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Wavelength Discrimination with a Chromatically Alternating Stimulus

Wavelength-discrimination functions were measured with monochromatic stimuli of 410–660 nm at equal luminance of 220 td, presented as temporally alternating fields at the frequencies of 0.5–12.0 Hz. When the alternation frequency was less than 1.0 Hz, wavelength discrimination was the same at all test wavelengths as that obtained by the classical bipartite-field method. As the frequency was raised, the discrimination thresholds increased more near 450–470 nm than at other wavelengths, and tritanopic-like wavelength-discrimination functions were obtained at frequencies higher than 4.0 Hz. Our results may be explained by the notion that the blue-cone mechanism has poorer temporal resolution than the red- and green-cone mechanisms.

Introduction

Color discrimination is one of the most fundamental properties of human color vision. A number of investigations on color discrimination have been performed with various experimental conditions to reveal the human color-vision mechanism. Among these experimental conditions were stimulus field size, luminance level, retinal location, and temporal asynchrony of presenting the stimulus.[1–7] It has been conventional in these studies that two colors be adjacently presented in two closely juxtaposed bipartite fields, so that the two colors are spatially separated. However, one may compare two colors using temporally separated fields instead of spatially separated fields; that is, the two colors are presented in temporally alternating fields.[8–14] Ikeda and Shimozono[8] reported that brightness matching of two colors could be performed in alternating fields with a frequency of less than 4 Hz. The luminous-efficiency functions determined by this method agreed well with those obtained by the normal bipartite-field method. Kaiser, Comerford, and Bodinger[9] used slowly alternating fields for saturation discrimination and also obtained similar results to those by the bipartite-field method. This means that slowly alternating fields can be used as well as the bipartite field for color comparison.

When the alternation frequency is low, clear color alternation is perceived for two colors with a large color difference, whereas when the colors of the fields are identical no color alternation is observed. Suppose that two monochromatic lights λ, $\lambda + \Delta\lambda$ are equated in luminance and alternated at a constant frequency. When $\Delta\lambda$ is equal to zero, the alternating fields appear the same in chromaticness. If the alternating fields still appear chromatically identical when $\Delta\lambda$ increases, it may be said that for these two monochromatic lights it is not possible to discriminate the difference $\Delta\lambda$. As $\Delta\lambda$ increases, a point is reached at which color alternation is just observed in the alternating fields. This value of $\Delta\lambda$ is then defined as the wavelength-discrimination threshold.

It has been shown that a chromatic-discrimination threshold obtained by the alternating-stimulus method depends upon the alternation frequency.[10–14] Regan and Tyler[10] reported that wavelength-discrimination thresholds measured with wavelength-modulated flicker were constant or increased slowly as the alternation frequency was raised up to about 5 Hz, and then increased rapidly as the frequency increased beyond 5 Hz. They also showed that the wavelength-discrimination functions with a flicker frequency of 0.5 Hz were quite similar to those obtained by the bipartite-field method, but at 5 Hz they differed in shape in the blue–green region. The discrimination thresholds for 500–520 nm were found to be largest among those for the blue–green region at 0.5 Hz, whereas they were smallest at 5 Hz. However, since no data were reported for wavelengths shorter than 480 nm, it was not clear how the discrimination thresh-

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olds in the blue region vary depending on the alternation frequency. Kambe[11] showed that the wavelength discrimination measured by chromatic flicker of 5 Hz greatly deteriorated for the whole spectrum when compared with that of 1 Hz. At 5 Hz, the discrimination thresholds were found to be more than 20 nm at all wavelengths of 400–620 nm except at a few points. These results appeared quite different from those of Regan and Tyler, though the two investigations employed the same field size of 2° and similar luminance levels of 20–25 td.

In this investigation, we measured wavelength-discrimination functions using the alternating-stimulus method to determine, first, whether this alternating-stimulus method yields a different discrimination function from that obtained by the conventional bipartite-field method, especially in the blue region and, second, how the wavelength-discrimination function varies as the frequency of alternation increases. Our study differs from the investigations previously reported in that we chose test wavelengths over the whole spectrum (410–660 nm), and that complete wavelength-discrimination functions were obtained for a large range of alternation frequencies (0.5–12.0 Hz).

Method

Apparatus

We used a conventional two-channel Maxwellian-view system with a 500 W xenon arc lamp as a light source. Two grating monochromators produced monochromatic lights with half-band widths of 6 nm. Neutral-density wedges were driven by stepping motors to adjust the luminances of the monochromatic lights. The observer could vary the wavelength and luminance of the two channels by using switches connected to the LSI–11 microcomputer that controlled the monochromators and the wedges. The stimulus alternation was controlled with two high-speed electromagnetic shutters, opened and closed so that the two lights were delivered 180° out of phase. The shutters were placed at focal planes of the light beams. The rise time for each channel was less than 1 msec. Slight adjustments for both on/off durations and the relative phase of the two shutters could be carried out by the microcomputer to reduce any temporal artifacts. Circular stimulus fields of 2° visual angle were used for the alternating-stimulus method. Opposite vertical halves of each circular field were occluded to make two adjacent semicircular fields for the bipartite-field method.

Procedure

This research used two observers, KU and TF, a male and a female, 32 and 24 years of age, respectively. Both had normal color vision according to the Ishihara test and on the basis of wavelength-discrimination curves.

The test stimuli ranged from 410 to 660 nm in 10-nm steps. In the preliminary experiment, first, each observer equated these test stimuli and two other wavelengths of 670, 680 nm to a reference light in luminance by means of heterochromatic flicker photometry. The reference light was 570 nm monochromatic light at 220 td. Flicker frequencies were adjusted between 15.0 and 20.0 Hz for each observer in order that a narrow range of luminance adjustment was required to obtain the minimum flicker criterion. The method of adjustment was used and the observer performed 10 repetitions for each test stimulus.

Second, comparison stimuli, chosen from 400 to 680 nm in 10-nm steps, were equated to the test stimuli in luminance by monochromatic flicker photometry. In this case, each of the test stimuli, which had already been equated in luminance, was used as reference light for each of the comparison stimuli with the same wavelength. The observer, again, performed 10 adjustments for each comparison stimulus. For the comparison wavelength of 400 nm, the test stimulus of 410 nm was used as reference light.

In the wavelength-discrimination experiments, the microcomputer adjusted positions of the wedge in the comparison channel so that when the observer gradually changed the comparison wavelength, the comparison stimuli were always of equal luminance. Linear interpolation of the wedge position was employed when necessary.

In the main experiments, wavelength-discrimination functions were obtained by the alternating-stimulus method for two observers. The test stimulus λ_t was alternated with the comparison stimulus λ_c at an alternation frequency f. Alternation frequency, chosen from 0.5–12.0 Hz, was set constant in a session. The method of limits was employed to determine the discrimination threshold. On the beginning of a trial, the experimenter always set λ_c equal to λ_t. The observer made sure that the two fields appeared equal in chromaticness. If the observer perceived any difference in chromaticness, he or she slightly adjusted λ_c so that no chromatic difference was perceived between the two fields. Then the observer either increased or decreased λ_c until alternation of chromaticness was detected in the alternating fields. Since it was not possible to completely eliminate temporal artifacts in exchange of the fields, the observer could detect, although not so easily, temporal discontinuity between the two fields even when they had the same luminance and wavelength. We employed the criterion of whether the observer perceived alternation in *chromaticness,* and had the observer ignore the achromatic temporal discontinuity. We discuss this criterion later in the Discussion.

Two repetitions were carried out in both increasing and decreasing series for each λ_c in a session. Three sessions were performed for observer KU and two sessions for observer TF, making a total of 6 and 4 repetitions, respectively, for each increasing and decreasing series.

Wavelength-discrimination measurement using a bipartite field was also performed for KU. Test and comparison stimuli were steadily presented in the left and right semicircular fields. The whole field was 2° visual angle. The procedure employed here to determine the discrimination thresholds was the same as for the alternation method. Furthermore, we measured the wavelength-discrimination thresholds as functions of the alternating frequency for two test wavelengths, 460 and 570 nm, in order to closely examine the frequency characteristics of the discrimination threshold. In a session, the test wavelength was fixed and the alternation frequency was varied between 0.5 and 18.0 Hz in either ascending or descending order.

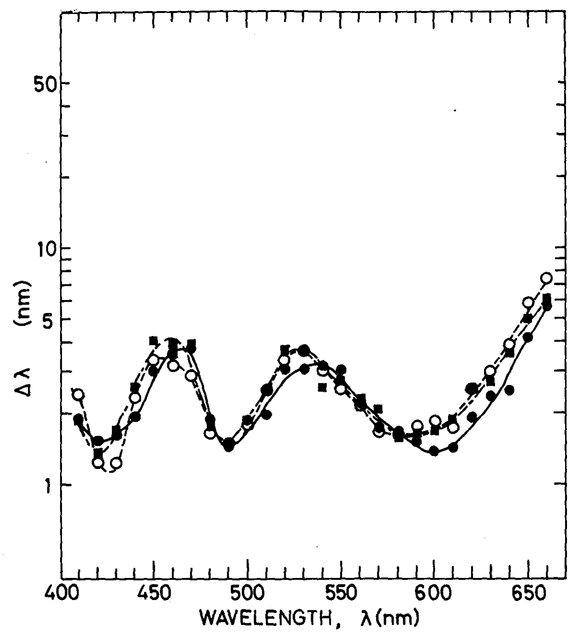
Results

The wavelength-discrimination threshold $\Delta\lambda_+$ was defined as $\lambda_c - \lambda_t$ when λ_c was larger than λ_t, that is, λ_c was obtained by increasing the wavelength, and $\Delta\lambda_-$ was defined as $\lambda_t - \lambda_c$ when λ_c was smaller than λ_t. We used Wright's method[17] to show the wavelength-discrimination functions. Wright did not simply take the average of $\Delta\lambda_+$ and $\Delta\lambda_-$ to make the wavelength-discrimination functions, but plotted $\Delta\lambda_+$ and $\Delta\lambda_-$ at $\lambda_t + (\Delta\lambda_+)/2$ and $\lambda_t - (\Delta\lambda_-)/2$, respectively, on the abscissa when $\Delta\lambda_+$ and $\Delta\lambda_-$ were quite high values. For threshold values higher than 10 nm, we plotted $\Delta\lambda_+$ and $\Delta\lambda_-$ in the figure by Wright's method. The algebraic mean was taken for the other smaller threshold values.

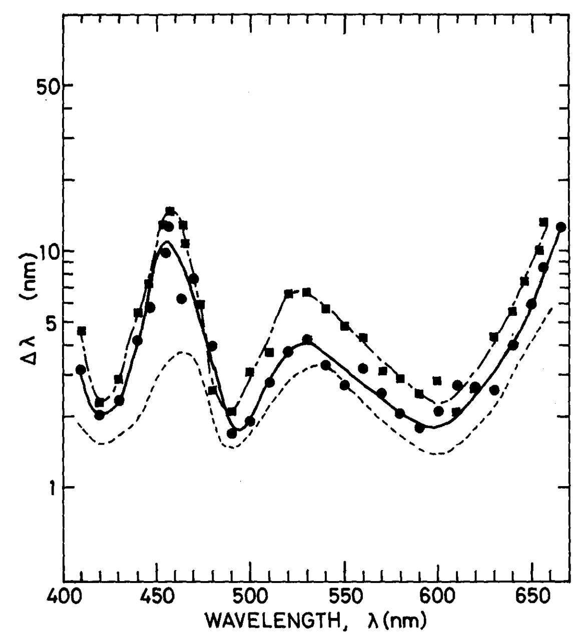
Figure 1 shows the discrimination threshold $\Delta\lambda$ on a logarithmic scale as a function of test wavelength in the range of 410–660 nm for observer KU. For clarity, the results for 0.5 and 1.0 Hz, 2.0 and 4.0 Hz, and 8.0 and 12.0 Hz, are separately shown in Figs. 1(a), (b), and (c), respectively. The lines in the figures were drawn visually to fit the data points. In Fig. 1(a), it is evident that wavelength-discrimination functions measured by the alternation method at 0.5 and 1.0 Hz have almost the same values of $\Delta\lambda$ across all test wavelengths. Moreover, the shape and absolute value of these functions agree well with the function determined by the bipartite-field method which is also shown in Fig. 1(a), indicating that when the alternation frequency was less than 1.0 Hz the alternation method yielded no apparent differences in wavelength discrimination for 410–660 nm from the bipartite-field method.

Figure 1(b) shows $\Delta\lambda$ for 2.0 and 4.0 Hz. For comparison, the discrimination thresholds for 0.5 Hz are also shown in the figure using a dashed line. Most striking results were found in the blue region, that is, that the discrimination thresholds at 450–470 nm increased greatly as frequency was raised to 4.0 Hz. At other wavelengths, the discrimination thresholds differed less among the frequencies tested, with the result that the shape of the wavelength-discrimination function changed so that the peak at 460–470 nm was clearly higher than that at 520–530 nm at 2.0 and 4.0 Hz.

Figure 1(c) shows $\Delta\lambda$ for 8.0 and 12.0 Hz. When compared with those for 4.0 Hz, which are also shown by the dotted line in the figure, the discrimination thresholds increased for all test wavelengths. In the blue region, they were greater than in the other regions, for example, $\Delta\lambda$ at 460 nm reached more than 50 nm for 12.0 Hz. Two maxima and three minima of the discrimination function for 8.0 Hz appeared at the same wavelength regions as for 0.5 and 4.0

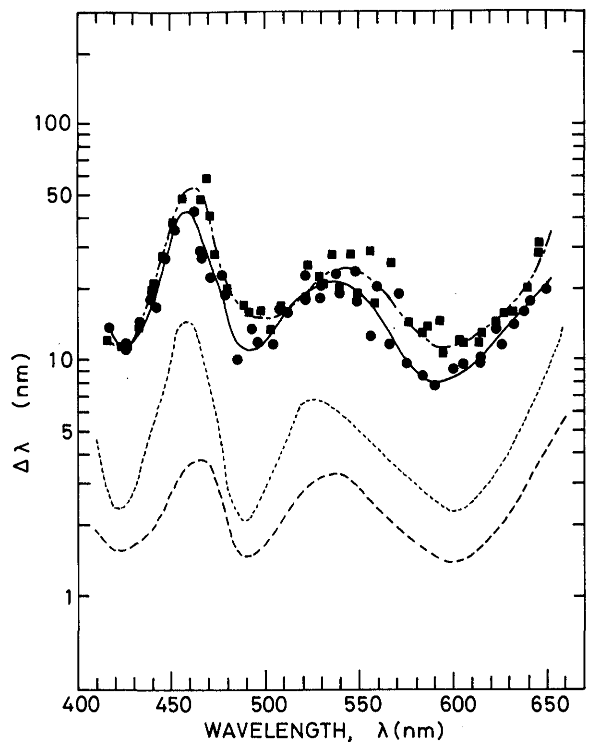


(a)



(b)

FIG. 1. Wavelength-discrimination thresholds $\Delta\lambda$ obtained by the chromatically alternating stimulus method for observer KU. (a) Alternation frequencies are (●) 0.5 and (■) 1.0 Hz. (○) Wavelength-discrimination thresholds obtained by the bipartite-field method (b) Alternation frequencies are (●) 2.0 and (■) 4.0 Hz. (---) Wavelength-discrimination functions for 0.5 Hz. (c) Alternation frequencies are (●) 8.0 and (■) 12.0 Hz. Results at (---) 0.5 and (•••) 4.0 Hz.



(c)

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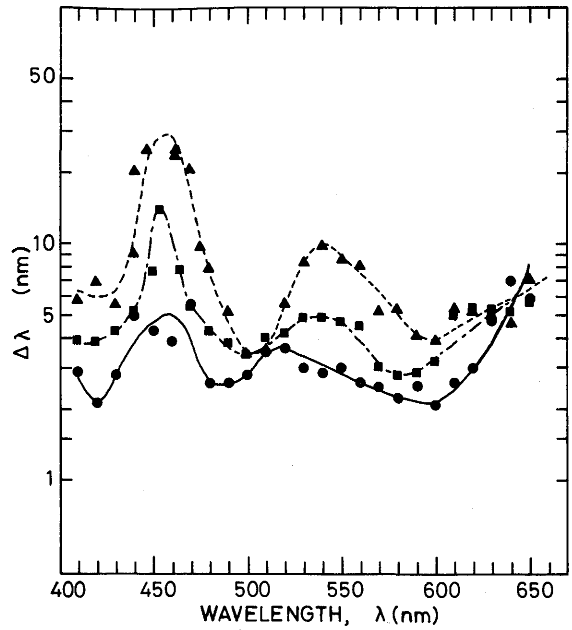


FIG. 2. Same as Fig. 1, but for observer TF. Alternation frequencies are (●) 0.5, (■) 4.0, and (▲) 12.0 Hz.

Hz, but for 12.0 Hz, the minimum at about 500 nm and the maximum at about 540 nm were slightly shifted toward longer wavelengths.

The results obtained for observer TF are shown in Fig. 2. Alternation frequencies tested were 0.5, 4.0, and 12.0 Hz. Although the discrimination thresholds did not increase as much as those for observer KU as the alternation frequency was raised up to 12.0 Hz, it is also evident for TF that, in the blue region at 450–460 nm, the discrimination thresholds for 4.0 and 12.0 Hz turned out to be apparently higher than those at the other wavelengths. The shapes of the wavelength-discrimination functions are quite similar to those obtained for observer KU. The minima in the blue–green region and the maxima in the green region were found to be clearly shifted toward longer wavelengths by 20 nm when the alternation frequency was raised from 0.5 to 4.0 Hz. These are quite similar to the results of Regan and Tyler.[10]

It is obvious in Figs. 1 and 2 that the discrimination thresholds increased most markedly in the blue region for both observers. In order to see more precisely how the discrimination threshold varies as a function of the alternation frequency, we measured discrimination-threshold *vs.* frequency functions using 460 and 570 nm as test wavelengths. In Fig. 3, we plot log ratio of discrimination thresholds, $\log(\Delta\lambda/r)$, where r stands for mean of $\Delta\lambda$s at 0.5 and 1.0 Hz, so that one can directly compare the frequency characteristics of wavelength discrimination for 460 nm and 570 nm. Solid and dashed lines are smooth curves drawn by the eye through data points.

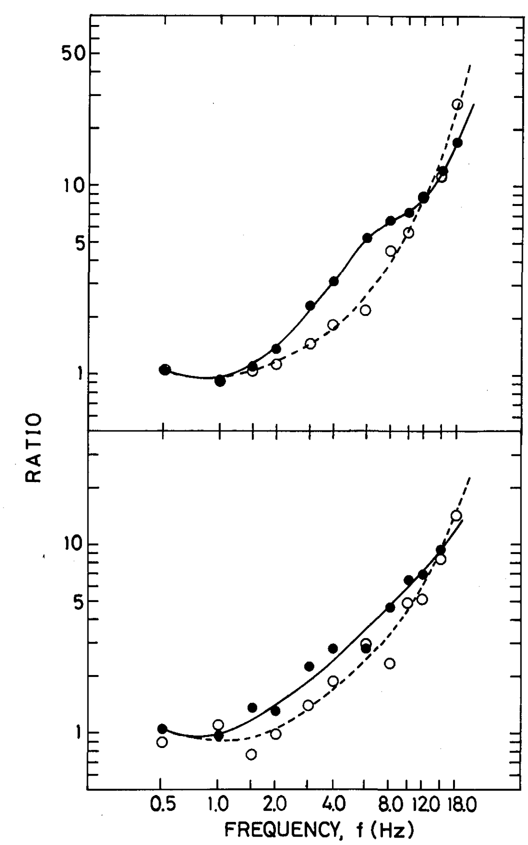


FIG. 3. Log ratio of wavelength-discrimination thresholds, $\log(\Delta\lambda/r)$, where r stands for mean threshold value of $\Delta\lambda$s at 0.5 and 1.0 Hz as functions of alternation frequency, f. (●) $\log(\Delta\lambda/r)$ for 460 nm. (○) $\log(\Delta\lambda/r)$ for 570 nm. Observers: KU (top) and TF (bottom).

It is shown in Fig. 3 that the ratio for 460 nm increases more rapidly than that for 570 nm as frequency increases. For KU, the curve for 460 nm has almost the same values as those for 570 nm up to 1.5 Hz, but between 1.5 and 12.0 Hz the 460 nm curve, having higher values, deviates from the 570 nm curve, and at 12.0 Hz the two curves meet again. For TF, the shapes of the two curves are slightly different from those of KU but these frequency characteristics for 460 and 570 nm are still apparent.

Discussion

Our criterion employed in the present experiments was whether the observer perceived chromatic alternation in the fields, ignoring achromatic temporal artifacts that were not completely eliminated. A similar criterion was used by van der Horst[12] in his "chromatic flicker" study, and Wisowaty[15] called this criterion the perception of chromatic alternation (PCA), which was shown in his careful experiments to be an excellent technique to isolate chromatic pathways. We assume that chromatic channels in the visual system determine the threshold-wavelength difference for chromatic alternation obtained by the present method.

In Fig. 1, it is shown that the wavelength-discrimination functions for frequencies 0.5 and 1.0 Hz obtained by the alternation method are almost the same as that measured by the bipartite-field method, which is consistent with the results by Regan and Tyler.[10] We found here that, at wavelengths less than 480 nm, the two methods yielded no difference in the wavelength-discrimination function. Test and comparison stimuli impinged on the same retinal position with the alternation method, whereas they stimulated two different retinal positions with the bipartite-field method. This means that chromatic-adaptation effects caused by the test and comparison stimuli seem to be quite different between the two methods. The test and comparison stimuli are chromatically indistinguishable until the threshold wavelength difference is reached. The chromatic-adaptation effect might be the same for the two methods when $\Delta\lambda$ is less than the threshold. However, when $\Delta\lambda$ is equal to the threshold, the test and comparison stimuli are no longer identical but appear just-noticeably different. Therefore, the chromatic adaptation caused by test stimuli is not necessarily the same as that caused by comparison stimuli. However, in the present experiments, it turned out that the chromatic adaptation caused by test and comparison stimuli yielded no apparent difference in wavelength discrimination.

The discrimination-threshold *vs.* frequency functions shown in Fig. 3 can be compared with results previously reported.[10,12–14] The chromatic-threshold functions measured at 220 td with R–G chromatic flicker by van der Horst[12] and the wavelength-discrimination-threshold functions for 592 and 622 nm at 25 td reported by Regan and Tyler[10] have quite similar frequency characteristics to those for 570 nm obtained in the present experiment. In these experiments, the discrimination thresholds are almost constant up to 2.0–3.0 Hz and then increase as frequency increases,

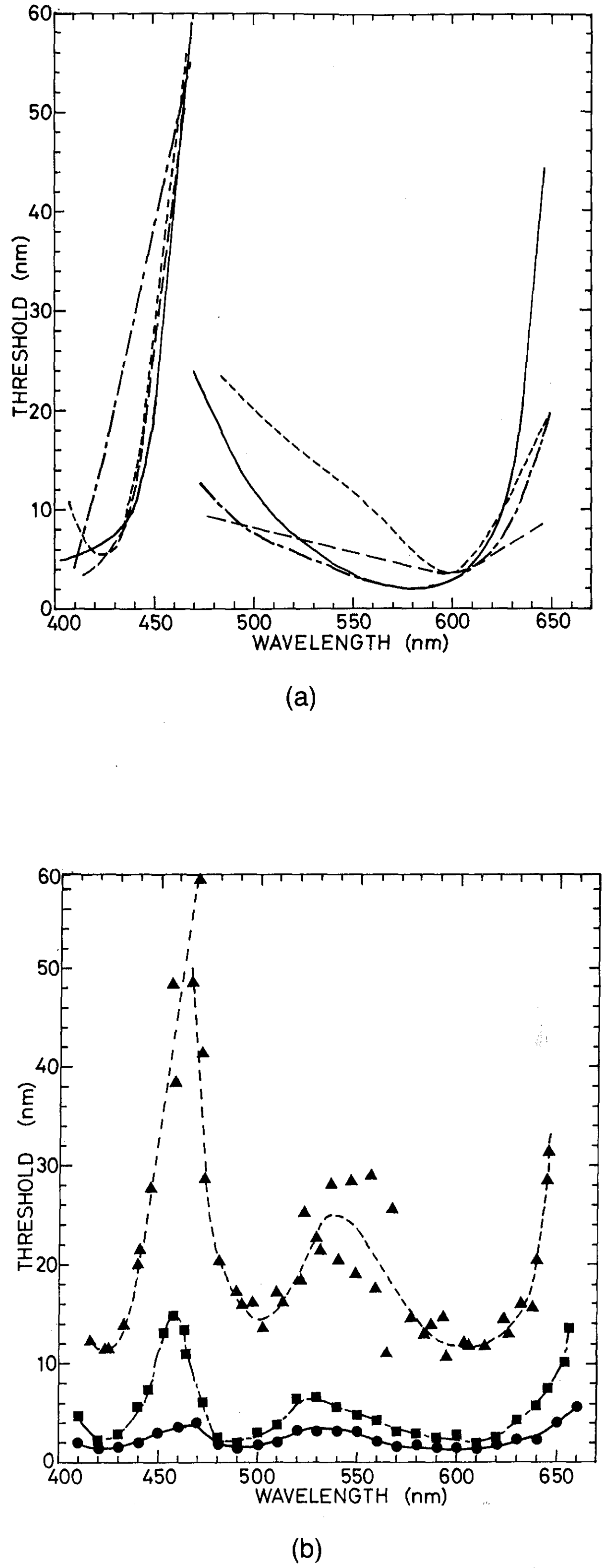
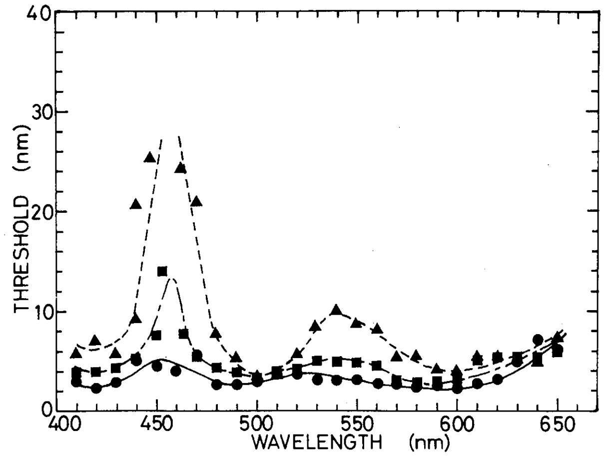


FIG. 4. (a) Tritanopic wavelength-discrimination functions measured by Wright.[17] Each curve represents results from different observers. (b) Wavelength-discrimination functions obtained by the alternating-stimulus method in the present experiments. Data points are plotted by Wright's method. Alternation frequencies are (●) 0.5, (■) 4.0, and (▲) 12.0 Hz. Observer: KU. (c) Same as (b), but for observer TF.



(c)

FIG. 4. (continued from previous page)

reaching values twice as large as those for 0.5–1.0 Hz at 4.0–6.0 Hz. The frequency characteristics for 460 nm in Fig. 3, on the other hand, resemble more the temporal-modulation sensitivity of the blue mechanism reported by Wisowaty and Boynton[14] and Kelly,[16] that is, that the thresholds start increasing beyond 1.5–2.0 Hz more rapidly than the red and green mechanisms.

On the basis of the opponent-color theories, the blue–yellow channel, receiving the input from the blue cones, is responsible for threshold discrimination of equal-luminance wavelengths in the range of about 450–510 nm, and the red–green channel in the other parts of the spectrum. This view has been supported by the empirical wavelength-discrimination data for three types of dichromats[17,18] together with theoretical analyses based on the opponent-color models.[19,20] If the blue-cone mechanism was inoperative, the wavelength-discrimination thresholds would increase near 460 nm since the red–green channel cannot discriminate these wavelengths.

Figure 4(a) shows the tritanopic wavelength-discrimination functions collected by Wright.[17] We replotted our functions at 0.5, 4.0, and 12.0 Hz in Figs. 4(b) and (c) for KU and TF. It can be seen in Fig. 4 that, in the blue region of 450–470 nm, our results agree fairly well with the tritanopic discrimination functions. Thus, it is likely that the deterioration in wavelength discrimination determined by the alternation method in this blue region is attributed to temporal deficiency of the blue-cone mechanism. But our functions also have higher values in the green and yellow region of 500–600 nm when compared with the tritanopic discrimination functions [Fig. 4(a)], which indicates that the red- and green-cone mechanisms deteriorate as well with higher frequencies as shown by the 570 nm curves in Fig. 3.

Our results may be interpreted in the following way. At frequencies less than 2.0 Hz, the blue-cone mechanism can function as well as the red- and green-cone mechanisms so that wavelength discrimination is accomplished with the same accuracy as by the normal bipartite-field method. When the frequency is set between 4.0 and 8.0 Hz, the blue-cone mechanism deteriorates more than the red- and green-cone mechanisms, making the discrimination thresholds relatively high in the blue region of 450–470 nm. When the frequency is further raised, all mechanisms are greatly degraded and the thresholds increase for all wavelengths.

It has been reported that small stimulus fields yield tritanopic-like wavelength-discrimination functions.[2,3] In the present study, we show that tritanopic-like wavelength-discrimination functions can be also obtained in the temporal domain with specific alternation frequencies.

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