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Chromatic Valence Curves: Alternative Interpretation Derived by the Direct Matching Method

Abstract. *The amount of red chromatic valence of the red-green opponent colors channel of the human visual system has been reported to be greatly reduced in short wavelengths when the hue-matching method is used to measure red valence instead of the more typical cancellation method. Receptive fields with a silent surround were postulated to explain the reduction, and it was emphasized that the reduced valence curve represented the true chromatic valence curve of the visual system. In the present studies the previous results are interpreted to be a direct consequence of the method and the particular matching stimuli used. It is shown that the reduction can be explained by the existing color-matching data without appealing to the silent surround hypothesis.*

A new method was introduced by Ingling *et al.* (*1*) to measure the chromatic valence curves of the opponent-colors theory (*2*) which Ingling *et al.* claim to be superior to the usual cancellation method in that the new method reveals true amounts of the chromatic sensations. The new method, which is called the direct hue-matching method, entails matching the hue of a test stimulus with a mixture of two primaries. For example, if one is interested in obtaining the red chromatic valence of a 450-nm light in the short wavelength region of the spectrum, the 450-nm light is juxtaposed in a split field with a mixture of a blue primary of 480 nm and a red primary of 680 nm. The amounts of red in both fields are equated by adjusting the radiances of the primaries. The red chromatic valence is given by the amount of the red primary in the mixture.

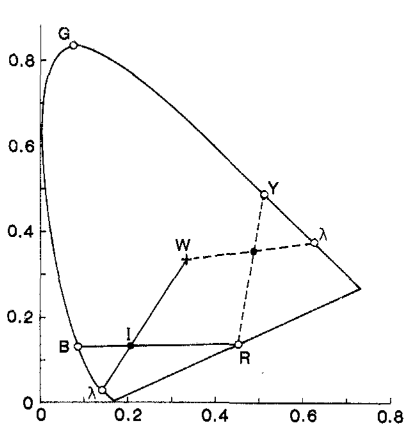

Fig. *1*. Scheme to explain the hue-matching method.

Using this method, Ingling *et al.* (*1*) observed a great reduction of the red chromatic valence in the violet region of the spectrum when compared with that obtained by the cancellation method. To explain the difference Ingling *et al.* postulated a silent surround receptive field in which the inhibitory surround becomes effective only when the excitatory center is active, the situation which prevails in the cancellation method. According to their hypothesis, the red chromatic valence at short wavelengths is overestimated in the cancellation method in which the silent surround becomes active to reduce the effectiveness of the green canceling light.

Although the hypothesis is attractive and is helpful in searching for color vision mechanisms in human subjects, we have another interpretation of the results, one which does not require such a hypothesis. From the data of Ingling *et al.* one cannot ascertain the subject's "end point" in the experiment when the relative radiances of the primaries were adjusted. The expression "hue matching" was used, which suggests that the subject achieved a hue match between the test stimulus and the mixture of primaries in spite of the difference in their saturation. However, the expression "same amount of redness" was also used, which suggests that the subject equated the absolute amount of redness in the mixture of 480 nm and 680 nm to that in the test stimulus of 450 nm, for example, in determining its red chromatic valence. The luminance of both fields was kept at 100 trolands. However, these two expressions define, at least in principle, quite different criteria. In determining an equal amount of redness the subject would disregard the amount of blueness in the fields and concentrate only on the amount of redness. The hue of two fields might differ considerably in overall appearance while assuring the same amount of redness. In hue matching the subject would concentrate on reaching the same balance between redness and blueness in the mixture as that in the test stimulus.

With an experimental setup similar to that of Ingling *et al.* (*1*), we asked subjects to adjust the mixture of radiances in experiments that used both criteria. A test stimulus of wavelength 420 nm was matched with the mixture of 680 nm and a short wavelength that corresponded to the unique blue detected by each subject. All five subjects participating in the experiment found it easy to use the hue-matching criterion. Four of the subjects, however, found it impossible to achieve

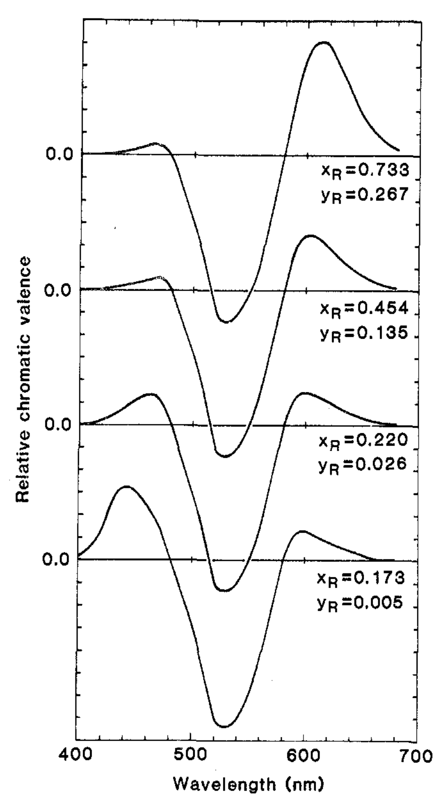

Fig. 2. Red-green chromatic valence curves derived by calculations based on hue matching with various red primaries (x_R, y_R).

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the equal amount of redness end point. The last subject attempted to achieve the end point although he had no confidence in his ability to do so. The results showed that he used the hue-matching criterion. We therefore concluded that the results reported by Ingling *et al.* were derived on the basis of hue matching rather than on determining the equal amount of chromatic sensation.

If our interpretation is correct, the results of Ingling *et al.* may be analyzed and derived for the standard observer by the use of the CIE chromaticity coordinates. To make the derivation general we assume the blue (B) and red (R) primaries to be at the chromaticity coordinates (x_B, y_B) and (x_R, y_R) as shown in Fig. 1. The subject then adjusts radiances of B and R so that the mixture comes to the intersection I (x_I, y_I) of two lines, $\overline{BR}$ and $\overline{\lambda W}$, where λ denotes the test stimulus and W a reference white. For simplicity we neglect the Abney or the Aubert effects; their influence on the final result is only slight and we assume that the same hue line is represented by a straight line connecting λ to W. By applying the algebra inherent in the chromaticity diagram, we can obtain the amount of red primary C_R necessary to match the equi-energy spectrum of λ in the form

$$C_R = \bar{y}(\lambda) \Big/ \left(\frac{x_R - x_I}{x_I - x_B} \cdot \frac{y_B}{y_R} + 1 \right) \quad (1A)$$

where $\bar{y}(\lambda)$ is the color matching function representing spectral luminosity. The amount of red at the long wavelengths is similarly obtained by mixing the red and yellow primaries R and Y as indicated by the dotted lines in Fig. 1. A similar geometry is also used for the green primary although it is not shown here.

The computed results for the red-green chromatic valence curves are shown in Fig. 2 for the primaries, 480 nm, 520 nm, 580 nm, and 680 nm, respectively, as chosen by Ingling *et al.* (*1*). The upper portion above the horizontal zero line is positive and shows the red chromatic valence, and the lower portion is negative and gives the green. The unit along the ordinate is arbitrary. Equi-energy white was used as the reference white. Equal amounts of red and green sensations derived by red and green primaries, respectively, should cancel each other out completely to leave only yellow sensation. The unique yellow line connecting Y and W served to determine a unit amount of red and green primaries. We notice in the topmost frame a reduced amount of red chromatic valence at short wavelengths, which agrees with the results obtained by Ingling *et al.* The small amount of redness in the violet region is simply a natural result of using 680 nm as the red primary which can provide only a desaturated mixture that contains a small amount of redness. If, therefore, a red primary closer to the violet end is used along the purple line, the mixture becomes more saturated and a larger amount of red chromatic valence in the violet region is obtainable. An extreme example of such a case is shown at the bottom of Fig. 2, in which a red primary of 400 nm was employed. The redness is quite large, as expected, and the hypothesis of silent surround becomes superfluous. We note, however, that the red chromatic valence in the long wavelength region is greatly decreased and one may be tempted to postulate a silent surround receptive field active in this spectral region. Any intermediate values of red chromatic valence can be obtained by using red primaries along the purple line as demonstrated in the middle two curves. The green curve remains the same because the green primary was fixed at 520 nm in these examples.

Appendix

The C_R equation (Eq. 1A) is derived as follows. In the hue-matching experiment the total luminance of mixture R and B was kept constant throughout all test wavelengths λ and we can assume

$$Y_R + Y_B = 1 \quad (1B)$$

where Y_R and Y_B are tristimulus values of R and B, respectively. By utilizing the center-of-gravity rule we have

$$\frac{x_R - x_I}{x_I - x_B} = \frac{X_B + Y_B + Z_B}{X_R + Y_R + Z_R} = \frac{Y_B}{y_B} \Big/ \frac{Y_R}{y_R} \quad (2)$$

Substitution of Eq. 1B into Eq. 2 will give

$$\frac{1 - Y_R}{Y_R} = \frac{x_R - x_I}{x_I - x_B} \cdot \frac{y_B}{y_R} \quad (3)$$

or

$$Y_R = 1 \Big/ \left(\frac{x_R - x_I}{x_I - x_B} \cdot \frac{y_B}{y_R} + 1 \right) \quad (4)$$

If the red primary is chosen to be monochromatic along the spectral locus, its radiance $L_{e,R}$ is given by

$$L_{e,R} = \frac{Y_R}{\bar{y}_R} \quad (5)$$

Red chromatic valence C_R for equi-energy of λ can be obtained by multiplying $\bar{y}(\lambda)$ with the above $L_{e,R}$ in the same way as the hue matching was achieved for equal luminance of λ. Namely,

$$C_R = \bar{y}(\lambda) \cdot L_{e,R} = \frac{\bar{y}(\lambda)}{\bar{y}_R} \Big/ \left(\frac{x_R - x_I}{x_I - x_B} \cdot \frac{y_B}{y_R} + 1 \right) \quad (6)$$

As $\bar{y}_R$ is a constant, we may express it as unity so that we finally obtain Eq. 1A.

If the red primary is chosen as a mixture of a long wavelength L and a short wavelength S so that it comes on the purple line such as shown in Fig. 1, its tristimulus value Y_R is given by

$$Y_R = Y_L + Y_S \quad (7)$$

If we let the primary R section the purple line in the ratio $t:s$, we have, by the center-of-gravity rule,

$$\frac{Y_S}{Y_L} = \frac{t\, y_S}{s\, y_L} \quad (8)$$

We insert Eq. 8 into Eq. 7 to eliminate Y_S and express Y_L in terms of Y_R, the last being substituted further by Eq. 4. We finally obtain the expression

$$Y_L = 1 \Big/ \left(\frac{x_R - x_I}{x_I - x_B} \cdot \frac{y_B}{y_R} + 1 \right) \left(\frac{t\, y_S}{s\, y_L} + 1 \right) \quad (9)$$

The radiance of $L_{e,L}$ is given by an equation similar to Eq. 5

$$L_{e,L} = \frac{Y_L}{\bar{y}_L} \quad (10)$$

Equations 9 and 10 are used to derive the red chromatic valence C_R. Namely,

$$C_R = a \cdot \bar{y}(\lambda) \Big/ \left(\frac{x_R - x_I}{x_I - x_B} \cdot \frac{y_B}{y_R} + 1 \right) \quad (11)$$

where

$$a = 1 \Big/ \bar{y}_L \left(\frac{t\, y_S}{s\, y_L} + 1 \right)$$

a is a constant and we express it as unity. The final formula for C_R is again the same as that in Eq. 1A.

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