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Color discrimination and appearance of short-duration, equal-luminance monochromatic lights

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Wavelength-discrimination thresholds were measured with stimulus durations of 8, 500, and 2000 msec for test wavelengths of 420 to 630 nm at equal luminance of 100 Td. With the short duration of 8 msec, the discrimination thresholds increased for most wavelengths, but they decreased for the wavelengths near 460 nm. This short-duration wavelength-discrimination function was found to be quite different in shape from that at 2000 msec but similar to one at a low-luminance level of 2.5 Td at 500 msec. Hue, saturation, and brightness of short-duration monochromatic stimuli were also estimated by a color-naming procedure. Changes in color appearance produced by a short stimulus duration were consistent with the tendency that was characterized as tritanopic in previous studies. However, the present results on color discrimination do not necessarily support this tritanopic effect. A possible explanation is discussed.

INTRODUCTION

When colored lights are presented for a short duration they appear quite different in hue, saturation, and brightness from those presented for a long duration. Previous research has shown that color discrimination and appearance clearly depend on the stimulus duration.[1–9] Weitzman and Kinney[1,2] and Kaiser[3] reported, using a color-naming method,[10] that when monochromatic lights were presented for a short duration while the luminance and the size of the stimulus were kept constant, green at long durations shifted to blue or blue-green, a neutral point was found in the yellow region (around 575 nm), and no confusion was found between reds and greens. They characterized these changes as tritanopic, since the tritanope cannot discriminate green and blue and the neutral point of the tritanope is located near 570 nm.[11] They attributed this effect to a lowered effectiveness of the blue mechanism, which was caused by reduction of the total energy of a stimulus (area × intensity × duration).

Color matching has also been employed to observe changes in color appearance with short-duration stimuli.[5–7] Short-duration stimuli were found to appear less saturated and to be shifted in hue for some colors, but no systematic tendency of changes in color appearance was reported in these studies. Color discrimination has not been studied extensively for a short-duration stimulus. Only a few investigators using quite limited experimental conditions have reported on this aspect.[8,9] These investigations showed a deterioration in color discrimination with decreasing stimulus duration for only one or two test colors. It is necessary, therefore, to test more colors to derive general characteristics for the effects of short duration on color discrimination.

If the blue mechanism loses effectiveness when the total energy of a stimulus decreases, as was suggested by previous investigators,[1–3] it is expected that a tritanopic wavelength-discrimination function will be obtained with small-field, low-luminance, or short-duration monochromatic stimuli. It was shown by McCree[12] that small-field wavelength-discrimination functions were similar to the tritanopic wavelength-discrimination function,[13] but low-luminance wavelength-discrimination functions were found to be quite different in shape from the tritanopic one. The peak threshold in the wavelength-discrimination function at about 450 nm obtained at high luminance gradually disappeared as luminance decreased, which was the opposite of the tendency of the tritanopic function. Thus it is disputable that field size, luminance level, and stimulus duration have the same effects on color discrimination, although they seem to have similar effects on color appearance, as was reported previously.

It has been suggested by many studies that the blue mechanism has poorer temporal resolution than the red and the green mechanisms.[14,15] However, more recently, several investigations have shown that the blue mechanism is not temporally defective, and there is no difference in temporal properties among chromatic mechanisms.[16,17] If the blue mechanism has poor temporal resolution, a tritanopic wavelength-discrimination function is expected to be obtained when a short stimulus duration is used to generate a wavelength-discrimination function.

It is of considerable interest to study how color discrimination changes and how it relates to color appearance as stimulus duration decreases. In this paper we report on a systematic study of wavelength discrimination and color appearance with short-duration monochromatic stimuli. The research reported below consisted of two experiments. Experiment 1 was performed to obtain a set of wavelength-discrimination function profiles at a short duration. Experiment 2 was a color-naming experiment in which we compared the color names of monochromatic stimuli presented for a short duration with those for a long duration.

METHODS

Apparatus

A conventional three-channel Maxwellian-view system was used. The source was a 500-W xenon-arc lamp. Two mono-

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chromatic lights were produced by means of grating monochromators with half-bandwidths of 6 mm in the first and second channels. The third channel produced an adapting white light. Monochromators and neutral-density wedges in the first and second channels were driven by stepping motors controlled by a microcomputer. The observer could move the monochromators and the wedges with the computer. Three high-speed electromagnetic shutters, also driven by the computer, in each channel controlled the stimulus duration and the interstimulus interval. These shutters were placed at focal planes of the light beams to make the rise time less than 1 msec.

Two circular stimulus fields were presented to the observer in Experiment 1. The stimulus field subtended a visual angle of 45′ and were horizontally separated by a gap of 30′. With this size and separation, two circular stimulus fields fall within a fovea of 2°. The left-hand field, produced by the second channel, constituted a reference field, and the right-hand field, produced by the first channel, a comparison field. The circular adapting white field, subtending a visual angle of 3°, was presented to the observer only between trials to maintain a constant adaptation level. A small, dim red fixation point was continuously seen in the center of the gap between the two stimulus fields. In Experiment 2, only the reference field was used to perform color-naming experiments. The observer's head was fixed by a dental bite board, and his right eye alone viewed the stimuli.

Procedure

The present experiment employed two male obervers, KU and SS, 33 and 26 years of age, respectively. They have normal color vision.

In preliminary experiments, monochromatic stimuli used in both reference and comparison fields were equated in luminance by flicker photometry for each observer. The wavelengths tested ranged from 410 to 630 nm in 10-nm steps. The reference field was shifted horizontally so that it was precisely superimposed upon the comparison field to perform flicker photometry. First, all monochromatic stimuli in the reference field were equated in luminance to a 570-nm monochromatic light of 100 Td in the comparison field. Then each test stimulus in the comparison field was equated in luminance to the stimulus of the same wavelength in the reference field. In other sessions, stimuli were equated in luminance of 2.5 Td in order to permit wavelength-discrimination experiments at a low luminance level. The wedge positions obtained in this flicker photometry were stored in the computer to produce equal-luminance stimuli in the main experiments. Linear interpolation of the wedge position was employed when necessary.

We performed pilot experiments to determine appropriate stimulus durations that were used in the main experiments. Wavelength-discrimination thresholds were obtained as a function of stimulus duration, varying from 2000 to 5 msec, for reference wavelengths between 420 and 630 nm. The wavelength-discrimination thresholds with 200–1000-msec durations were found to be slightly smaller than those with 2000-msec durations for most wavelengths. With 200–20-msec durations, the thresholds did not vary systematically, but with 5–10-msec durations they changed by a greater amount. Therefore we chose three durations of 8, 500, and 2000 msec for Experiment 1.

In Experiment 1, wavelength-discrimination thresholds for 16 wavelengths between 420 and 630 nm were obtained. In a trial, a comparison stimulus was first equated in wavelength and luminance to a reference stimulus by the computer. Then the observer began adjusting the comparison wavelength until a just-detectable chromatic difference was perceived between the reference and the comparison stimuli. The intensity of the comparison stimulus was also adjusted by the observer so that any brightness difference between the two fields was eliminated to ensure that only chromatic difference was detected. In a session, stimulus duration was fixed at 8, 500, or 2000 msec, and the interstimulus interval was 3 sec. The reference wavelength was selected at random. Four thresholds, two at longer and two at shorter wavelengths relative to the reference wavelength, were made for each reference wavelength in a session. Stimulus duration was chosen at random between sessions. A total of 16 thresholds was obtained, 8 at shorter wavelengths and 8 at longer, for a reference wavelength for a given duration.

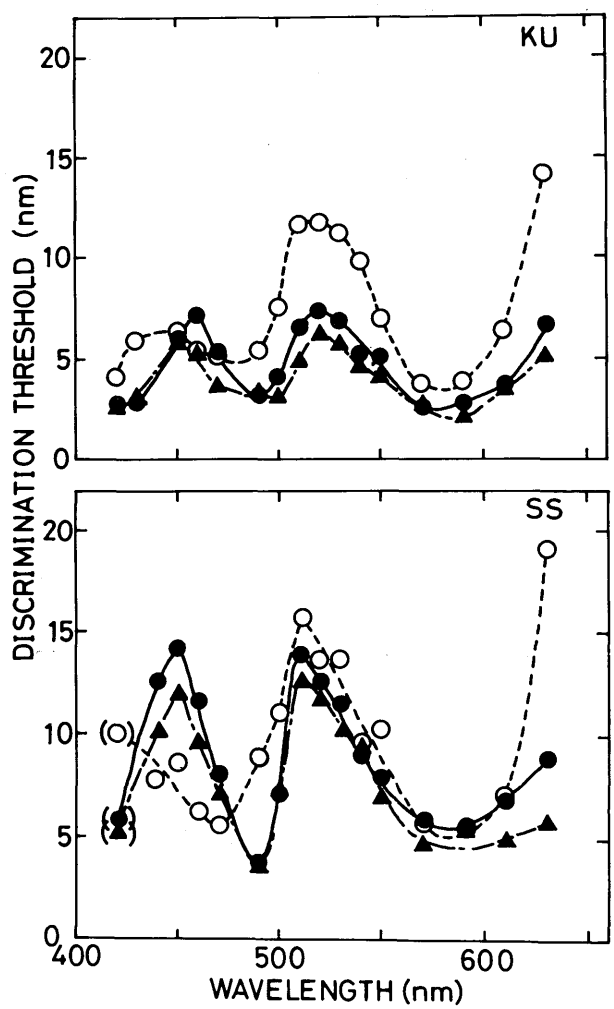

Fig. 1. Wavelength-discrimination functions with stimulus durations of 8 (○), 500 (▲), and 2000 (●) msec at a luminance level of 100 Td. Observers: KU (top) and SS (bottom). The points at 420 nm for SS, shown in parentheses, were obtained at a luminance level of 45 Td.

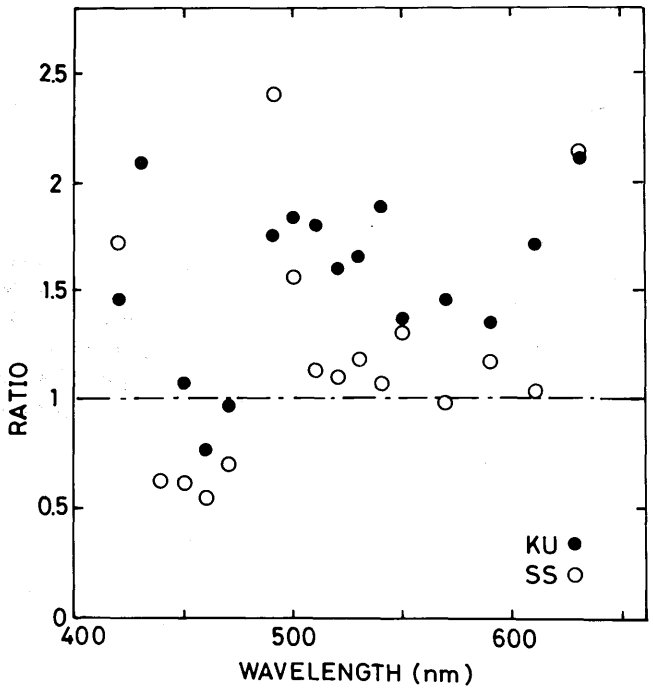

Fig. 2. The ratios of the wavelength-discrimination thresholds at 8 msec to those at 2000 msec for two observers, KU (●) and SS (○).

In Experiment 2, the observer estimated hue, saturation, and brightness of a reference stimulus by a color-naming procedure. The reference stimuli ranged from 420 to 630 nm in 10-nm steps. The luminance level was fixed at 100 Td. In a trial, the stimulus duration was randomly set at either 8 or 2000 msec, with the constraint that each duration was used equally often during a session. The observer reported the ratio of two of four unique hues, red, green, yellow, and blue, perceived in a reference stimulus,[10] the perceived percentage chromatic content,[16] and a magnitude estimation of the brightness of the reference stimulus. A 550-nm monochromatic light, for example, may be estimated as "four green and six yellow, 45% chromatic and six brightness." Although all reference stimuli were equated in luminance, brightness estimates could vary depending on the wavelength of a reference stimulus because of the brightness–luminance discrepancy.[16] All estimations were repeated 10 times for each wavelength and duration.

RESULTS

Experiment 1: Wavelength-Discrimination Functions with Short Stimulus Durations

Figure 1 shows wavelength-discrimination functions obtained with durations of 8 (open circles), 500 (filled triangles), and 2000 (filled circles) msec for both observers. The thresholds in the figure represent mean values of thresholds for both longer- and shorter-wavelength discrimination. The thresholds at 420 nm for observer SS, shown in parentheses in the figure, were obtained with a luminance level of 45 Td because, owing to apparatus limitations, sufficient intensity of the 420-nm stimulus could not be obtained to produce a luminance of 100 Td as measured by flicker photometry for SS.

It is evident from Fig. 1 that wavelength-discrimination functions at 500 and 2000 msec are similar in shape, but the threshold values at 500 msec are slightly smaller than those at 2000 msec. The shape of the curve for 8 msec, on the other hand, was found to be quite different from those at 500 and 2000 msec. The thresholds at about 460 nm are smaller at 8 msec than those at 2000 msec, whereas the thresholds at other wavelengths increased when the duration decreased from 2000 to 8 msec. Two maxima of the wavelength-discrimination functions, one at 450–460 nm and the other at 510–520 nm, have almost the same values at 500 and 2000 msec, but at 8 msec the values at 450–460 nm became smaller than that at 510–520 nm.

We calculated the ratios for the thresholds at 8 msec and those at 2000 msec and plotted them as a function of wavelength. Figure 2 gives these ratios for the two observers. The ratios for the wavelengths near 460 nm are less than 1, and those for other wavelengths greater than 1, which means that wavelength discrimination is worst at the short stimulus duration for all wavelengths except near 460 nm, where

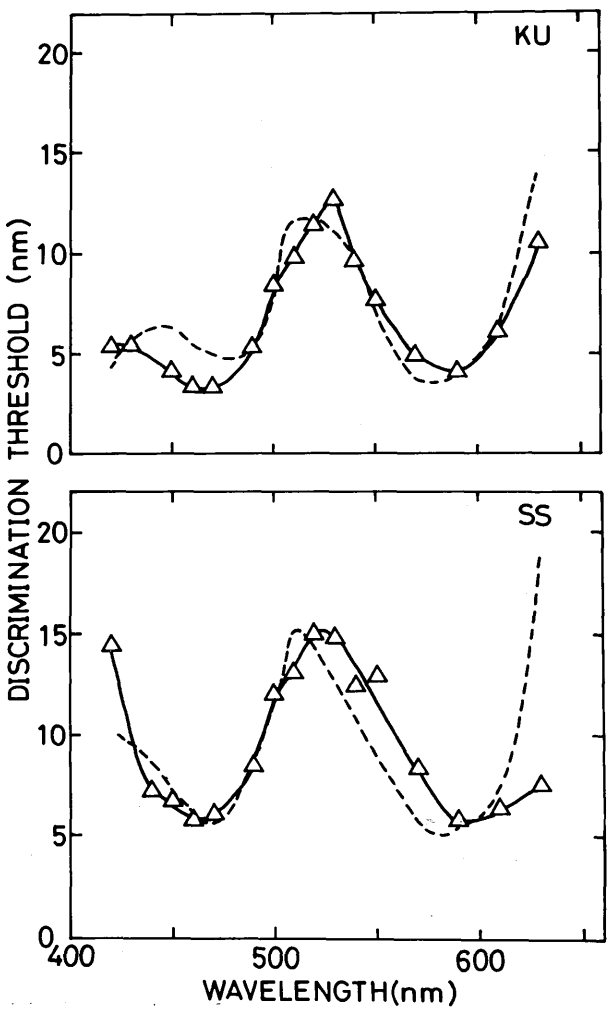

Fig. 3. The wavelength-discrimination functions obtained at the low-luminance level of 2.5 Td with a stimulus duration of 500 msec (△). Dashed curves indicate the functions obtained for the conditions of 100 Td and 8 msec replotted from Fig. 1. Observers: KU (top) and SS (bottom).

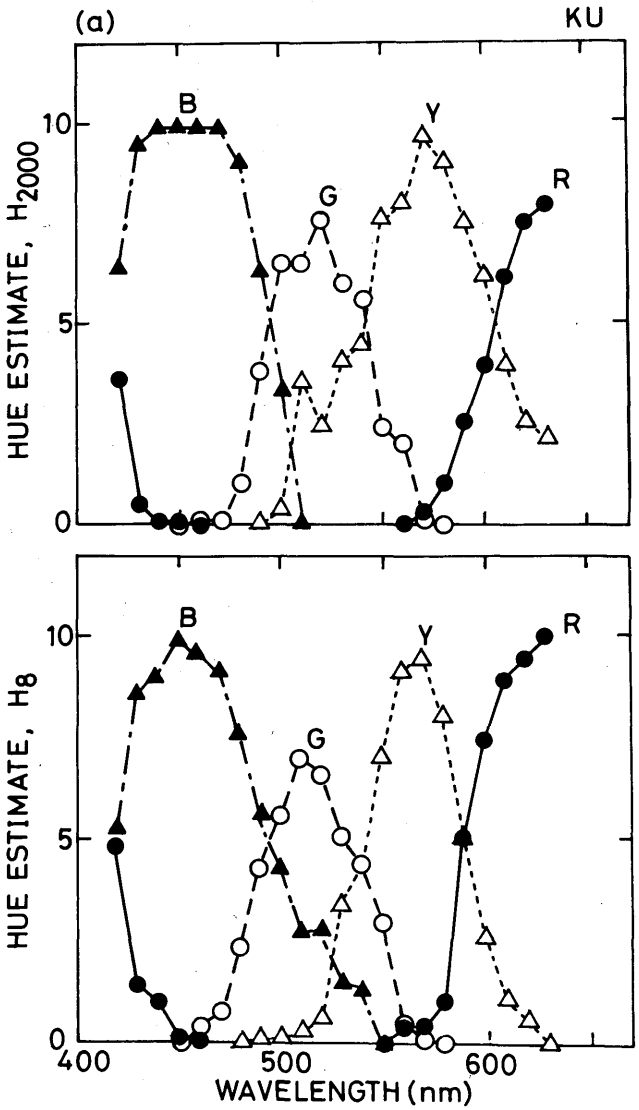

Fig. 4. Hue estimates of equal-luminance monochromatic lights for stimulus durations of 2000 msec (top) and 8 msec (bottom) for observer KU. R (●), Y (△), G (○), and B (▲) indicate red, yellow, green, and blue hue estimates, respectively.

better wavelength discrimination occurs for the short stimulus duration.

It was noticed that the shape of the wavelength-discrimination functions for a short duration shown in Fig. 1 was quite similar to that obtained at low-luminance levels.[12] We measured wavelength-discrimination functions at a low-luminance level of 2.5 Td using the same observers. The stimulus duration used here was 500 msec. The luminance level of 2.5 Td was chosen so that when the monochromatic lights in the yellow region (about 570 nm) were presented for 500 msec at 2.5 Td, they appeared approximately as bright as the same monochromatic lights seen for 8 msec at 100 Td.

In Fig. 3, open triangles indicate the discrimination thresholds measured at 2.5 Td with 500-msec stimuli, whereas dashed lines represent the wavelength-discrimination functions at 100 Td with 8-msec stimuli replotted from Fig. 1. For both observers, these two functions agree quite well in both shape and threshold values.

Experiment 2: Hue, Saturation, and Brightness of Short-Duration Monochromatic Lights

Figure 4 shows hue estimates with stimulus durations of 2000 and 8 msec for observer KU, and Fig. 5 shows the same estimates for observer SS. R, Y, G, and B in the figures represent red, yellow, green, and blue hue estimates, respectively. It is shown in Figs. 4 and 5 that when the stimulus duration was shortened from 2000 to 8 msec the monochromatic stimuli changed in appearance in a certain systematic way. Blue responses decreased at wavelengths shorter than 490 nm but increased at longer wavelengths. Green responses increased at wavelengths shorter than 490 nm, but no apparent change was observed at longer wavelengths. Yellow responses decreased at all wavelengths except in the region of 550–570 nm. Red responses increased consistently at wavelengths longer than 560 nm and shorter than 450 nm.

Saturation estimates, shown in Fig. 6, decreased between 520 and 580 nm but increased in other regions as the stimulus duration was reduced from 2000 to 8 msec for both observers (filled and open circles, respectively). These changes in hue and saturation found in the present experi-

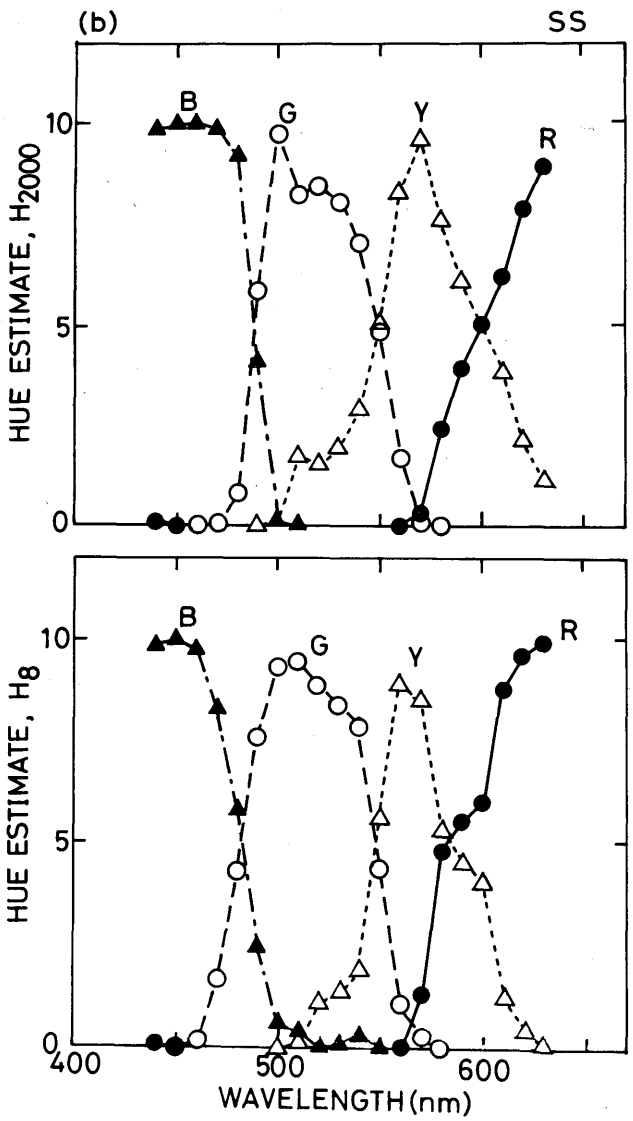

Fig. 5. Same as Fig. 4 but for observer SS.

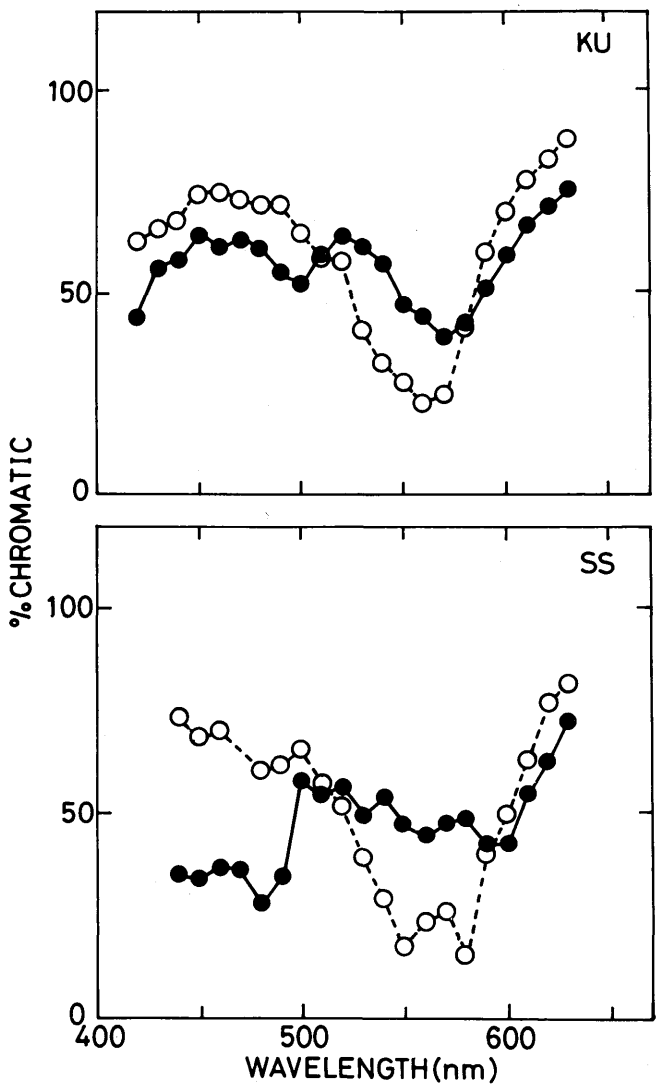

Fig. 6. Saturation estimates of equal-luminance monochromatic lights for stimulus durations of 2000 msec (●) and 8 msec (○). Observers: KU (top) and SS (bottom). The ordinates represent percent chromatic content in the stimuli.

ments are consistent with those reported previously[1–3] in the transition from yellow to white, the confusion between blue and green, and the lack of confusion between reds and greens.

Figure 7 gives brightness estimates for the two observers. It is clear that monochromatic stimuli observed with 8-msec stimuli appeared consistently darker than those at 2000 msec for all wavelengths. The stimuli near 570 nm were darkest in all wavelengths for both durations. This is because of the brightness–luminance discrepancy[18] for equal-luminance monochromatic lights. This discrepancy holds, but less prominently, for short-duration monochromatic lights.

DISCUSSION

When the stimulus duration of equal-luminance monochromatic lights is shortened from 2000 to 8 msec, wavelength-discrimination ability deteriorates for most wavelengths. However, for wavelengths near 460 nm, the wavelength difference can be detected better with a shorter-duration stimulus. These results are inconsistent with the prediction that short-duration monochromatic stimuli yield a tritanopic wavelength-discrimination function, in which discrimination thresholds increase greatly at 450–460 nm when compared with a normal function because of reduced efficacy of the blue mechanism. It seems, therefore, that the blue mechanism does not lose its sensitivity with a short-duration wavelength difference but rather that it becomes more sensitive to a small wavelength change.

It was found that the wavelength-discrimination function for a short-duration stimuli was similar to that for stimuli with low luminance, but it was quite different from a function produced by a small field.[12] Therefore the effects of short duration and low luminance on wavelength discrimination cannot be characterized as the same as the small-field tritanopic effects.

However, the changes in color appearance with the short stimulus duration found in the present study are consistent

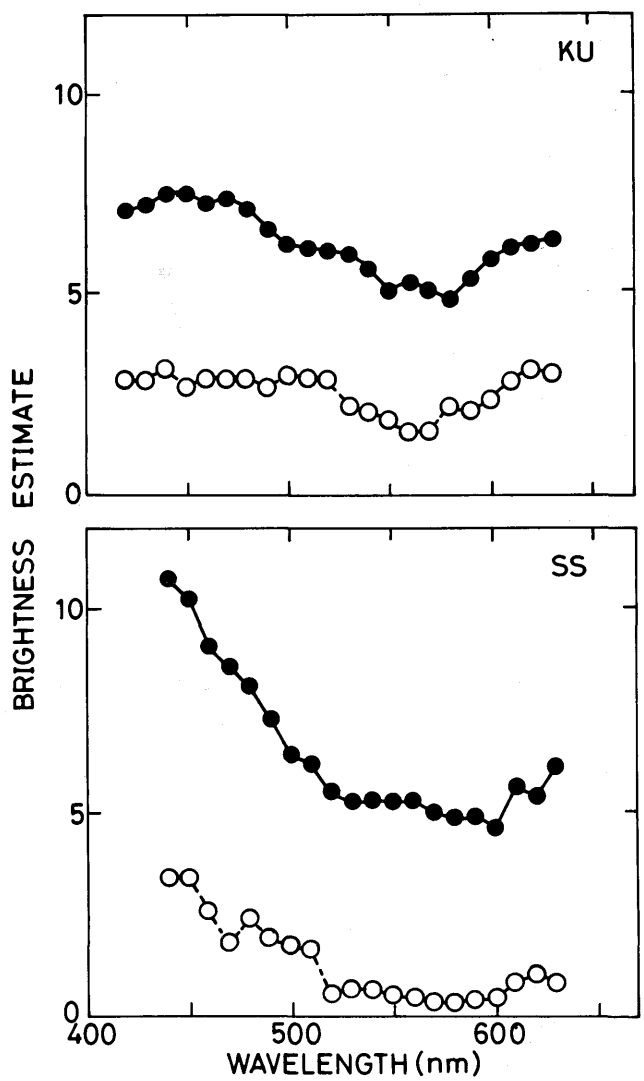

Fig. 7. Brightness estimates of equal-luminance monochromatic lights for stimulus durations of 2000 msec (●) and 8 msec (○). Observers: KU (top) and SS (bottom).

with those previously reported.[1-3] These changes were characterized as tritanopic in those studies. To explain this discrepancy between wavelength discrimination and appearance, we tried to derive wavelength-discrimination functions by using our color-naming results.

The first step, shown in Fig. 8, was to replot the R and G estimates from Figs. 4 and 5, with G estimates plotted in a negative direction for the sake of clarity. Then smooth curves were drawn by eye through the data. All subsequent calculations were based on these smooth curves. Finally, we computed the differences in the heights of these curves at adjacent wavelengths, added the absolute values of each adjacent pair of differences to arrive at a number proportional to the average difference for each wavelength, and plotted the inverse of these summed differences as the derived wavelength-discrimination functions shown in Fig. 9.[19] The values on the ordinates of Fig. 9 are arbitrary numbers, and values of the function for an 8-msec stimulus duration were doubled to give results comparable with those in Fig. 1. The derived functions are fairly similar in shape to those obtained experimentally (Fig. 1), which means that changes in color appearance correlate well with those in wavelength-discrimination functions produced by a short stimulus duration in the present experiments.

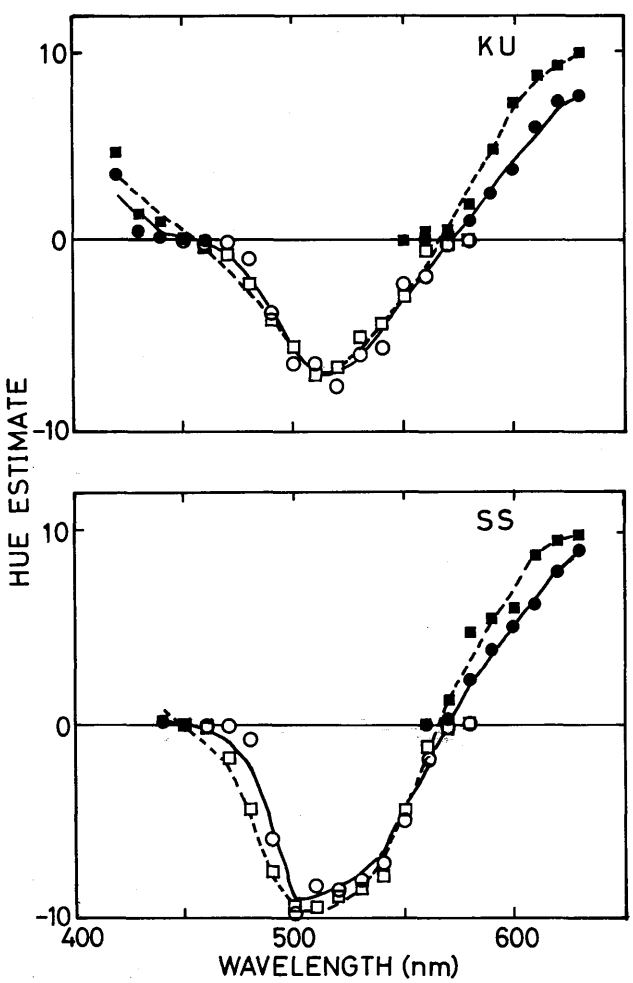

Fig. 8. R and G estimates replotted from Figs. 4 and 5 for 2000 msec (R, ●; G, ○) and 8 msec (R, ■; G, □). G estimates are shown with negative values for the sake of clarity. Solid curves are drawn by eye to make smooth functions. Observers: KU (top) and SS (bottom).

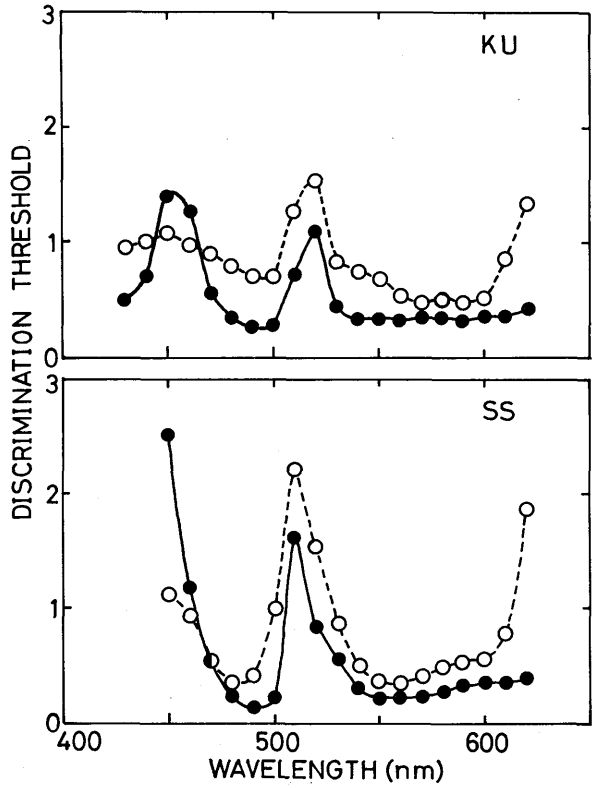

Fig. 9. Wavelength-discrimination functions derived from R and G estimates shown in Fig. 8 for 2000 msec (●) and 8 msec (○). Observers: KU (top) and SS (bottom).

The results for wavelength discrimination and color appearance obtained in the present study seem not to conflict with each other, as described above. When the stimulus duration was shortened, blue responses near 460 nm decreased and were replaced by green responses. This is one of the reasons why color-appearance changes are regarded as tritanopic. However, our derivation of a wavelength-discrimination function from color-naming data indicates that, because of the decrease in blue responses near 460 nm, wavelength discrimination improved. It is suggested, therefore, that a short stimulus duration may cause a tritanopic effect in the sense that blue responses near a 460-nm monochromatic light decrease. But this effect is not so strong as the one that would be expected if there were no blue mechanism. It may be the case that blue responses are almost saturated near 460 nm in the case of a long stimulus duration, so that small wavelength differences cannot be detected. When a short stimulus duration is used, blue responses decrease to the point where a greater change in output response is obtained by the same change in wavelength as in input. Although this consequence of a nonlinear blue mechanism can possibly explain the discrepancy between experimental data of color appearance and discrimination, it will be necessary to do more intensive study in order to verify this notion.

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