

# Temporal integration of chromatic double pulses for detection of equal-luminance wavelength changes

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Detection probabilities for wavelength changes were measured as functions of stimulus onset asynchrony (SOA) with the chromatic double-pulse method. Two test stimuli of a wavelength  $\lambda_t$  were successively exchanged with a reference stimulus of a wavelength  $\lambda_r$  in equal luminance for a short duration with a SOA. Durations were 5 and 50 msec, and the SOA varied between 5 or 50 and 2000 msec.  $\lambda_r$ 's were 571 and 518 nm, chosen from wavelengths near unique yellow and unique green so that wavelength difference  $\Delta\lambda = \lambda_t - \lambda_r$  was perceived mainly as redness and greenness for  $\lambda_r = 571$  nm and yellowness and blueness for  $\lambda_r = 518$  nm. The results showed that temporal integration characteristics for these equal-luminance wavelength changes were quite consistent: complete integration with SOA up to 20 msec, partial integration with SOA between 20 and 200 msec, and probability integration with SOA greater than 200 msec. They did not show any inhibitory integration that was found for luminance changes.

## INTRODUCTION

It has been shown in a number of psychophysical investigations that the human visual system functions as a temporal integrator in various psychophysical tasks.<sup>1</sup> In any of these tasks two or more stimuli are integrated to yield a single unified perception when they are presented within a certain interval. This temporal integration function has been considered an important aspect in revealing the temporal nature of the human visual system.

The temporal integration functions for both achromatic and chromatic responses in the human color visual system have been extensively studied by using various psychophysical techniques, for example, critical duration of a single pulse,<sup>2-4</sup> achromatic and chromatic flicker fusion,<sup>5-11</sup> two-pulse resolution,<sup>12</sup> double-pulse threshold,<sup>13,14</sup> and successive chromatic discrimination.<sup>15</sup> It has been shown that temporal integration characteristics depend on the response criterion used in the psychophysical tasks,<sup>16</sup> indicating that both a peripheral sensory encoding stage and a more central decision stage are involved in determining the time course of integrating stimuli.<sup>17</sup> However, despite differences in the experimental conditions, it was generally implied in these studies that the temporal integration was greater for the chromatic response than for the achromatic one and that the achromatic impulse response in photopic condition was diphasic; a fast excitation phase was followed by a slow inhibition phase, whereas the chromatic impulse response seemed to have a slow excitation phase.

It is still disputable, however, whether the chromatic response has an inhibitory phase as the achromatic response does and whether the temporal characteristics are the same among different chromatic mechanisms. Although some evidence that the blue mechanism is poorer in temporal resolution<sup>2,3,10</sup> has been accumulated, it was recently reported that no effect of wavelength was found on temporal chromatic integration, supporting the notion that the red-green and yellow-blue chromatic systems have similar temporal integration properties.<sup>4</sup>

In the present research we employed a new technique to measure temporal integration characteristics of chromatic responses. The chromatic double-pulse method, in which a reference chromatic stimulus is exchanged with two test stimuli successively presented in equal luminance, was used in the present study. Aims of this study were to determine the time course of the temporal integration for chromatic responses and to compare the temporal integration properties for different chromatic responses, i.e., redness, greenness, yellowness, and blueness.

## METHOD

### Apparatus

We used a conventional three-channel Maxwellian-view system. The source was a 500-W xenon-arc lamp. Two monochromatic lights were produced by two grating monochromators with half-bandwidths of 6 nm in the first and the second channels. These channels produced the test stimuli. The third channel produced another monochromatic light by means of an interference filter, providing a reference stimulus. The interference filters used in this channel were 518 and 571 nm with half-bandwidths of 11 nm.

Two neutral-density wedges controlled luminances of the first and the second channels. In the third channel, neutral-density filters were used to vary the luminance. Three electromagnetically driven shutters, placed at a focal plane of the light beam in each channel, could deliver short pulse stimuli. The rise time of the stimuli in any channel was less than 1 msec. The monochromators and the wedges were driven by stepping motors controlled by a microcomputer. The observer could vary wavelengths and luminances of the first and the second channels with switches connected to the computer. The on/off timing of the shutters could be adjusted by the computer to minimize any temporal artifact.

Circular stimulus fields of 45' visual angle, consisting of two test and a reference field of the same size, were presented at 38' in the nasal retina of the observer's right eye. They

were spatially superimposed. The test fields were temporally substituted for the reference field that was otherwise continuously presented. The surroundings of the stimulus fields were dark except for a small dim red fixation point.

### Procedure

Three males, SS, KU, and TT, 26, 34, and 24 years of age, respectively, participated as observers. They all had normal color vision and were experienced in many psychophysical experiments.

We used a modified temporal double-pulse method to yield only chromatic change without any achromatic or luminance transient. Two chromatic test stimuli were substituted for a steady chromatic reference stimulus for a short duration  $D$ . The luminances of the test stimuli were kept equal to that of the reference stimulus. This equal-luminance technique has been used in previous studies<sup>3-5,7-10,12,18</sup> to isolate chromatic responses. Two test stimuli were successively presented with a stimulus onset asynchrony (SOA). In the present experiments, these test stimuli were monochromatic lights of the same wavelength,  $\lambda_t$ . The reference stimulus was also made of a single wavelength,  $\lambda_r$ . The wavelength difference  $\Delta\lambda$  between  $\lambda_t$  and  $\lambda_r$  was chosen for a given duration  $D$  so that a chromatic change caused by  $\Delta\lambda$  could be detected when the SOA was equal to  $D$  but when the SOA was long enough the change could not be detected. Thus the detection probability for chromatic change varies between 1 and 0 as a function of the SOA.

We measured the probability of detecting four chromatic responses, i.e., redness, greenness, yellowness, and blueness. Two  $\lambda_r$ 's of 571 and 518 nm were chosen from wavelengths near unique yellow and unique green, respectively. When  $\lambda_t$  moves in the direction of long wavelength from 571 nm, the chromatic change made just detectable by  $\Delta\lambda$  in the stimulus field is that of redness. When  $\lambda_t$  decreases from 571 nm, greenness can be detected. Detection of yellowness and blueness can be measured in a similar way when  $\lambda_r$  is 518 nm.

Two preliminary experiments were performed. The first one used flicker photometry to equate all test and reference stimuli at a luminance of 100 Td. The flicker photometry was carried out for each observer to equate the test stimuli from 410 to 670 nm in 10-nm steps both in the first and in the second channels in luminance to the 571-nm reference of 100 Td in the third channel. The 518-nm reference in the third channel was also equated in luminance to the 510-nm stimulus in the first channel. The wedge positions of these test stimuli in equal luminance were stored in the computer. Linear interpolation was used when necessary.

The second preliminary experiment was an estimation of the range of  $\Delta\lambda$ .  $\Delta\lambda$  should have been properly chosen in the main experiment so that a given chromatic change was easily detectable when the SOA was equal to  $D$  but hardly detectable with a SOA of 2000 msec. The observer adjusted wavelength of a test stimulus in either the long- or short-wavelength direction until he could just perceive a given chromatic change. Two  $\Delta\lambda$ 's were obtained with a SOA of 5 or 50 and 2000 msec. We chose  $\Delta\lambda$ 's that were used in the main experiments between these two extreme  $\Delta\lambda$ 's. The luminance of the test stimuli was automatically maintained at a 100-Td constant by the computer while the observer varied the wavelength of the test stimulus.

In the main experiments, the detection probabilities of the four chromatic responses were measured as functions of SOA. Test-stimulus durations  $D$  were 5 and 50 msec. We employed the method of constant stimuli. In a trial, a reference stimulus was steadily presented, and then after a tone signal two test stimuli were successively exchanged with the reference with a SOA that was chosen at random from either 5 or 50 to 2000 msec. The observer responded with yes or no<sup>19</sup> according to whether he detected a given chromatic change in the stimulus field. We employed the criterion of the perception of chromatic change, by which the observer

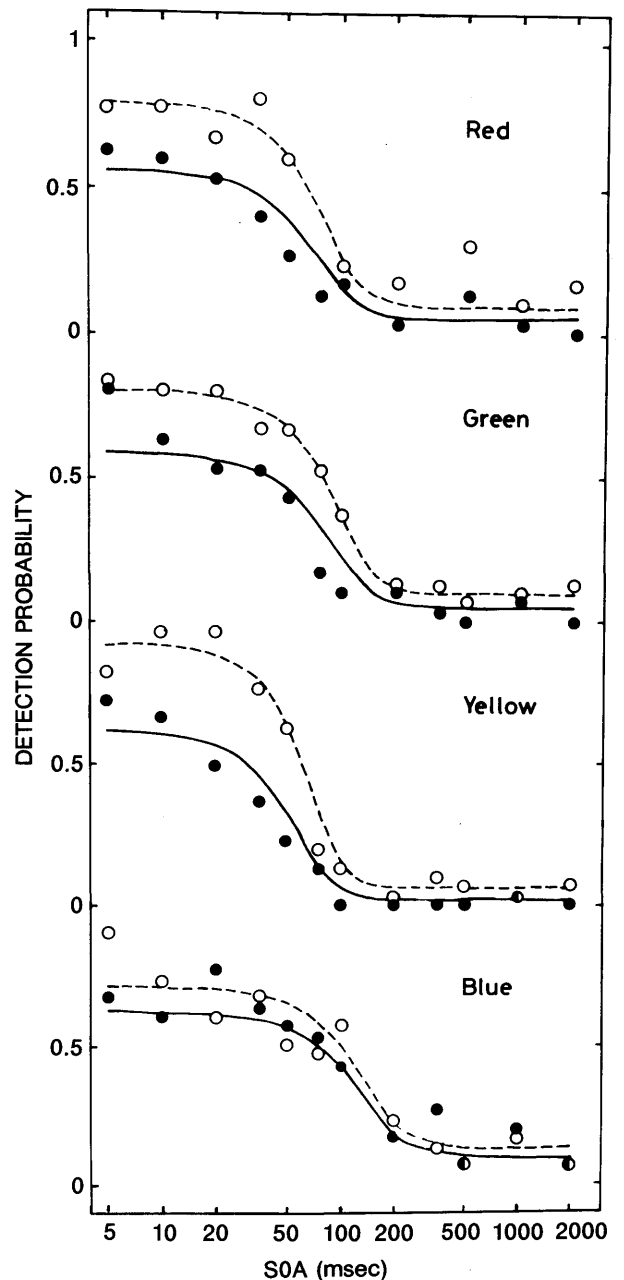


Fig. 1. Detection probability for red, green, yellow, and blue responses (top to bottom) as a function of SOA. Stimulus duration was 5 msec. A reference wavelength of 571 nm was used for red and green responses and 518 nm for yellow and blue responses. Observer: SS. Wavelength difference  $\Delta\lambda$  between test and reference stimuli: 20 and 15 nm for red, -35 and -30 nm for green, 75 and 65 nm for yellow, and -35 and -33 nm for blue.

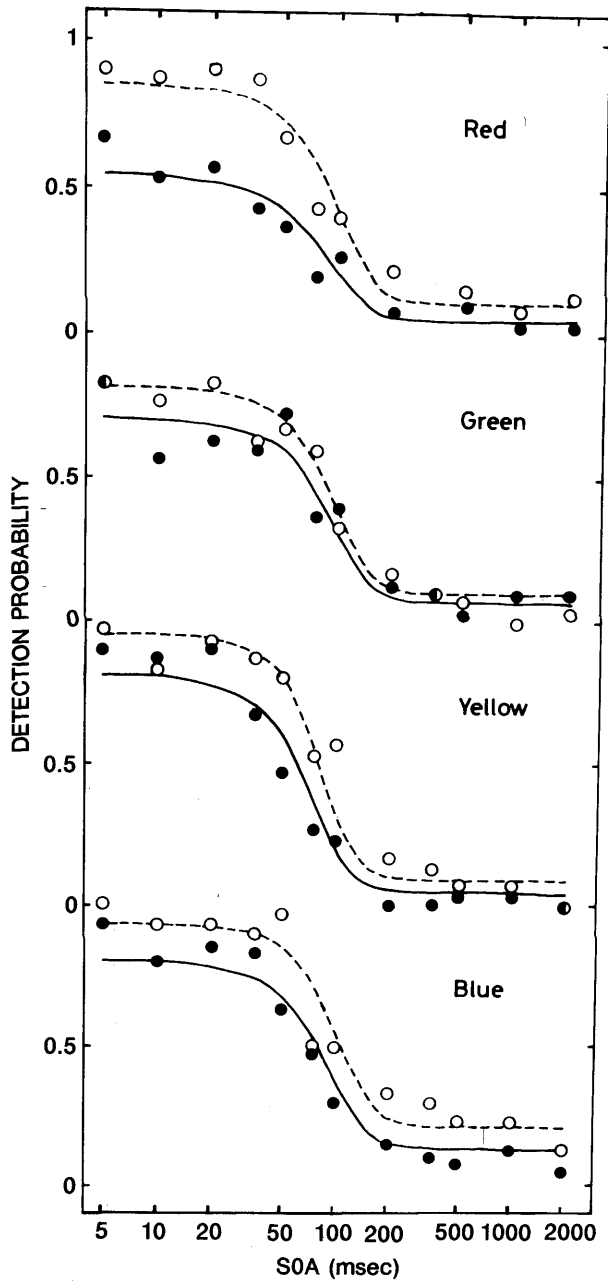


Fig. 2. Same as Fig. 1 but for observer KU.  $\Delta\lambda$ : 15 and 10 nm for red, -40 and -35 nm for green, 65 and 60 nm for yellow, and -27 and -25 nm for blue.

detected only chromatic changes and ignored other changes, if any. This criterion was similar to the perception of chromatic alternation (PCA) used by Wisowaty<sup>9</sup> in his chromatic flicker experiments. He showed that PCA is an excellent criterion for isolating chromatic pathways. Trials were separated by 3 sec.

A session consisted of 10 trials for each SOA. Three sessions were run to make a total of 30 repetitions for a detection probability at each SOA. Two  $\Delta\lambda$ 's were chosen in each chromatic response condition for the 5-msec duration, but one  $\Delta\lambda$  for the 50-msec duration.

In addition to this chromatic condition, the detection probabilities of increment and decrement luminance changes were measured for comparison. Only a wavelength of 571 nm was used for test and reference stimuli in this

condition. Test stimuli were of higher and lower luminance than 100 Td for increment and decrement conditions, respectively. The observer's task was to detect achromatic increment and decrement changes in the stimulus field. The duration  $D$  used here was kept constant at 5 msec.

**RESULTS**

Figures 1, 2, and 3 show the detection probability for each chromatic response as a function of SOA for observers SS, KU, and TT, respectively. Open and filled circles represent the results obtained with two different  $\Delta\lambda$ 's that were used to detect the same chromatic change. The dashed and solid

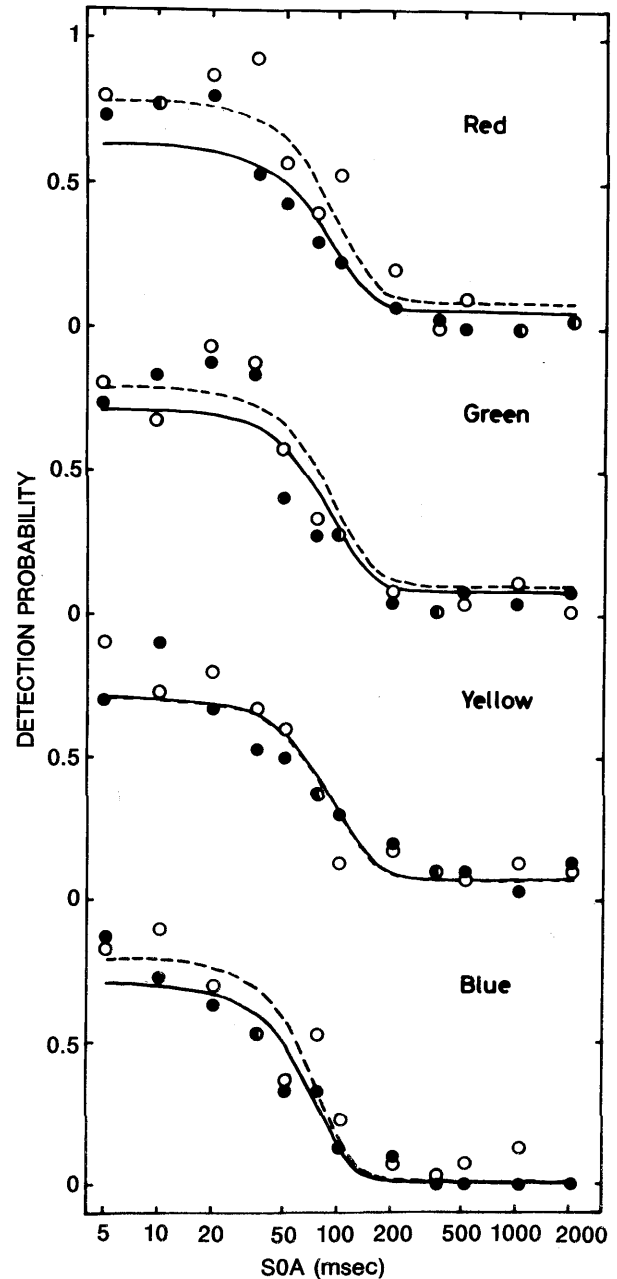


Fig. 3. Same as Fig. 1 but for observer TT.  $\Delta\lambda$ : 20 and 15 nm for red, -45 and -40 nm for green, 55 and 50 nm for yellow, and -25 and -23 nm for blue.

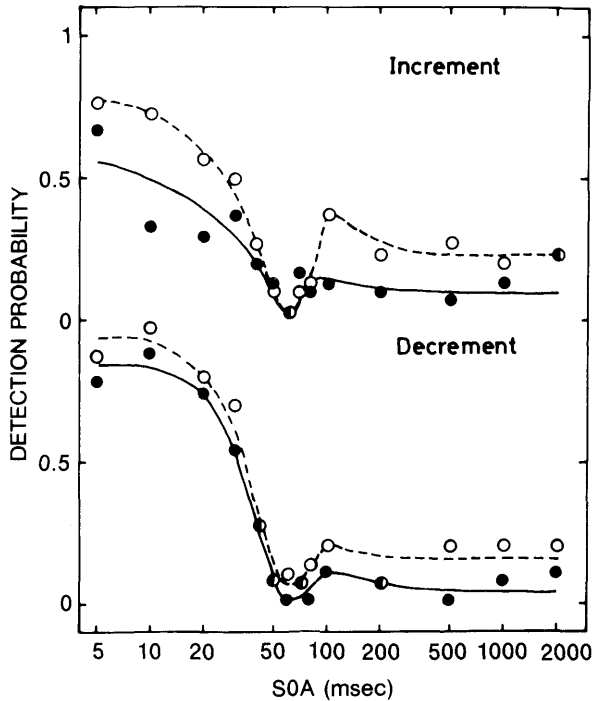


Fig. 4. Detection probability for increment and decrement luminance changes as a function of SOA. Stimulus duration was 5 msec. The same wavelength of 571 nm was used for reference and test stimuli. Observer: SS. Luminance difference between test and reference stimuli: 0.18 and 0.14 log unit for increment and  $-0.50$  and  $-0.46$  log unit for decrement.

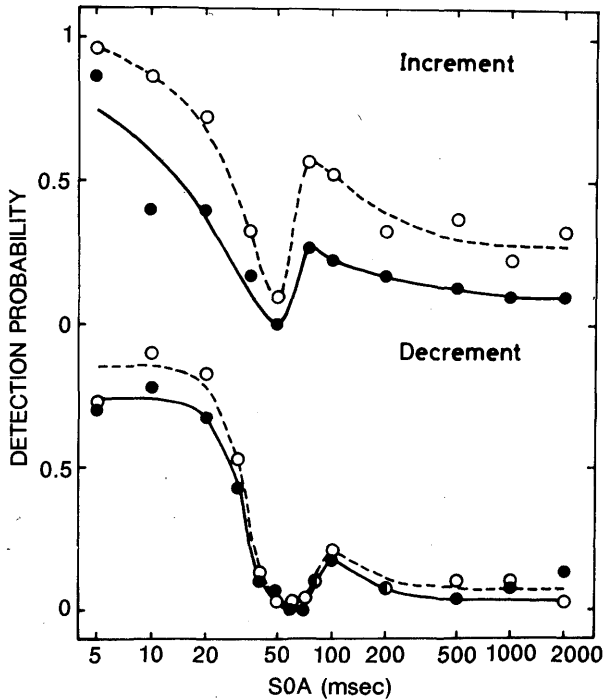


Fig. 5. Same as Fig. 4 but for observer KU. Luminance difference: 0.14 and 0.11 log unit for increment and  $-0.14$  and  $-0.11$  log unit for decrement.

curves in the figures were derived from a theoretical analysis described below.

In Figs. 1-3 the general tendency is that the detection probabilities of red, green, yellow, and blue responses change

in a quite consistent way as functions of SOA. They are almost constant with SOA up to 20 msec, decrease rapidly with increasing SOA, and reach an asymptote at a SOA of about 200 msec. These characteristics may be divided into complete, partial, and probability integration regions, respectively. For the same chromatic responses, the probabilities obtained with longer  $\Delta\lambda$ 's are greater than those with shorter  $\Delta\lambda$ 's, as expected. These detection properties hold for all chromatic responses and all observers.

Figures 4 and 5 show the detection probabilities of increment and decrement luminance differences for observers SS

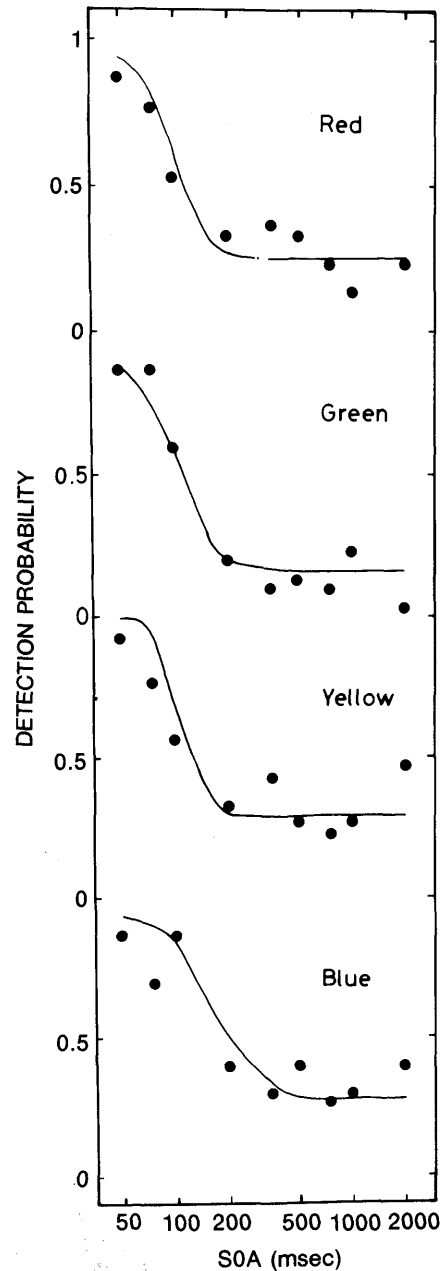


Fig. 6. Detection probability for red, green, yellow, and blue chromatic responses (top to bottom) as a function of SOA. Stimulus duration was 50 msec. A reference wavelength of 571 nm was used for red and green responses and 518 nm for yellow and blue responses. Observer: SS. Wavelength difference  $\Delta\lambda$  between test and reference stimuli: 3.5 nm for red,  $-6.5$  nm for green, 13 nm for yellow, and  $-11$  nm for blue.

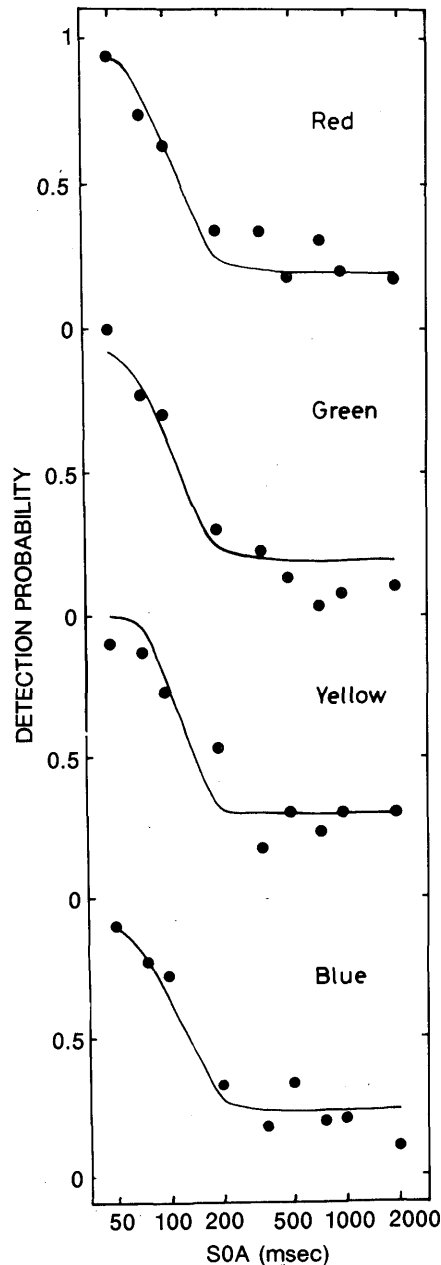


Fig. 7. Same as Fig. 6 but for observer KU.  $\Delta\lambda$ : 2.0 nm for red, -3.0 nm for green, 9.5 nm for yellow, and -7.5 nm for blue.

and KU, respectively. The open and filled circles represent two different increment and decrement values. The dashed and solid curves were drawn by eye to represent the data as smooth functions.

It is evident from both Figs. 4 and 5 that the detection probability for luminance change decreases as the SOA increases from 5 to 50–60 msec, then increases with a SOA up to 100 msec, and finally decreases slowly to the constant value. The dip of the detection-probability function is clearly shown at a SOA of 50–60 msec in these figures, which indicates that the inhibitory integration takes place when two increment or decrement pulses are separated by 50–60 msec. These results confirmed the original findings reported by Ikeda.<sup>13</sup>

The results obtained with 50-msec duration are shown in Figs. 6 and 7 for observers SS and KU, respectively. It is

shown that the detection probability drops as the SOA increases from 50 to 200–500 msec and are almost constant beyond these SOA values. There is, again, no clear difference in the time course among four chromatic responses. The solid curves in Figs. 6 and 7 were also derived from the theoretical analysis described below.

## DISCUSSION

We obtained the detection-probability functions for red, green, yellow, and blue chromatic responses and those for achromatic responses. When the functions for these chromatic responses (Figs. 1–3) are compared with those for achromatic responses (Figs. 4 and 5), one finds that the inhibitory integration clearly found in the achromatic probability function does not exist in the chromatic probability function. This implies that there is no inhibitory phase in the chromatic response in the present stimulus conditions.

It was shown in the present experiments that there was no clear difference in temporal properties among four chromatic responses. However, it would be useful to derive impulse responses for each chromatic response by using linear systems analysis in order to make a comparison among temporal properties of four chromatic responses and between our results and those reported previously. Two assumptions were made in the present analysis. First, the impulse response  $H(t)$  is defined as output from an  $n$ -stage low-pass filter, expressed by Eq. (1):

$$H(t) = A/c(t/c)^{n-1} \exp[-(t/c)]/(n-1)!, \quad (1)$$

where  $A$  is a proportional constant and  $c$  is a time constant. This function has a general formula to describe the  $n$ -stage low-pass filter and is convenient for mathematical manipulation. Similar functions were used previously.<sup>4,20</sup> The response  $R(t)$  caused by the stimulus  $I(t)$  is determined as the linear summation of  $H(t)$ , which is described in the convolution integral shown in Eq. (2):

$$R(t) = \int_0^t I(t')H(t-t')dt'. \quad (2)$$

Second, the detection probability  $P$  of the response  $R(t)$  is given by the temporal-probability summation defined by Eq. (3) (Ref. 21):

**Table 1. Values of Parameters in Eqs. (1), (2), and (3) to Give the Best Fit to the Experimental Data in Figs. 1, 2, and 3**

Observer	Response	A1	A2	$c$ (msec)	$n$	$B$
SS	Red	6.25	5.50	25	5	5
	Green	7.30	6.45	30	5	5
	Yellow	7.25	6.25	25	4	6.5
	Blue	6.80	6.40	40	5	4
KU	Red	7.50	6.30	30	5	5
	Green	7.35	6.90	30	5	5
	Yellow	8.00	7.25	25	5	6
	Blue	7.00	6.25	25	6	4.5
TT	Red	7.20	6.60	30	5	5
	Green	7.20	6.90	30	5	5
	Yellow	6.90	6.90	30	5	5
	Blue	9.90	9.60	30	5	8

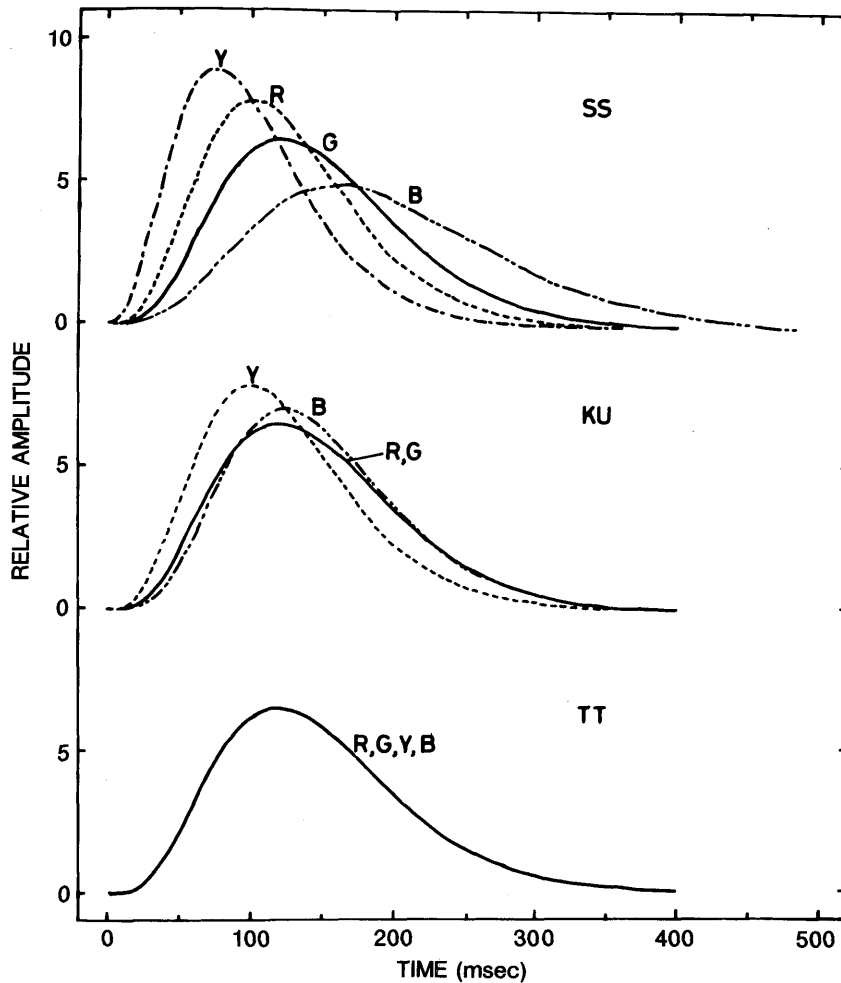


Fig. 8. Impulse responses for red (R), green (G), yellow (Y), and blue (B) chromatic responses for three observers SS, KU, and TT.

$$P = 1 - \exp\left[-\int_0^T |R(t)|^B dt\right], \quad (3)$$

where  $B$  is the empirical parameter and  $T$  is chosen large enough that  $R(T)$  becomes equal to 0. It was shown by Watson<sup>21</sup> that this function included as special cases the peak-or-trough detector model<sup>6,14</sup> and the power integrator model by setting  $B$  equal to  $\infty$  and 2, respectively.

If the parameters  $A$ ,  $c$ ,  $n$ , and  $B$  in Eqs. (1)–(3) are determined by using the experimental data, the impulse response  $H(t)$  can be obtained for each chromatic response. The dashed and solid curves in Figs. 1–3 are theoretical functions of  $P$  obtained by the least-squares method to give the best fit to the experimental data. These two curves, which correspond to two different  $\Delta\lambda$ 's, were made different only in the  $A$  values in Eq. (1) when they were fitted to the data, provided that any difference in the  $\Delta\lambda$  value yielded only a magnitude difference of  $R(t)$ . Figures 1–3 show that the theoretical curves fit the data points quite well.

Table 1 gives the values of the parameters of Eqs. (1)–(3) obtained by the fitting procedure for red, green, yellow, and blue responses.  $A_1$  and  $A_2$  in Table 1 correspond to longer and shorter  $\Delta\lambda$ 's, respectively.

The solid curves in Figs. 6 and 7 were obtained by using the same parameters  $c$  and  $n$  in Table 1 in the corresponding conditions. These curves were determined by adjusting  $A$

and  $B$  in Eqs. (1) and (3). As a result, the values of  $B$  turned out to be the same as in Table 1 in all conditions for both observers. Again, the theoretical curves fit the data points fairly well.

Figure 8 shows the impulse responses calculated with the parameters given in Table 1 for each chromatic response of each observer. It is found from Fig. 8 that the impulse responses of red and green are quite similar for observer SS and identical for observers KU and TT. The impulse response of blue appeared to be slowest and that of yellow fastest for SS and KU, but surprisingly it is again the same as the red and green function for TT. It seems to be reasonable, therefore, to conclude that the impulse responses for redness and greenness are almost identical and that those for yellowness and blueness are quite similar to the red and green impulse response although some inconsistency exists among observers.

We used the wavelength difference  $\Delta\lambda$  between a test stimulus  $\lambda t$  and a reference  $\lambda r$  to yield red, green, and blue responses. The observers reported that  $\Delta\lambda$  could be easily detected by redness and greenness when  $\lambda r$  was 571 nm and no other chromatic change was perceived at detection threshold. However, when  $\lambda r$  was 518 nm,  $\lambda t$  shorter than  $\lambda r$  always appeared desaturated blue at detection threshold; that is, the observer detected blueness contaminated with whiteness. For yellow detection,  $\lambda t$  sometimes appeared

reddish yellow so that pure yellowness could not be detected. It might be the case that the observer's task was difficult in yellowness and blueness detection and consequently the data on these chromatic responses became inconsistent among observers.

The temporal properties of chromatic responses measured in the present study agree markedly well with some previous results. Smith *et al.*<sup>4</sup> reported that their threshold temporal integration functions measured with a single pulse were described by a single impulse-response function of  $n = 5$  and  $c = 32$  msec, which was inferred from the chromatic modulation transfer function measured by Wisowaty and Boynton<sup>8</sup> and Wisowaty.<sup>9</sup> These values of  $n$  and  $c$  coincide with those values of red and green responses in Table 1. Smith *et al.*<sup>4</sup> used a luminance level of 15 Td and white adaptation, whereas we used a 100-Td luminance level and moderate chromatic adaptation (571 and 518 nm). Despite these differences, our results turned out to be quite similar to those of Smith *et al.*, which suggests that chromatic adaptation and relatively high luminance levels do not influence chromatic temporal characteristics.

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19. There might be a criticism of the present yes-no procedure in that criterion shifts might have been systematically related to the SOA because the observer could hear the shutters and might have been able to estimate the SOA at each trial. However, in the present study, we obtained the integration time courses both in the achromatic and in the chromatic condition. The achromatic time courses were similar to those obtained previously,<sup>13</sup> so it was unlikely in the present procedure that the observer shifted his criterion by using estimates of SOA. Observer TT did not know the purpose of the present study during the experiments, although KU was one of the authors and SS knew the question of interest to some extent. But the results from the three observers came out to be similar, suggesting no criterion shifts by the well-trained observers.
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