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TEMPORAL DETERIORATION OF WAVELENGTH DISCRIMINATION WITH SUCCESSIVE COMPARISON METHOD

KEIJI UCHIKAWA* and MITSUO IKEDA

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

Abstract—The wavelength discrimination threshold ($\Delta\lambda$) was measured with a successive comparison method, in which two stimuli of different wavelengths were presented in the left and right half of 2.2° or 2.7° bipartite field, respectively, with a certain stimulus onset asynchrony (SOA). The stimulus duration was kept constant at 110 msec. The $\Delta\lambda$ value for five different wavelengths, 430, 470, 520, 570 and 610 nm, was found to be constant up to SOA = 60 msec and increased gradually till SOA = 190 msec. The wavelength discrimination functions with SOA of 0 and 550 msec were also obtained for 430 through 650 nm in 10 nm steps. At all wavelengths the values with SOA of 550 msec were about twice as large as those with SOA of 0 msec. The present results indicate that the wavelength discrimination deterioration is complete within a relatively short period of time.

INTRODUCTION

Since Spering's partial report experiments (Spering, 1960) a number of investigations have shown evidence for the existence of a short-term visual memory or storage for various visual tasks, such as letter detection (Averbach and Coriell, 1961; Eriksen and Collins, 1967), pattern perception (Haber and Standing, 1969; Hogben and Di Lollo, 1967; Ikeda and Uchikawa, 1978; Ikeda, Uchikawa and Saida, 1979), length comparison (Ikeda *et al.*, 1977) and line position comparison (Uchikawa and Andrews, 1980). The integrating time-period for memory has been fairly well established at durations of between 100 msec and 500 msec. However, there exist only a few studies relating to short-term visual storage for color perception; the role of which is very important in visual information processing. Successive color comparison is quite common in our everyday life. We compare two colors at different locations by alternating fixations from one color to the other. As stored information about color decays quickly in the visual system we should expect a gradual deterioration of color discrimination from that obtained with the simultaneously, juxtaposed color comparison method (Wright and Pitt, 1934; MacAdam, 1942).

Previous partial report experiments show that colors are well discriminated in short-term visual storage if quite large color differences exist among the stimuli (Dick, 1961; Clark, 1969; Banks and Barber, 1977). Newhall *et al.* (1957) and Burnham and Clark (1955) employed the successive color matching method and found a greater variability with the successive method than with the simultaneous one. These results indicate the inability of the visual system to store color information accurately for a long period of time.

* Present address: Department of Psychology, York University, Downsview, Ontario M3J 1P3, Canada.

In the investigations by Newhall *et al.* and Burnham and Clark, however, a relatively long interval of about 30 sec was employed between the two successively presented stimuli. The present study aims, therefore, to investigate color information loss at a very early stage, less than 1 sec, with the method of the successive wavelength discrimination. Two stimuli of different wavelengths were presented successively with some temporal delay and subjects responded whether they perceived two stimuli different. If the color information is gradually lost in the time course the discrimination must decline as a function of temporal delay.

The first experiment investigates the time course of deterioration of color discrimination. The second investigates the wavelength characteristics of the discrimination at two different intervals.

METHODS

Apparatus

A conventional three channel Maxwellian view system was used as schematically shown in Fig. 1. Two

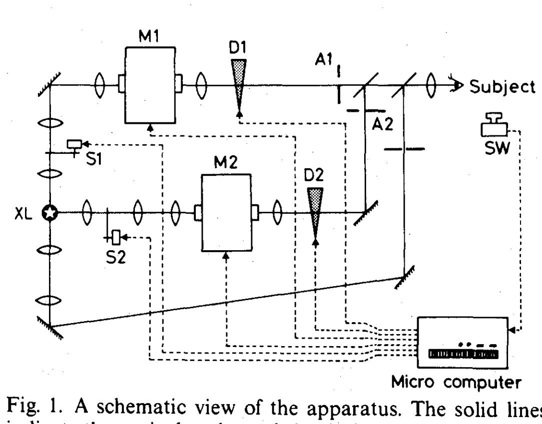

Fig. 1. A schematic view of the apparatus. The solid lines indicate the optical paths and the dashed lines the connections to the microcomputer.

light beams from a 500-W xenon arc lamp (XL) passed through monochromators M1, M2, neutral density wedges D1, D2 and apertures A1, A2, respectively and formed the right and left halves of a bipartite field; each composing a test field and a comparison field. The gap between the two fields was either 11′ or 41′ of visual angle, and the corresponding width of the whole field was either 2.2° or 2.7°. The third channel at the bottom served as a fixation point providing a small dim white dot at the center of the bipartite field throughout an experimental session. Two monochromators and two neutral density wedges were driven by stepping motors and controlled by a microcomputer. Any wavelength and any desired intensity were readily set out for both test and comparison fields. The half band width of the monochromators was set to 3 nm.

High-speed magnetic shutters S1 and S2 were used to deliver the stimuli. They could deliver flashes at 100 Hz. Light was focused on the blades of the shutters to ensure the fast onset and offset of the output light, the rise time being less than 1 msec. The right field test wavelength (λt) always preceded the left field comparison wavelength (λc) with a certain stimulus onset asynchrony (SOA). The duration of test and comparison stimuli was always kept constant to 110 msec. Responses by a subject were fed directly into the computer via the switch SW so that the analysis of data could be done immediately after every session.

Experiment 1

Subjects

Two persons (KU and HU) with normal color vision served as subjects.

Procedure

It is important to present two stimuli in equal brightness because the discrimination of two stimuli might be done only in terms of the brightness difference rather than the chromatic difference. Therefore, the luminous efficiency function for both test and comparison fields were obtained beforehand from 410 nm through 680 nm in 10 nm steps with the heterochromatic direct brightness matching method against a reference field with the brightness level of 76 td. In the main experiment the microcomputer adjusted the wedges D1 and D2 to assure the equal brightness for the test and comparison fields. Linear interpolation was used whenever necessary.

Five wavelengths 430, 470, 520, 570 and 610 nm were employed for the test field. In the first series of Experiment 1, SOAs were 0, 110, 220, 550, 1090 and 5450 msec. The gap of 11′ in the bipartite field was used. In the second series, SOAs of 0, 55, 110, 160 and 220 msec were employed to investigate precisely the very early stage of deterioration. The gap was enlarged to 41′ to avoid the brightness reduction due to the metacontrast effect with these short SOAs.

In one session a test wavelength was randomly chosen among the five wavelengths. Nine comparison wavelengths were selected in such a way that the two extreme wavelengths appeared distinctly different from the test. The constant stimuli method was used to determine the wavelength difference threshold ($\Delta\lambda$). Nine pairs of the test stimulus and the comparison stimuli were randomly presented with a certain SOA; any one of the pairs being presented for 5 times. A subject pressed one of the two buttons to respond either "same color" or "different colors" after each presentation. We employed several dummy test stimuli with wavelengths different from the test stimulus but in the region of the comparison wavelengths, to compensate for the subject "learning" the test color. Thus on the right field a stimulus randomly chosen from the test and the dummies was presented, which was followed by the comparison stimulus on the left field. A session consisted of the presentation of stimulus 100 times to 140 times, and required about 15–30 min. KU repeated four sessions and HU three sessions, providing a total of twenty (KU) and fifteen (HU) responses for each test-comparison pair with a fixed SOA at the end of the experiment.

Results

Two examples of frequency distributions of "different" response for the test wavelength 610 nm are given in Fig. 2. The comparison wavelength (λc) are presented along the abscissa and the test wavelength (λt) is indicated by an arrow. The percentage of "different" is plotted along the ordinate. Two solid ogive curves were derived with the least square method to give the best fit to the experimental points when they were added linearly. With SOA equal to 0 msec (Fig. 2a) the ogives are very close to each other, indicating that good discrimination is taking place

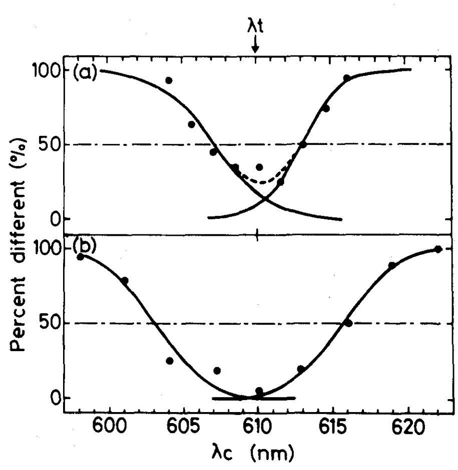

Fig. 2. Two examples of frequency distributions of "different" response. (a): SOA = 0 msec, (b): SOA = 550 msec. Subject: KU. The test wavelength λt is indicated by an arrow. Two solid ogive curves give the best fit to the solid points when they are added linearly as shown with the dashed line.

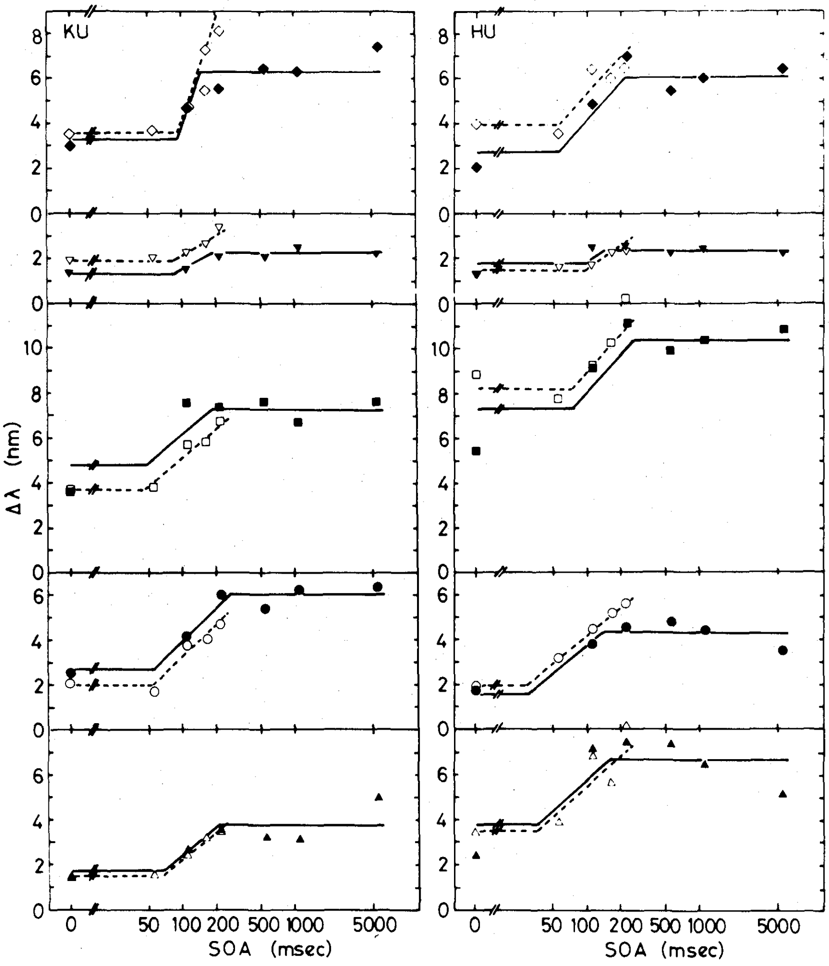

Fig. 3. Wavelength discrimination threshold $\Delta\lambda$ as a function of SOA for two subjects. ▲, △: 430 nm, ●, ○: 470 nm, ■, □: 520 nm, ▼, ▽: 570 nm, ◆, ◇: 610 nm. The solid and the open points correspond to the first and second series, respectively. The solid and the dashed lines indicate the empirical curves of $\Delta\lambda$-SOA function.

between the test stimulus and the comparison stimuli. With SOA, 550 msec (Fig. 2b), however, the two curves are separated, which clearly show a deterioration in the discrimination of the two colors. The difference threshold $\Delta\lambda$ was defined as half of the distance between two wavelengths at 50% points on the ogives. They are 3.0 nm and 6.4 nm respectively in the examples of Fig. 2. Similar response curves were obtained, though not shown here, for all dummy wavelengths employed only with some shift to either side of λt. The similarity ensured the reliability of the subject's response.

The wavelength discrimination threshold $\Delta\lambda$ value is plotted as a function of SOA for each subject in Fig. 3. Solid and open symbols correspond to the first and second series, respectively. $\Delta\lambda$ values are small at SOA = 0 msec as expected and also at 55 msec for all test wavelengths investigated, but they gradually increase as SOA increases until SOA of 220 msec, where some constant values are reached.

$\Delta\lambda$ Values for the second series appear to be shifted vertically as a whole compared to those of the first series. Because of no consistent direction of the shifts observed in both subjects the differences should be only due to the criterion shift rather than to the different gap sizes.

Those experimental points suggest a rather simple empirical curve of $\Delta\lambda$-SOA function to exist as shown in Fig. 4. Values, $\Delta\lambda_0$, $\Delta\lambda_c$, T_0, and T_c were calculated by applying this empirical curve to give the best fit to the experimental points with the least square method.

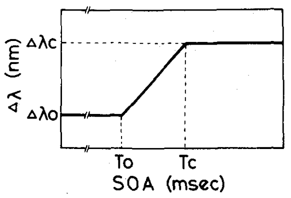

Fig. 4. An empirical curve to represent the time course of the wavelength discrimination deterioration.

Table 1. T_0, T_c values in msec for the five test wavelength

		Test wavelength λt in nm 430	470	520	570	610	Mean
KU:	T_0	65	55	46	81	92	66
	T_c	210	270	180	190	150	190
HU:	T_0	36	29	73	94	55	52
	T_c	160	140	260	140	220	180

The shapes of the empirical curves at short SOAs for filled points were determined by utilizing open points. The results are shown by solid and dashed lines in Fig. 3. It should be noted that a certain vertical shift of the dashed line will result in the solid line in each figure. Table 1 summarizes T_0, T_c values for five test wavelengths; their mean values being 66, 190 msec for KU and 52, 180 msec for HU, respectively.

Experiment 2

Subject

Another subject (SO) with normal color vision was added to KU and HU of Experiment 1.

Procedure

The wavelength discrimination threshold ($\Delta\lambda$) was obtained for the range of 430–650 nm in 10 nm steps

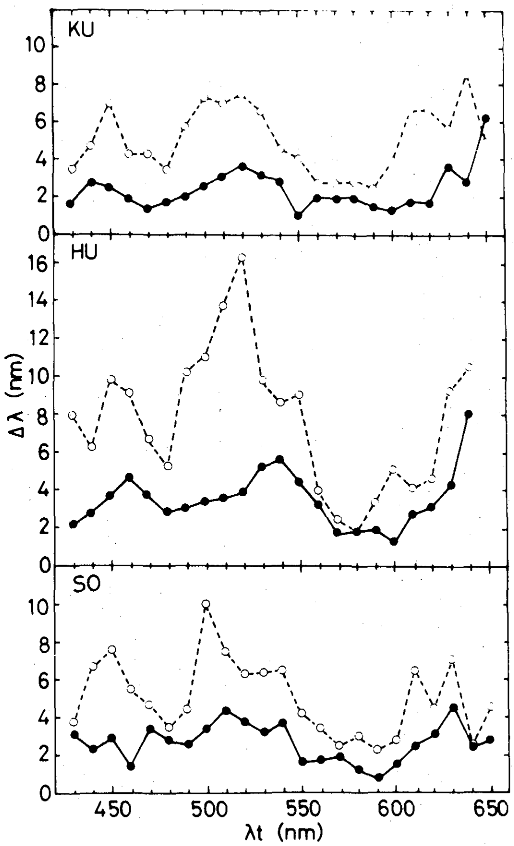

Fig. 5. Wavelength discrimination threshold $\Delta\lambda$ as a function of the test wavelength λt for three subjects. ●: SOA = 0 msec, ○: SOA = 550 msec.

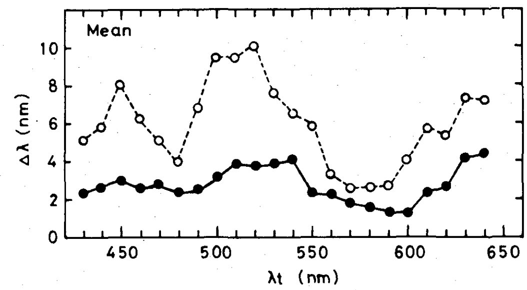

Fig. 6. The mean value of the wavelength discrimination threshold as a function of the test wavelength λt. ●: SOA = 0 msec, ○: SOA = 550 msec.

for two SOAs, 0 and 550 msec. The up-and-down method was used to determine $\Delta\lambda$. The wavelength of the comparison field was changed either closer to or further from the test wavelength depending upon the subject's response "different" or "same". Such up-and-down change of the comparison wavelength was repeated 10 to 20 times before a threshold was obtained. Two thresholds corresponding to comparison wavelength shorter and longer than the test wavelength were obtained within a session. The difference threshold ($\Delta\lambda$) was defined as a mean of the two thresholds. Two dummy stimuli were employed nearby the test wavelength and presented in the same way as in Experiment 1.

The brightness matching data were utilized here also for the same reason mentioned in Experiment 1. The test stimulus arrangement with the gap of 11′ was used throughout.

Results

Figure 5 shows $\Delta\lambda$ as a function of λt for three subjects. Figure 6 gives the mean of the three subjects. The $\Delta\lambda$–λ functions for the simultaneous presentation (SOA = 0 msec) are denoted by the solid circles in each figure. They are very similar to those reported previously (Wright and Pitt, 1934; Siegel and Dimmick, 1962; Siegel, 1964; Bedford and Wiszecki, 1958). The minima occur at 590–600 nm and 460–480 nm with $\Delta\lambda$ of 1–2 nm and the maxima at 510–540 nm and 440–460 nm. The $\Delta\lambda$–λ function with SOA of 550 msec are shown by open circles. At all wavelengths investigated the $\Delta\lambda$ values are always larger than those with SOA of 0 msec, indicating the deterioration in the color discrimination. The two minima and the two maxima also exist, though their locations shifted a little along the wavelength λt.

DISCUSSION

The present experiments provided a direct method for investigating the temporal deterioration of color discrimination in memory. It was shown in Experiment 1 that good wavelength discrimination was maintained till a SOA of 60 msec and the discrimination gradually deteriorated at longer SOAs. The discrimination threshold $\Delta\lambda$ finally reached an asymptote at a SOA of 190 msec. These results indicate that a short-term visual storage for color exists with a integrating time-period of 60 msec in the visual system. Despite the differences in experimental conditions this integrating time-period is not much different from those values of 100–500 msec reported by Eriksen and Collins (1967), Hogben and Di Lollo (1974) and Uchikawa and Andrews (1980). This suggests a visual mechanism for the color storage similar to that for pattern storage.

It is noticed that the ratio $\Delta\lambda_c/\Delta\lambda_0$ in Experiment 1 is constant giving a value of about 2 regardless of the test wavelength. Such constant value can be also observed in Experiment 2. Newhall *et al.* (1957) obtained a value of 6.2 times when compared the average area of the successive match ellipses to that of the simultaneous match ellipses in the CIE 1931 chromaticity diagram. This gives about 2.5 times in one direction, which is highly equal to 2 obtained above. This suggests, therefore, that very little deterioration of the color discrimination takes place after 190 msec.

It is interesting to compare the wavelength discrimination function obtained for the successive presentation in Experiment 2 to that derived from color naming data. Color naming can be considered as a successive color discrimination task involving memory, because a subject has to discriminate a color presented from colors in his memory to make a judgement in a color naming procedure. Several investigators have estimated the wavelength discrimination functions by using their color naming data (Smith, 1971; Boynton, 1975). Those function turned out to be qualitatively almost same in shape as the function where the stimuli were simultaneously viewed. However, Smith (1971) showed that the maximum location of the function at the green region was shifted about 20 nm to the shorter wavelength side. This characteristic is consistent with the results from all subjects reported in the present experiments, suggesting that same color mechanism in the visual system was activated by two different methods. The experimental conditions, such as luminance level, stimulus size and presentation duration, are very different between the previous experiments and our experiments so that further investigation are needed in order to compare, in detail, the wavelength discrimination function with successive comparison method to that with the color naming method.

In many of our practical situations, colors are spread all around us. This forces us to compare colors with certain time delays. Therefore one must realize that when using wavelength discrimination data obtained by the simultaneous juxtaposed condition, it is about twice as sensitive as that obtained in successive viewing condition.

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