[Paper]

Temporal Integration for Wavelength Change of an Equal-luminance Single Pulse

Keiji UCHIKAWA*

Abstract

Temporal integration of a single pulse was studied using a chromatic detection paradigm. In test and reference stimulus fields (45′ diameter, 30′ horizontal separation), monochromatic lights of the same wavelength were steadily presented at 100 Td. For a duration D, an isoluminant wavelength pulse was substituted in place of the test stimulus. The wavelength difference threshold $\Delta\lambda$, delimiting the detection of chromatic change between the test and reference stimuli, was measured as a function of D. Four wavelengths, 460, 530, 570, and 610 nm, were used for reference stimuli, and D was varied from 5 to 2000 ms. It was found that the $\Delta\lambda$-vs-D functions of 460 and 530 nm differed in shape from those of 570 and 610 nm, indicating slower chromatic responses for shorter reference wavelengths. Chromatic impulse response functions (IRFs), derived in the present study, were compared with those obtained by the double-pulse method previously reported. A possible reason for discrepancy in temporal integration properties among different chromatic responses obtained in several investigations is discussed.

Introduction

Temporal integration properties of chromatic responses have been investigated with various methods, most of which employ three types of stimuli: single-pulse, double-pulse, and flicker stimuli. In these studies, the stimulus was presented in a condition of isoluminant substitution, that is, only chromatic temporal variation was produced in the stimulus field so that luminance temporal variation would not influence detection of chromatic variation by the visual system. Detection threshold was measured as a function of stimulus duration by the single-pulse stimulus method,[1,2,5] and as a function of stimulus onset asynchrony (SOA) by the double-pulse stimulus method[3]. Chromatic modulation transfer functions (MTFs) were obtained by the chromatic-flicker stimulus method.[4-6] Although these experiments used different methods, it was consistently shown that the chromatic impulse-response functions (IRFs) derived in these studies are monophasic and have time constants greater than that of the luminance response.

Concerning temporal properties of different chromatic responses, such as red, green, yellow, and blue, it has been claimed that the response of blue mechanism is slower than the other chromatic mechanisms.[7,8] In fact, Regan and Tyler[1] measured wavelength-excursion thresholds under isoluminant conditions to detect wavelength changes, and obtained longer critical durations for 480 and 527 nm than those for 580 and 600 nm. However, Smith *et al.*[2] showed no difference between critical durations for the temporal integration of chromatic responses when using purity-change stimuli with different dominant wavelengths, ranging from 430 to 650 nm. Uchikawa and Ikeda[3] performed chromatic-detection experiments using isoluminant wavelength-change double-pulse stimuli at 518 and 570 nm; and reported no clear difference between IRFs that were derived from different chromatic responses.

Smith *et al.*[2] pointed out that the small luminance artifact might cause longer integration time for short wavelengths than for long wavelengths in Regan and Tyler's experiments. Experimental conditions, however, are quite different among the investigations cited above. One of the critical differences seems that chromatic

* Department of Information Processing, Tokyo Institute of Technology Graduate School 4259 Nagatsuta, Midori-ku, Yokohama 227

stimulus was made as wavelength-change from a certain reference wavelength by Regan and Tyler[1] and Uchikawa and Ikeda[3], whereas as purity-change from a white reference by Smith *et al.*[2]. Therefore, it would be necessary to ascertain whether different chromatic responses, yielded by wavelength-changes from different reference wavelengths, do not differ in their temporal integration properties without luminance artifact.

In this report, the wavelength difference threshold $\Delta\lambda$, delimiting the detection of chromatic change, was measured as a function of the stimulus duration D for four wavelengths. The present study aims to see whether chromatic responses, obtained by the wavelength-change single-pulse stimulus method, are the same without luminance artifact. Furthermore, we derived chromatic IRFs utilizing the present data and compared those obtained with the double-pulse method under similar experimental conditions previously reported by Uchikawa and Ikeda[3].

Method

Apparatus

A three-channel Maxwellian-view optical system was used in the present experiment (Fig. 1). The source XL was a 500-W xenon-arc lamp. Two monochromatic lights, produced by two grating monochromators M1 and M2, in channels 1 and 2 provided a wavelength-pulse stimulus and a reference stimulus in apertures AP1 and AP2, respectively. In channel 3, another monochromatic light was produced using an interference filter IF, and provided a test stimulus in an aperture AP3. AP1 and AP3 were spatially positioned to make a single test field. The wavelength-pulse from channel 1 was substituted for the test stimulus for a certain duration in the test field. Monochromators M1 and M2 and neutral-density wedges W1 and W2 in channels 1 and 2 were driven by stepping motors, which the observers could move with the aid of a microcomputer. Three high-speed electromagnetic shutters SH1, SH2 and SH3, placed at focal planes of the light beams in all channels and controlled by computer, presented the stimuli. The on/off timing of the shutters could be adjusted in 0.1 ms steps by computer to make a precise substitution of the wavelength-pulse for the test stimulus.

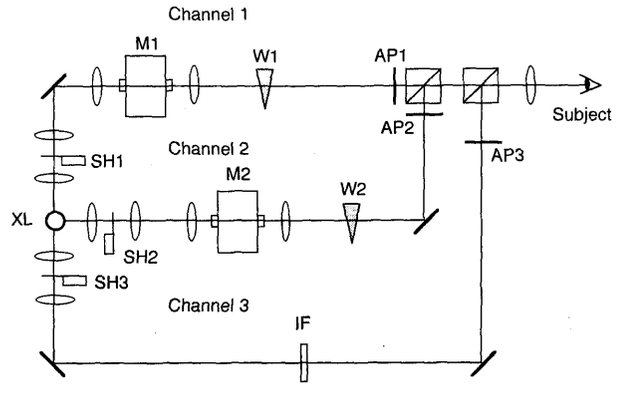


Fig. 1. *A three-channel Maxwellian-view optical system used in the present experiments. See text in details.*

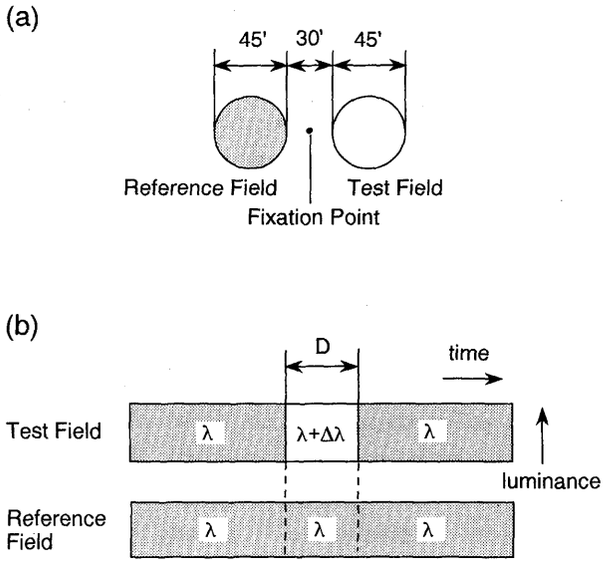


Fig. 2. *(a) Two circular stimulus fields. The right field was the test field, and the left the reference field. (b) Time course of the stimulus presentation. In the test field, the isoluminant* $\lambda+\Delta\lambda$ *wavelength-pulse was substituted for the test* λ *stimulus for a duration D.*

Two circular stimulus fields were presented to the observer (Fig. 2(a)). Each stimulus field subtended 45' of visual angle. They were separated horizontally edge to edge by 30'. The right field was the test field, and the left the reference field. A dim red point of about 5', presented at the midpoint between the two stimulus fields, was used as a fixation point.

The observer's head was fixed by a dental bite board, and his right eye alone viewed the stimuli.

Procedure

Two male observers, KU and RT, 33 and 22 years of age, respectively, were employed in the present experiment. Their color vision tested normal.

Four wavelengths, 460, 530, 570 and 610 nm, were used for the reference stimulus. The test stimulus was always of the same wavelength as the reference except during the wavelength-pulse in the test field. The wavelengths used for the wavelength-pulse ranged from 410 to 630 nm. In preliminary experiments, monochromatic stimuli of all wavelengths, used for the reference and test fields, were equated in luminance at 100 Td by the minimum flicker criterion for both observers.

In the main experiments, wavelength-difference thresholds $\Delta\lambda$ for detection of chromatic change between the wavelength-pulse and reference stimuli were determined using the method of adjustment. In a trial, as shown in Fig. 2(b), the reference and test stimuli were steadily presented, and then, for a certain duration D, the isoluminant wavelength-pulse was substituted for the test stimulus. The reference stimulus was invariant and the test stimulus matched the refernce stimulus except during the wavelength-pulse. This stimulus presentation was repeated with a 3s inter-stimulus-interval until a threshold was determined by the observer.

At the beginning of a trial, the wavelength-pulse was set equal in wavelength to the reference and, after each presentation of the wavelength-pulse, the observer adjusted the wavelength-pulse in the test field so that a chromatic difference between the test and reference fields was just detectable. In a session, two thresholds were obtained both in the direction of longer wavelengths and shorter wavelengths from the test for a given duration. Four sessions were performed to obtain a total of eight thresholds for both directions of wavelength change. Nine durations, 5, 10, 20, 50, 100, 200, 500, 1000, and 2000 ms, were studied while one of these durations was selected at random for use between sessions.

Results and Discussion

Thresholds of wavelength-difference are shown as functions of duration in Fig. 3 for observer KU and in Fig. 4 for observer RT. Four reference wavelengths, 460, 530, 570, and 610 nm, are shown at the right side of each figure. Open symbols represent thresholds set in the direction of longer wavelengths and closed symbols those set in the direction of shorter wavelengths. These conditions of longer and shorter wavelength directions are designated here as 460(+) and 460(—), 530(+) and 530(—), 570(+) and 570(—), and 610(+) and 610(—),

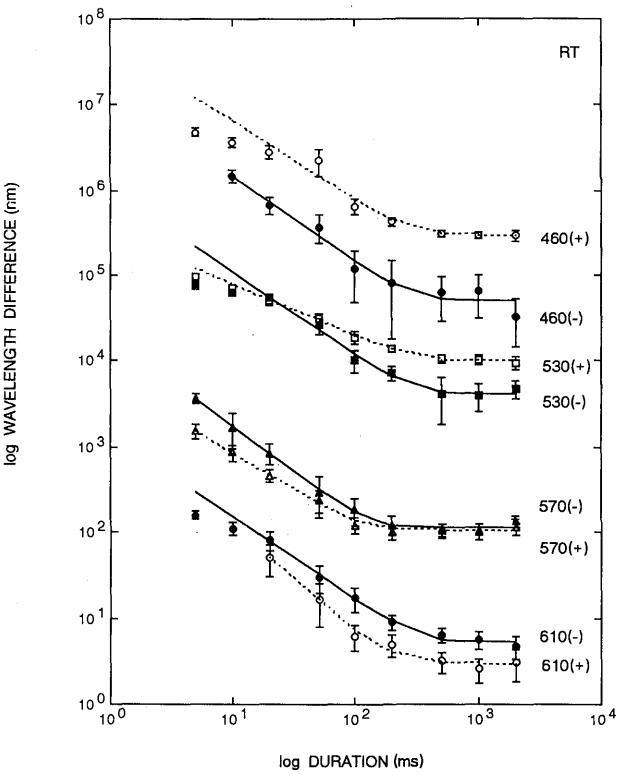


Fig. 3. *Wavelength difference threshold $\Delta\lambda$ as a function of stimulus duration. Reference wavelengths are shown on the right side of each pair of curves. Open symbols and (+) sign indicate thresholds obtained in the direction of longer wavelengths from a reference wavelength and closed symbol and (-) sign those in the direction of shorter wavelengths. The ordinate position of 460, 530, and 570 nm data are shifted upward in 4.5, 3, and 1.5 log-unit steps for clarity. Curves drawn along the data points are theoretical functions derived from a model described in the text. Observer: KU.*

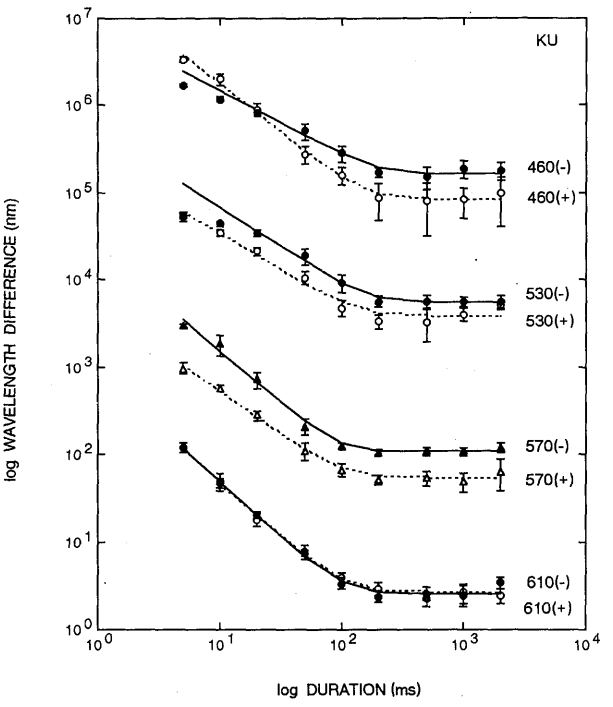
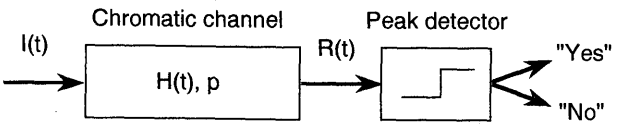


Fig. 4. *Same as Fig. 3, but for observer RT.*

respectively. The threshold points for 460, 530, and 570 nm reference wavelengths are shifted upward in 4.5, 3, and 1.5 log-unit steps for clarity. Error bars shown at the threshold points represent standard deviations of eight trials. Curves drawn along points are theoretical functions described below.

Figs. 3 and 4 show that thresholds in both directions for all wavelengths decrease as the duration increases from the shortest values, and then reach asymptotes at longer durations. The shortest duration used was 5 ms for all conditions except 610(+) (10 ms for KU, 20 ms for RT) and 460(—) (10 ms for RT). In these conditions, the amount of wavelength change required exceeded obtainable values on our equipment before thresholds could be reached at 5 or 10 ms duration. It is evident in Figs. 3 and 4 that temporal integration of wavelength difference occurred for the shorter durations during which the threshold decreases, and that this temporal integration ceased at a certain duration, which has been called the critical duration.

The temporal properties of the threshold-vs-duration functions shown in Figs. 3 and 4 turned out to be similar, but not the same among the four reference wavelengths. It is shown, for example, both in Figs. 3 and 4 that thresholds for 570(+) and 570(—) reach asymptotes at shortest durations. Since the critical duration critically depends on how two straight lines with slopes of -1 and 0 are fitted to the data points at complete-integration durations and those at no-integration durations, respectively, and the data points at partial-integration durations may not be used,[9] we derived temporal impulse-response functions (IRFs) to see the differences in these temporal properties. Use of an impulse-response function also makes it possible to compare the present results with those obtained by other methods as previously reported.



H(t): Impulse response function
p: Nonlinear factor

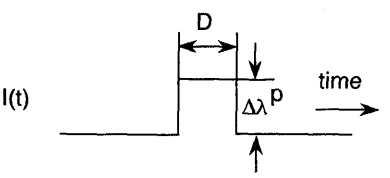


Fig. 5. *A model used in the present study in order to obtain the chromatic impulse response functions.*

In the model we wish to present here, shown schematically in **Fig. 5**, the chromatic impulse-response H(t) is the assumed output of a n-stage low-pass filter defined by the following equation[3]

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

where A is a proportionality constant and c is a time constant. The response R(t) in the chromatic channel is defined by an equation of the convolution integral

$$R(t) = \int_0^t I(t')H(t-t')dt',$$

where I(t) is the stimulus of which the amplitude is determined by the wavelength-difference $\Delta\lambda$. We employed a simple peak detector to determine threshold. This detector made a "yes" response when the amplitude of R(t) exceeded a given threshold level at any time t. This indicated that the wavelength difference $\Delta\lambda$ is detectable, whereas it made a "no" response when the amplitude of R(t) was below the threshold level. If the parameters, A, C, and n, of H(t) are determined by fitting the theoretical threshold-functions to the experimental data points, H(t) can be obtained for each set of data. We assumed that the amplitude of R(t) is proportional to $\Delta\lambda^p$, where p is a nonlinear factor for converting from the stimulus $\Delta\lambda$ to the response R(t). When $\Delta\lambda$ is small enough, it is assumed, in the first approximation, that R(t) can be considered proportional to $\Delta\lambda$.[1] However, this proportionality does not necessarily hold for greater value of $\Delta\lambda$. Therefore, we used a power factor p as a nonlinear factor to give the best fit between the theoretical functions and the data.

The solid and dotted curves in Figs. 3 and 4 are the theoretical functions obtained by the least-squares method to make the best fit to solid and open symbols, respectively. At durations of 5 and 10 ms of the 460(—) and 530(—) conditions for observer KU and 460(+), 530(+), 530(—), and 610(—) for observer RT, this fitting turned out to be worse than for other conditions. This is probably due to a violation of the nonlinear relationship between R(t) and $\Delta\lambda$, described above, for quite large values of $\Delta\lambda$. We used threshold points obtained at durations longer than 20 ms to calculate the best fitting functions in these conditions. The values of the c, n, and p parameters are shown in Table 1.

Figs. 6 and 7 show chromatic impulse-response functions (IRFs) for observers KU and RT, respectively. They are designated as 460(+) and 460(—), 530(+) and 530(—), and 570(+) and 570(—), and 610(+) and 610(—) in the same way as in Figs. 3 and 4. In Fig. 6, it seems likely that chromatic IRFs for 570 and 610 nm are narrower and have their peaks at shorter time than those for 460 and 530 nm. This

Table 1. *Values of parameters c and n in the impulse-response function H(t), and a power factor p obtained to give the best fit to the experimental thresholds shown in Figs. 1 and 2.*

Observer	Condition	c(ms)	n	p
KU	460 (+)	25	7	1.113
	460 (-)	30	7	.742
	530 (+)	20	8	.835
	530 (-)	25	8	.891
	570 (+)	15	8	.988
	570 (-)	20	4	1.205
	610 (+)	40	2	1.193
	610 (-)	15	8	1.278
RT	460 (+)	50	6	.923
	460 (-)	80	3	.995
	530 (+)	80	3	.606
	530 (-)	55	5	.976
	570 (+)	25	4	.867
	570 (-)	45	2	1.085
	610 (+)	70	2	1.246
	610 (-)	70	4	.973

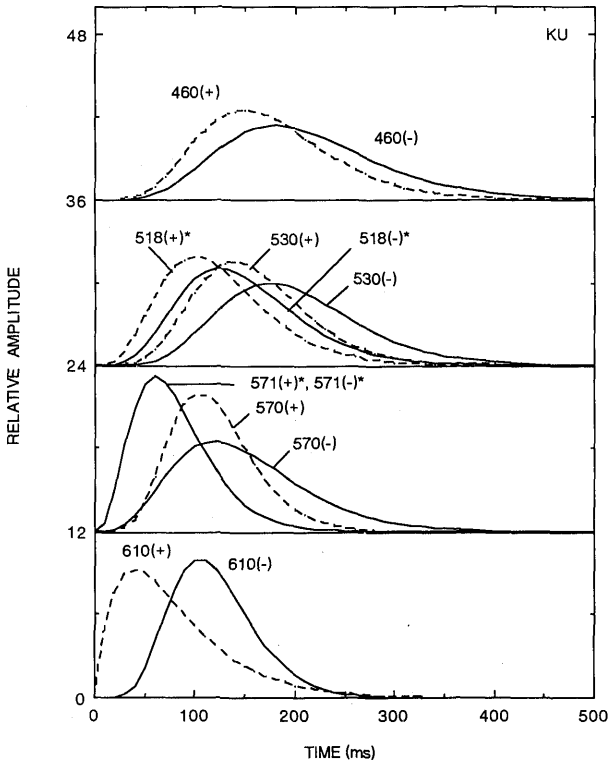


Fig. 6. *Chromatic impulse response functions (IRFs) for 460(+), 460(-), 530(+), 530(-), 570(+), 570(-), 610(+), and 610(-). IRFs indicated by 518(+)*, 518(-)*, 571(+)*, and 571(-)* are replotted from reference 3. Observer: KU.*

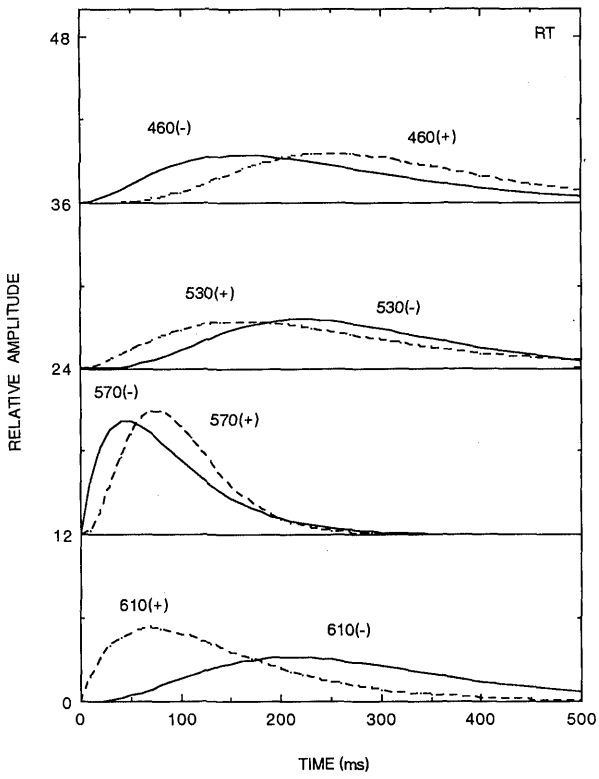


Fig. 7. *Same as Fig. 6, but for observer RT.*

tendency is also evident in Fig. 7 except for the IRF for 610(—) nm.

In Fig. 6, IRFs indicated by 518(+)*, 518(—)*, 571(+)*, and 571(—)* were those repotted from the results obtained by Uchikawa and Ikeda.[3] There they applied the double-pulse method in their experiments, but used a luminance level of 100Td, the stimulus field of 45′ visual angle presented at 38′ in the nasal retina, and the observer KU. These conditions are the same as in the present experiment. They used 518 and 571 nm reference wavelengths and the wavelength of the stimulus field was changed in the direction of longer and shorter values, which can be expressed as 518(+)* and 518(—) and 571(+)* and 571(—)*, respectively, in the present designation. It is shown that the IRFs obtained in the present experiments are fairly consistent with those derived by the double-pulse method.

The present results are consistent with that the longer critical durations for shorter reference wavelengths reported by Regan and Tyler[1]. It seems reasonable, therefore, to say that differences in temporal integration properties among different reference wavelengths are not caused mealy by the small luminance artifact. It is also true that Smith *et al.*[2] showed no difference in critical duration among chromatic changes in different directions from white. Regan and Tyler[1] and the present investigation utilized wavelength-change at isoluminance as compared with a reference wavelength. Across different reference-wavelengths, saturation as well as hue are not equal, which means that temporal chromatic-responses in the visual system made by wavelength-changes would occur in addition to different levels of chromaticness. However, when the reference is white, as used by Smith *et al.*[2], the reference chromaticness-level is zero for all test stimuli. This difference in chromatic quantity of reference stimuli, upon which chromatic changes were detected by the observer, may be a cause of the discrepancy between these studies. It would not be possible nor appropriate to estimate what the chromatic quantity is by using the present data. Further investigations carefully designed should be performed to answer the question of whether the visual system has the same temporal response function for all chromatic channels.

Acknowledgements

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