made by Baker12 fall within the match ranges of Alpern and Torii’s14 three observers. Alpern and Torii14 mention that a protanomalous observer similarly gave a widened range with no shift in midpoint (c.f., our observer, W. R.), following the 625 nm. bleach, stating that this result is in agreement with the self-screening hypothesis. With a 10:1 ratio added to discrimination field luminance, the match ranges of our observers were of the same magnitude as those of Alpern and Torii’s14 observers immediately following the 625 nm. bleach. This similarity under both the bleaching and background condition suggests a common explanation.

Crawford21 has shown that for the rod mechanism the shape of the dark-adaptation curve as a function of area is correlated with the change in increment thresholds as the background luminance is increased. He used the concept of equivalent background luminance to explain his dark-adaptation results, pointing out the similarity of raised thresholds obtained after cessation of a bright light, and raised thresholds obtained when a dim background is present. Du Croz and Rushton22 and Watkins23 have shown that the concept of equivalent background also applies to the various cone mechanisms. The increased range of anomaloscope settings found by Alpern and Torii14 may be due to a change in increment sensitivity of the red mechanism. In this case, following a red bleach, the return to the normal...
narrow equation should follow the time course of regeneration of the red-absorbing pigment.

Conclusions

Four normal observers and one observer classified as simple protanomalous yielded data identical to those of extreme protanomalous and protanopes when a red light was superimposed on an anomaloscope field. With a high-luminance red, the match range widened to include most of the R-G range, and the luminance of yellow needed to match the various R-G mixtures was identical to that of the protan. This does not mean that we produce a state of artificial protanopia: The observer sees the discrimination field as various shades of red. We do not obtain from normal subjects the shifted equation typical of simple protanomaly. In this respect, the technique aims at a progressive reduction of discrimination available to the "red" mechanism. Von Kries\textsuperscript{24} pointed out that the simple anomalous trichromat cannot be considered to have a reduction system of color vision but rather an alteration system.

REFERENCES