Contribution of Opponent-Colour Channels to Brightness

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Introduction

A saturated colour is perceived as brighter than a desaturated colour when the two are equated in luminance. This effect is well known as the Helmholtz-Kohlrausch effect, and can be demonstrated in spectral colours by the difference observed between the luminous efficiency function measured by flicker photometry and that obtained by heterochromatic brightness matching: the difference between the two functions resembles the saturation function (Wagner and Boynton, 1972; Comerford and Kaiser, 1975; Ikeda, Yaguchi, Yoshimatsu and Ohmi, 1982). In the case of nonspectral colours, obtained by mixing spectral colours, the Helmholtz-Kohlrausch effect is observed in the form of a failure of brightness additivity (Yaguchi and Ikeda, 1980). The theoretical explanation of this effect has been discussed by many investigators (Guth and Lodge, 1973; Ingling and Tsou, 1977; Bauer and Röhler, 1977; Yaguchi and Ikeda, 1982) and they agree in assuming that luminance is determined only by the achromatic channel, whereas brightness is determined by both the achromatic channel and the two opponent-colour channels.

In the present paper, we first reconfirm the contribution of opponent-colour channels to brightness by investigating the relationship between the shape of the luminous efficiency curve for brightness and the additivity failure of the reduction type that occurs when two wavelengths are mixed. Secondly, we analyse the additivity property in each subject and obtain a nonlinear model that describes the additivity failure.

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Method

Heterochromatic brightness matching was used both in measuring the luminous efficiency functions and in testing the additivity law for brightness. A 4-channel Maxwellian-view optical system was used to provide a bipartite field subtending 2 deg of arc, and an adapting field of 5 deg 50 min arc. Two monochromatic lights provided by two channels were presented in the left half of the bipartite field. Two other channels provided white light (of the same CIE chromaticity coordinates: $x = 0.32$, $y = 0.33$, and the same retinal illuminance). One of the latter channels provided the reference light presented in the right half of the bipartite field and the other the adapting field. The bipartite field and the adapting field were alternated every four seconds.

Three males, HY (28 years old), SR (25 years) and KK (24 years), and one female MA (23 years) with normal colour vision served as subjects. Measurements of the luminous efficiency functions and the additivity test with a 100-td reference light were carried out for the subjects SR and MA. For the other two subjects, HY and KK, three levels of reference light, 10, 100 and 1000 td, were investigated.

Additivity was tested for the bichromatic mixture of wavelengths λ_1 and λ_2. Let the radiances of monochromatic lights whose wavelengths are λ_1 and λ_2 be $L_{e,01}$ and $L_{e,02}$ when they are separately matched in brightness to a white reference light. Next, let the radiances of λ_1 and λ_2 be $L_{e,m1}$ and $L_{e,m2}$ when, presented as a mixture, they are matched in brightness to the same white reference light. If we define ϱ_1 and ϱ_2 as follows:

$$\varrho_1 = L_{e,m1}/L_{e,01}$$
$$\varrho_2 = L_{e,m2}/L_{e,02}$$

then the additivity property can be evaluated by the value $\varrho_1 + \varrho_2$. If $\varrho_1 + \varrho_2 = 1$, additivity holds; if $\varrho_1 + \varrho_2 > 1$, there is a failure of the reduction type ("subadditivity"); and if $\varrho_1 + \varrho_2 < 1$, there is a failure of the enhancement type ("superadditivity").

In the present experiment, in order to avoid a change of colour in the mixture, the ratio of ϱ_1 to ϱ_2 was fixed while the subject made his adjustment of brightness. The values of λ_1 and λ_2 were 500 nm (510 nm for subject KK) and 660 nm respectively. Eleven ratios of ϱ_1 to ϱ_2 were chosen.

Results and Discussion

Relationship Between the Luminous Efficiency Function and the Additivity Property

Luminous efficiency functions for heterochromatic brightness matching are shown for four subjects in Fig. 1. The curves are normalized at 570 nm. We see no significant difference between the luminous efficiency functions in the region 420–600 nm except for subject KK, who shows a rather broad luminous efficiency function. In the long-wavelength region, however, there are clearer differences between subjects.

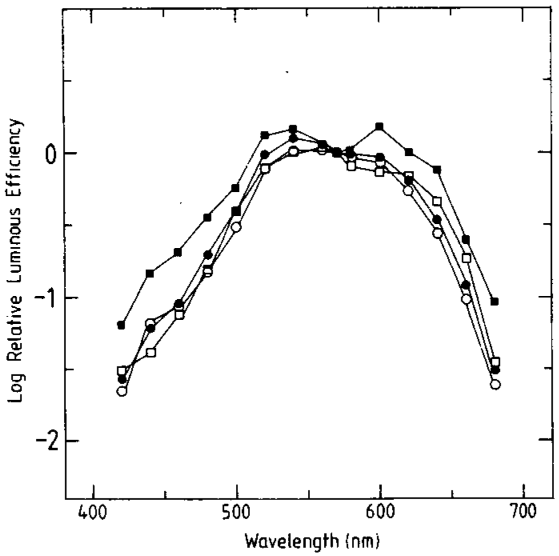

FIG. 1 Luminous efficiency functions at 100 td for four subjects, KK (filled squares), MA (open squares), HY (filled circles), and SR (open circles).

$\varrho_1 - \varrho_2$ plots are shown in Fig. 2 for the mixtures of 500-nm green (510 nm for KK) and 660-nm red for four subjects. A straight line connecting points (0,1) and (1,0) represents linear additivity, that is $\varrho_1 + \varrho_2 = 1$. Any points beyond this line to the upper right indicate an additivity failure of the reduction type, and points in the lower left region indicate an additivity failure of the enhancement type. The results of Fig. 2 show clear subadditivity for all subjects. Deviation from the straight line is not symmetrical: all subjects show the maximum additivity failure in a region toward the ϱ_1 axis. There is also a remarkable difference among subjects. The $\varrho_1 - \varrho_2$ plots of the subject KK are the farthest from the additivity line, indicating the largest reduction in brightness. From Figs 1 and 2 it may be said that the additivity failure of the reduction type is particularly marked for the subject whose luminous efficiency curve is broadest.

This relationship was reflected in other experimental results. Figure 3 shows for subject KK the luminous efficiency curves at three different retinal illuminances, 10, 100 and 1000 td. As retinal illuminance increases, the luminous efficiency curve broadens. Correspondingly, as shown in Fig. 4, the $\varrho_1 - \varrho_2$ curves of KK increasingly depart from the additivity line with increasing retinal

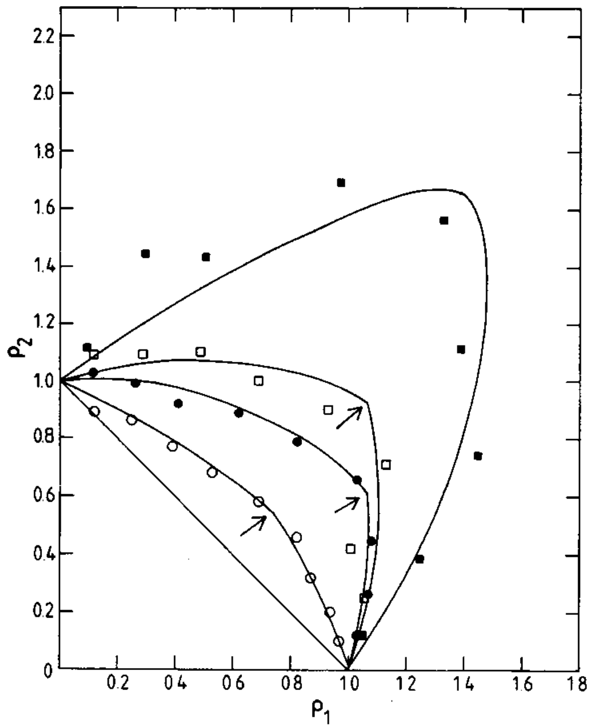

FIG. 2 $\varrho_1 - \varrho_2$ plots for 500–660 nm pair (510–660 nm for KK) for four subjects, KK (filled squares), MA (open squares), HY (filled circles), and SR (open circles). Arrows indicate the perceived red–green equilibrium for each subject. Solid curves are the theoretical $\varrho_1 - \varrho_2$ curves.

illuminance. For another subject HY, in contrast, the luminous efficiency curve did not significantly differ at different retinal illuminances; and similarly the $\varrho_1 - \varrho_2$ plots did not vary for this subject.

These experimental results are compatible with the hypothesis that both the broadening of the luminous efficiency curves and the subadditivity of brightness are caused by contributions of opponent-colour channels to brightness.

Theoretical Analysis of Asymmetrical Additivity Failure

The contribution of the opponent-colour channels to brightness is confirmed by the asymmetry of the $\varrho_1 - \varrho_2$ plots. The asymmetrical nature of additivity failure was observed by Tessier and Blottiau (1951) and Yaguchi and Ikeda (1982) in heterochromatic brightness matching, and by Boynton, Ikeda and Stiles (1964) and Kranda and King-Smith (1979) in detection of increments.

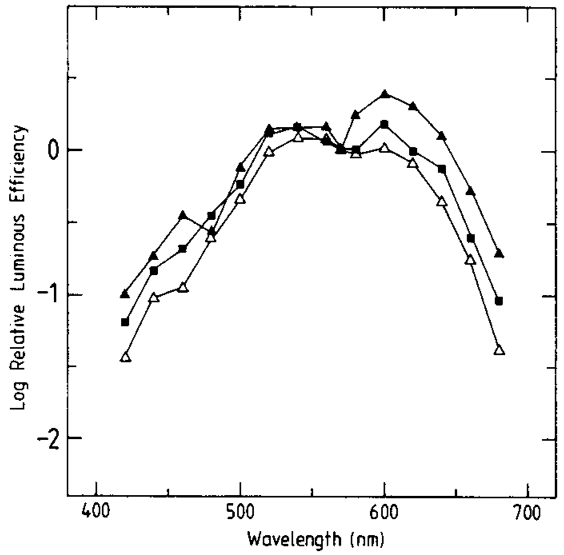

FIG. 3 Luminous efficiency functions at three levels of retinal illuminance, 10 td (open triangles), 100 td (filled squares), and 1000 td (filled triangles) for subject KK.

Yaguchi and Ikeda (1982) suggested that the hue cancellation in the red–green opponent-colour channel caused the brightness reduction: they showed that the maximum brightness reduction point in $\varrho_1 - \varrho_2$ plots coincided with the red–green equilibrium for each subject. They proposed a nonlinear model to explain the asymmetry. In this model, a unit brightness of a monochromatic light of wavelength λ_i is defined as:

$$A_i^2 + (|C_{1i}|^p)^2 + (|C_{2i}|^q)^2 = 1,$$

where A_i, C_{1i} and C_{2i} are the responses of the achromatic channel, the red–green opponent-colour channel, and yellow–blue opponent-colour channel, respectively. For a mixture of two monochromatic lights of wavelengths λ_1 and λ_2, this expression becomes

$$(\varrho_1 A_1 + \varrho_2 A_2)^2 + (|\varrho_1 C_{11} + \varrho_2 C_{12}|^p)^2 + (|\varrho_1 C_{21} + \varrho_2 C_{22}|^q)^2 = 1.$$

The nonlinearity of the red–green opponent-colour channel with an exponent p and that of the yellow–blue opponent-colour channel with an exponent q are assumed to explain the asymmetry found in $\varrho_1 - \varrho_2$ curves. The vector model proposed by Guth and Lodge (1973) equated p and q to unity, but it then cannot explain the asymmetrical $\varrho_1 - \varrho_2$ curve.

Exponents $p = 0.64$ and $q = 0.36$ were determined by numerous $\varrho_1 - \varrho_2$

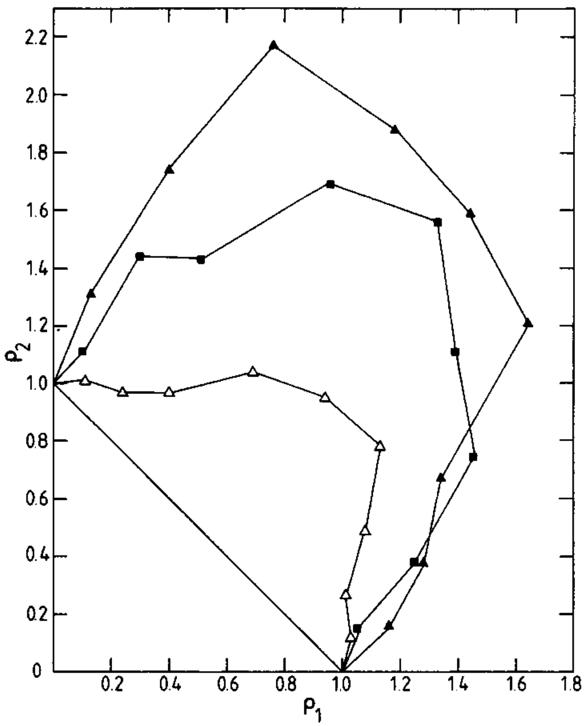

FIG. 4 $\varrho_1 - \varrho_2$ for 510–660 nm pair at three levels of retinal illuminance, 10 td (open triangles), 100 td (filled squares), and 1000 td (open triangles) for subject KK.

plots of various $\lambda_1 - \lambda_2$ pairs for the subject HY and then applied to the other subjects. The coefficients A_i, C_{1i} and C_{2i} were determined for each subject as follows. At the red–green equilibrium, the response of the red–green opponent-colour channel in the mixture of 500 nm and 660 nm should become zero. The ratios of C_{11} to C_{12} were chosen so that the value of $\varrho_1 C_{11} + \varrho_2 C_{12}$ became equal to zero at the red–green equilibrium point (obtained by colour naming) for each subject except for subject KK. Since KK did not carry out colour naming, the farthest point in his $\varrho_1 - \varrho_2$ plots was assumed to be his red–green equilibrium. Because the contribution of the yellow–blue opponent-colour channel to brightness seems to be negligible for the combination of 500 nm and 660 nm, values of $C_{21} = 0.0$ for 500 nm and $C_{22} = 0.002$ for 660 nm were adopted for all subjects.

The coefficients A_i, C_{1i}, and C_{2i} are presented for each subject in Table 1. The continuous solid curves in Fig. 2 are the theoretical $\varrho_1 - \varrho_2$ curves based on these coefficients; the arrows correspond to the red–green equilibrium for each subject. Each cusp appearing in the theoretical $\varrho_1 - \varrho_2$ curve corresponds to the zero response of the red–green opponent-colour channel, that is, the red–green equilibrium.

TABLE 1 The coefficients A_i, C_{1i} and C_{2i} of the theoretical $\varrho_1 - \varrho_2$ curves.

Subject	500 nm*			600 nm		
	A_1	C_{11}	C_{21}	A_2	C_{12}	C_{22}
SR	0.83	-0.41	0.00	0.72	0.55	0.002
HY	0.75	-0.52	0.00	0.33	0.91	0.002
MA	0.56	-0.75	0.00	0.43	0.84	0.002
KK	0.11	-0.99	0.00	0.50	0.79	0.002

* 510 nm was used for the subject KK.

The theoretical $\varrho_1 - \varrho_2$ curves fit the experimental $\varrho_1 - \varrho_2$ plots very well for all subjects. The subject who has the broadest luminous efficiency curve is expected to show a large contribution of the red–green opponent-colour channel to brightness. When this contribution is expressed as C_{11} for 500 nm it increases in the order: KK, MA, HY, and SR; but the contribution expressed as C_{12} for 660 nm does not vary systematically for the four subjects, as shown in Table 1. This unexpected problem might be caused by an inadequate choice of p and q.

We conclude that the contribution of the opponent-colour channels to brightness causes the broadening of the luminous efficiency curve as well as the additivity failure of the reduction type. Furthermore, the asymmetry of $\varrho_1 - \varrho_2$ plots for individual subjects can be explained by the nonlinear contribution of the opponent-colour channels to brightness.

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References

Bauer, H. D. and Röhler, R. (1977). Brightness generation in the human visual system. Colour-brightness: a contribution of cortical colour channels to brightness sensation. *Vision Res.* **17**, 1211–1216.

Boynton, R. M., Ikeda, M. and Stiles, W. S. (1964). Interactions among chromatic mechanisms as inferred from positive and negative increment thresholds. *Vision Res.* **4**, 87–117.

Comerford, J. P. and Kaiser, P. K. (1975). Luminous–efficiency functions determined by heterochromatic brightness matching. *J. opt. Soc. Am.* **65**, 466–468.

Guth, S. L. and Lodge, H. R. (1973). Heterochromatic additivity, foveal spectral sensitivity, and a new color model. *J. opt. Soc. Am.* **63**, 450–462.

Ikeda, M., Yaguchi, H., Yoshimatsu, K. and Ohmi, M. (1982). Luminous-efficiency functions for point sources. *J. opt. Soc. Am.* **72**, 68–74.

Ingling, C. R. and Tsou, B. H. (1977). Orthogonal combination of the three visual channels. *Vision Res.* **17**, 1075–1082.

Kranda, K. and King-Smith, P. E. (1979). Detection of coloured stimuli by independent linear systems. *Vision Res.* **21**, 733–745.

Tessier, M. and Blottiau, F. (1951). Variations des caractéristiques photométriques de l'oeil aux luminances photopiques. *Revue d'Optique.* **30**, 309–322.

Wagner, G. and Boynton, R. M. (1972). Comparison of four methods of heterochromatic photometry. *J. opt. Soc. Am.* **62**, 1508–1515.

Yaguchi, H. and Ikeda, M. (1980). Helmholtz-Kohlrausch effect investigated by the brightness additivity. *J. Illum. Inst. Japan.* **64**, 566–570.

Yaguchi, H. and Ikeda, M. (1982). Nonlinear nature of the opponent-color channels. *Color Res. Appl.* **7**, 187–190.