Heterochromatic brightness matching with checkerboard patterns

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Heterochromatic brightness matches with checkerboard patterns made up of a white reference and a chromatic test element for various element sizes from 3′ to 2°30′ square and with a 5° bipartite field were carried out with a color cathode-ray tube. The brightness-to-luminance (B/L) ratios of six chromatic stimuli were obtained, and the brightness additivity for the mixture of red and green was tested. When the reference and test elements were juxtaposed without a gap, the B/L ratio of the test chromatic stimulus decreased with decreasing element size. Brightness additivity failed for an element size of 30′ and a 5° bipartite field. Brightness additivity held for a small element size of 3′. When the reference and test elements were separated by a gap 3′ in width, the B/L ratios were generally greater than unity regardless of element size. Under these conditions, the brightness additivity also failed for the smallest, that is, the 3′ element size.

INTRODUCTION

A highly saturated color appears brighter than a white light when they are equated for luminance. This is a drawback of the present photometric system, so many papers have dealt with this problem.[1–8] The discrepancy between luminance and brightness may be explained by a model of color vision (e.g., Guth and Lodge,[9] Ingling *et al.*,[10] and Yaguchi and Ikeda[11]). The model suggests that there are three visual channels in cone-fed neural pathways. One is the achromatic channel, in which outputs of different types of cone combine by linear summation. The other two channels are the chromatic channels, in which the result is related to the difference between outputs of different types of cone. One of the chromatic channels is called the red–green opponent channel, and the other is called the yellow–blue opponent channel. It is suggested that the chromatic channels have poorer temporal and spatial resolution than the achromatic channel.[12] When we estimate brightness by direct heterochromatic brightness matching in a bipartite field of 1° or 2°, high temporal and spatial resolution is not required. Here both achromatic and chromatic channels are used for the criterion of brightness. On the other hand, since a high temporal resolution is required for flicker photometry, the achromatic channel concerns itself exclusively with a determination of luminance defined by flicker photometry. From these points of view it is safe to say that brightness perception depends on the temporal and spatial profile of the stimulus.

The property of brightness perception related to the temporal profile has been investigated by Ikeda and Shimozono.[13] They measured the luminous efficiency function by successive brightness matching with various alternating frequencies and showed that luminous efficiency decreased abruptly at around 4 or 6 Hz. With regard to the spatial property of brightness perception, Boynton and Kaiser[14] found that additivity holds for the criterion of a minimally distinct border (MDB) between two precisely juxtaposed fields, and Ikeda *et al.*[15] have suggested that the luminous efficiency function using heterochromatic brightness matching with point sources is similar to the Commission Internationale de l'Eclairage (CIE) $V(\lambda)$. Actual objects whose brightness is estimated, however, form a complex pattern that consists of many edges and many components of various shapes and sizes. The question can be asked: "Which spatial factor is the most important for brightness perception: the edge, the field size, or the spatial frequency?" So far, we have no data concerning the perception of brightness of such a complex pattern.

In the present experiment, checkerboard patterns made up of reference and test elements were used for heterochromatic brightness matching in order to examine the spatial factors of brightness perception. The experiments consisted of two parts. In the first experiment, the brightness-to-luminance (B/L) ratio of six colors was determined as a function of element size or spatial frequency. The B/L ratio is a straightforward factor representing the discrepancy between brightness and luminance. In the second experiment, additivity was examined for three different element sizes. The additivity test is an appropriate way to estimate whether the brightness perception is affected by one or more channels.

METHODS

Apparatus

The apparatus used to generate the desired test patterns has been described in detail by Cowan.[16] It consists of a television monitor controlled by an IKONAS graphic system and a PDP-11/23 computer. The monitor provided 512 × 320 pixels. Through control of the excitation of each of the red, green, and blue phosphors, each pixel was capable of generating a large number of different colors. With 1024 excitation levels per phosphor, a total of 10^9 different colors per pixel was available. A digitizing tablet was used to control the excitation of each phosphor and to transfer the observer's response to the computer.

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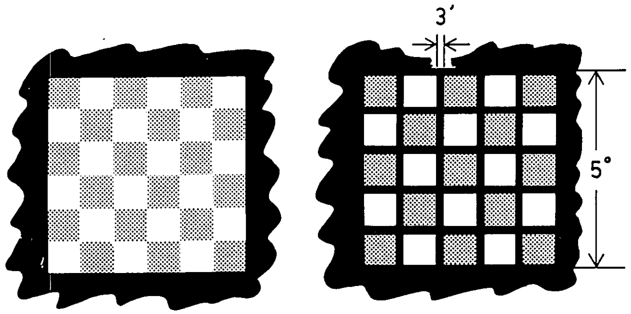


(a) (b)

Fig. 1. A schematic example of test patterns: (a) reference elements and test chromatic elements are juxtaposed without gap; (b) reference and test elements are separated by a grid whose width is 3′.

Table 1. The CIE 1931 Chromaticity Coordinates of Test Stimuli

Color	x	y
White	0.284	0.340
Yellow	0.379	0.533
Green	0.215	0.675
Cyan	0.179	0.339
Blue	0.150	0.067
Magenta	0.320	0.162
Red	0.620	0.329
GY	0.302	0.601
RY1	0.441	0.482
RY2	0.503	0.430
RY3	0.572	0.370

Calibration

The method used to calibrate the TV monitor was the one developed by Cowan.[17] The method provides CIE 1931 (x, y) chromaticity coordinates for each color stimulus used in the experiment.

The luminance of each stimulus was derived from the spectral radiance distribution of the stimulus and the luminous efficiency functions of the actual observers taking part in the experiment. Two observers took part in the experiment, and each had his luminous efficiency functions measured on the National Research Council of Canada trichromator[18] by employing flicker photometry in a 2° visual field.

Stimuli

The color stimuli were displayed in a checkerboard pattern. Two types of pattern were used, as illustrated in Fig. 1. In pattern (a) there is no gap between the test and reference elements. In pattern (b) a 3′ gap is introduced between the test and reference elements. In other words, pattern (a) permits edges between test and reference elements, but pattern (b) does not. The surround and the gap are an unlighted part of the cathode-ray tube (CRT). The actual size of each pattern is 11.6 cm square. Each pattern is viewed at a distance of 120 cm, giving an angular subtense of 5° square. The element size in each pattern is variable. In the experiment, seven element sizes were used: 3′, 4.5′, 9′, 15′, 30′, 1°15′, and 2°30′ square. Patterns with and without a gap were both made up of the same element size. Since the spatial frequencies were calculated for the elements plus the gap, the spatial frequencies for the patterns with and without gaps were different for each. The element sizes correspond to 10, 6.7, 3.3, 2, 1, 0.4, and 0.2 cycles per degree (cpd) for the pattern without the gap and to 5, 4, 2.5, 1.7, 0.9, 0.4, and 0.2 cpd for the pattern with the gap. In addition to the checkerboard pattern, a horizontally divided bipartite field of 5° was used in the experiment.

Table 1 shows the chromaticity coordinates of the test stimuli. The chromaticity coordinates of the reference stimulus were $x = 0.284$, $y = 0.340$. In experiment 1, six chromatic stimuli were used as test stimuli. The three test stimuli, red, green, and blue, were selected from the primary colors of the CRT. Each color was obtained by exciting each of three phosphors. Three other test stimuli, yellow, magenta, and cyan, were obtained by exciting two of three phosphors. Seven colors consisting of various proportions of the red and green primaries were presented as an additivity test in experiment 2.

Observers

Two 32-year-old males, HY and TF, with normal color vision checked by Ishihara charts, were employed as observers. Both observers used normal corrected acuity. A lens for correcting chromatic aberration of the eye designed by Powell[19] was used for both observers in order to remove chromatic aberration caused by the short wavelength of the blue phosphor. Observer TF participated only in experiment 1.

Procedure

The usual method of heterochromatic brightness matching is to keep the luminance of the reference stimulus constant and to adjust the luminance of the test stimulus to be equal in brightness to the reference stimulus. In this conventional method, the average luminance over the whole checkerboard pattern changes with the luminance of test stimuli. A pilot experiment, however, showed that the change of the average luminance somehow made it difficult to make a judgment of equal brightness with decreasing element size. We therefore used a counterbalance adjustment method, in which the luminance of the reference stimulus changed in a reverse direction of the change of the test stimulus to keep the average luminance over the pattern constant. In measurements of MDB, the counterbalance adjustment method was also used. At the beginning of each trial, luminances of the test and reference stimuli were set at 10 cd/m^2. The observer viewed the test pattern monocularly (right eye) without a fixation point.

The observer used the criterion of equal brightness between test and reference elements for both types of pattern, with and without a gap. When small element-size patterns were presented, however, the test pattern appeared to be of all one hue; that is, the observer could not discriminate the hue difference between the test and reference elements. It appeared as if the test color were fused with the white reference. In this particular case, the criterion became different from the criterion of equal brightness because the task of brightness matching was difficult. Both observers used the criterion of pattern uniformity.

In experiment 1, when a brightness match between the test stimulus of luminance L_{tst} and a reference stimulus of luminance L_{ref} was made, the B/L ratio was defined as $\mathrm{B/L} = L_{\mathrm{ref}}/L_{\mathrm{tst}}$. Eight element-sized patterns were presented in an experimental session. For each element-sized pattern, the observer made three consecutive matches for each of six test stimuli. Five experimental sessions were carried out for both observers.

In experiment 2, the additivity test was carried out in the conventional manner. Let the luminance of a primary stimulus be L_{10}, which is matched to a reference stimulus whose luminance is L_{ref1}. Similarly, let the luminance of another primary stimulus, L_{20}, be matched to a reference stimulus whose luminance is L_{ref2}. A test stimulus composed of the mixture of these two primary stimuli whose luminances are $L_{1\mathrm{m}}$ and $L_{2\mathrm{m}}$ is then matched to a reference stimulus of luminance L_{refm}. In the experiment the ratio of $L_{1\mathrm{m}}/L_{2\mathrm{m}}$ was kept constant. The luminances of reference stimuli L_{ref1}, L_{ref2}, and L_{refm} are different from one another because the counterbalance adjustment method was used. The luminances of the test stimuli must therefore be normalized to the luminance of each reference stimulus in order to obtain a relative luminance that corresponds to the value of an equal reference luminance. With the relative luminances, $n_{10} = L_{10}/L_{\mathrm{ref1}}$, $n_{20} = L_{20}/L_{\mathrm{ref2}}$, $n_{1\mathrm{m}} = L_{1\mathrm{m}}/L_{\mathrm{refm}}$, and $n_{2\mathrm{m}} = L_{2\mathrm{m}}/L_{\mathrm{refm}}$, we define ρ_1 and ρ_2 as follows:

$$\rho_1 = n_{1\mathrm{m}}/n_{10}, \qquad \rho_2 = n_{2\mathrm{m}}/n_{20}.$$

Additivity can be checked by evaluating $\rho_1 + \rho_2$. If $\rho_1 + \rho_2 = 1$, additivity holds; if $\rho_1 + \rho_2 > 1$, it fails by brightness reduction; and if $\rho_1 + \rho_2 < 1$, it fails by brightness enhancement.

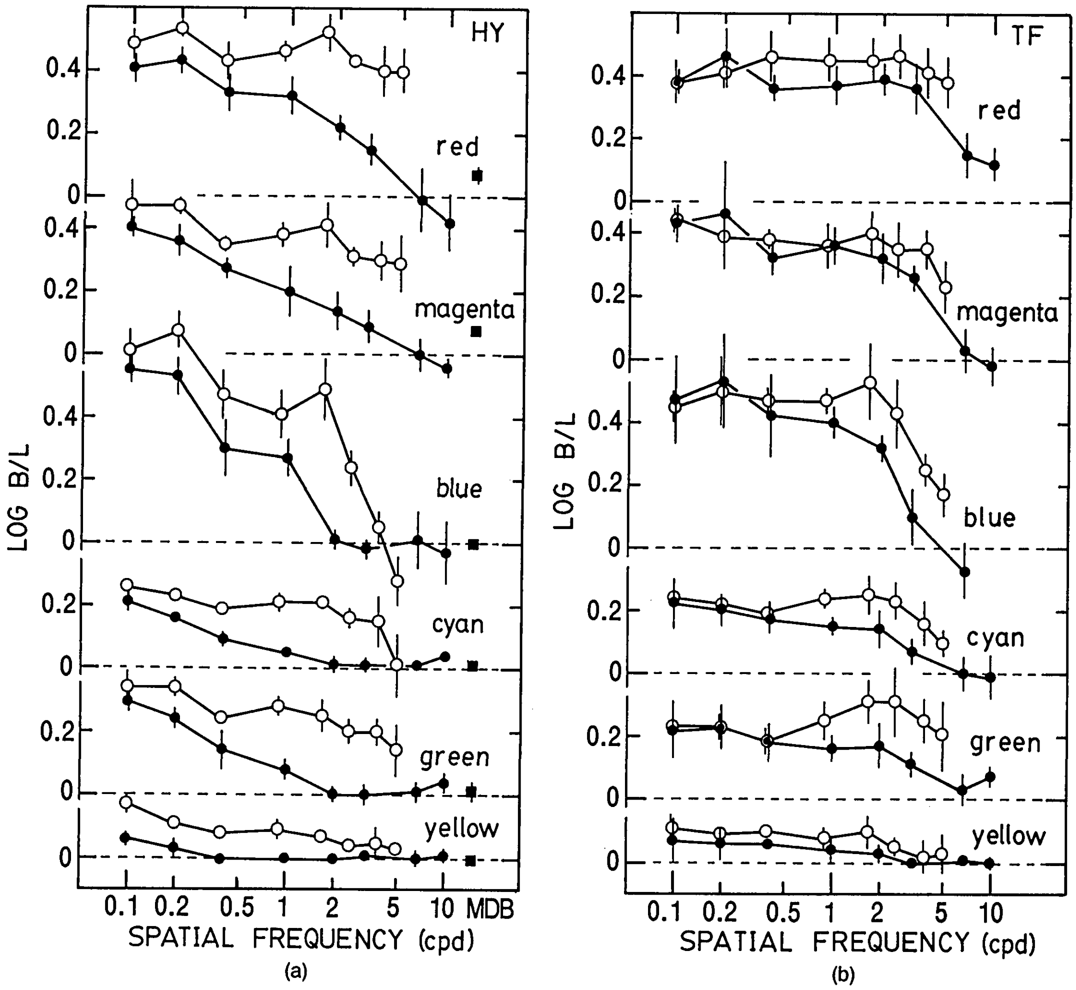
Red and green primary stimuli were used for the additivity test. Seven luminance ratios of red/green were selected to obtain the relationship between ρ_1 and ρ_2. In a single experimental session, a bipartite field and two element sizes, 3′ and 30′, were presented, and the observer made five consecutive matches for each luminance ratio of test stimuli. Five experimental sessions were carried out, and the mean was determined.

RESULTS

Experiment 1: The Brightness-to-Luminance Ratios

Figure 2 represents the B/L ratio for six test stimuli as a function of the spatial frequency of a checkered pattern for two observers. Error bars show ±1 standard deviation for five experimental sessions. The data of 0.1 cpd were obtained by using a 5° bipartite field.

Both observers show the following similar results. The B/L ratios of both patterns with gaps (open circles) and without gaps (filled circles) at the lowest spatial frequency are the same as for a bipartite field. The B/L ratio of the low spatial frequency depends on the saturation of the chromat-



(a) (b)

Fig. 2. The B/L ratios for six test chromatic stimuli as a function of element size from observers HY (a) and TF (b). Filled circles, patterns without gaps; open circles, patterns with gaps; filled squares, MDB. Error bars indicate ±1 standard deviation.

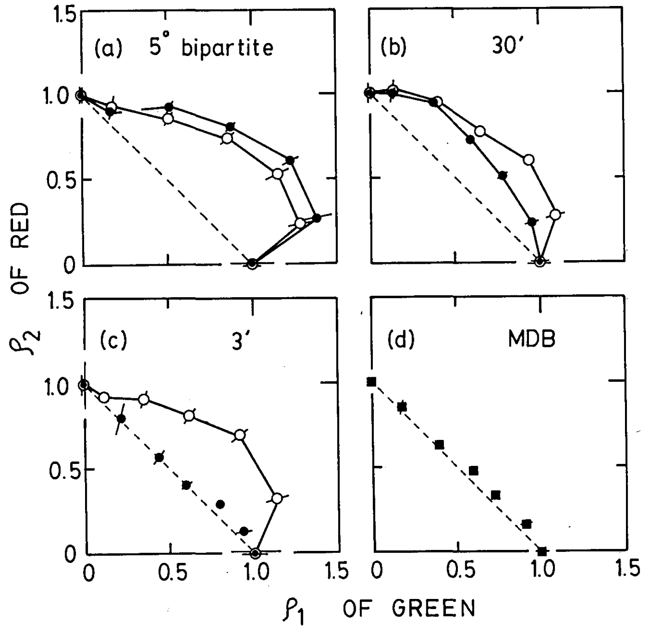


Fig. 3. ρ_1–ρ_2 plots for the heterochromatic brightness matching using a checkered pattern without gap (filled circles) and with gap (open circles). Plots are shown for (a) a bipartite field, checkerboard (b) patterns of 30′ and (c) 3′ square, and (d) a MDB. Errors bars indicate ±1 standard deviation.

ic stimulus; for example, yellow gives a low ratio, whereas blue gives a high ratio. The curve of patterns without gaps declines as the spatial frequency rises. On the other hand, there is little decline in the B/L ratios with spatial frequency for the pattern with a gap until the highest spatial frequencies. Furthermore, the pattern with a gap gives a higher B/L ratio than the pattern without a gap over almost all the range of spatial frequencies. The B/L ratio for blue of the pattern with a gap drops abruptly at around 2 cpd. The logarithms of the B/L ratios for the pattern without a gap reach 0 at 8 cpd except for the red of observer TF, which means that the criterion for these patterns is equivalent to that of flicker photometry. Furthermore, they are also close to the data obtained by the MDB criterion (filled squares for HY).

Experiment 2: Additivity

Figure 3 shows the ρ_1–ρ_2 plots obtained by the additivity test for the heterochromatic brightness matching using (a) a 5° bipartite field, element-size checkerboard patterns of (b) 30′ and (c) 3′, and (d) a MDB for observer HY. Error bars indicate ±1 standard deviation unit for five experimental sessions. ρ_1 corresponds to a relative amount of green primary in the mixture, and ρ_2 corresponds to relative amount of red primary. The ρ_1–ρ_2 plots obtained with a 5° bipartite field show additivity failure of the reduction type for patterns with gaps (open circles) and patterns without gaps (filled circles). For a checkerboard pattern with the element size of 30′, additivity failure of the reduction type still appears for both patterns. The degree of reduction, however, decreases for the pattern without a gap. For the smallest element size, 3′, the ρ_1–ρ_2 plots for patterns with gaps still show additivity failure of the reduction type. On the other hand, the ρ_1–ρ_2 plots for patterns without gaps are close to the line of $\rho_1 + \rho_2 = 1$, which indicates that additivity holds. The MDB result also shows additivity.

DISCUSSION

The B/L ratios for checkered patterns made up of white and chromatic elements smaller than 4.5′ square and not separated by a gap were close to 1.0. Additivity between green and red held when this pattern was used. This phenomenon may be explained as follows. Since the spatial integration of the chromatic channel is greater than that of the achromatic channel, the brightness difference between test and reference of small elements is exclusively detected by the achromatic channel. These results are consistent with the results obtained by using the criterion of visual acuity by Myers *et al.*[20] and Guth and Graham[21] and also with the results of increment threshold experiments for the detection of a structured pattern of small targets by Moorhead and Saunders.[22] On the other hand, for a pattern with a gap, the B/L ratio did not decrease with decreasing element size as much as that for the pattern without a gap. Additivity between green and red did not hold for the pattern with a gap regardless of element size.

The gap effect on brightness perception of checkerboard patterns is evident. Boynton *et al.*[23] discussed the gap effect and suggested that luminance discrimination was impaired but chromatic discrimination was either unaffected or improved. From the present results, the gap seems to reduce the achromatic channel's contribution and to enhance the chromatic channel's contribution. It is suggested that the gap hides the high-spatial-frequency information derived from the edge between test and reference lights. In other words, if there is a gap, the test color is not fused with the reference color, so it becomes easier to compare the brightness of test and reference separately. On the other hand, if there is no gap, the test color for small element sizes is fused with the reference color, so it becomes impossible to make explicit brightness matches. The observers are then obliged to use the criterion of pattern uniformity. When inhomogeneities were seen, this apparently was taken as a nonbrightness match. When the field was homogeneous the fields were considered to be equal in brightness.

From the results of B/L ratios and an additivity test using a checkerboard pattern of 3′ elements with a gap, it appears that the chromatic channel still contributes to the judgment of equal brightness. Previous results by Booker[6] and Ikeda *et al.*,[15] however, have shown that the judgment of equal brightness for a small field is determined solely by the achromatic channel. A probable reason for this inconsistency is the difference of the total area on the retina. Although the checkerboard pattern of small elements with a gap is considered a gathering of small fields, a larger portion of the fovea was used than in the case of the small bipartite field.

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