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Accuracy of memory for brightness of colored lights measured with successive comparison method

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Successive and simultaneous brightness comparisons between test colors and a comparison white were performed to study how accurately the brightness of colored lights was maintained in memory. The test colors were monochromatic lights chosen from 410 to 670 nm and a white light. The stimulus duration was 1 sec, and test-comparison stimulus-onset asynchronies in successive comparisons were more than 11 sec depending on the experiments. The results show that the variability of successive brightness comparisons was 1.5–2.0 times greater than that of simultaneous brightness comparison. This degree of deterioration of brightness discrimination is reasonably consistent with those of hue and saturation discrimination previously reported. Brightness shifts in the darker direction were found for most colors.

INTRODUCTION

Simultaneous color comparison by using a bipartite field has been employed as a standard method when brightness, hue, and saturation of colored lights are measured as a base of colorimetry and photometry. However, it has been pointed out that successive color comparison is a more common task than simultaneous color comparison.[1–4] In our everyday lives, we seldom compare two colors simultaneously because simultaneous comparison is possible only for two colors that are closely juxtaposed so that one can observe both colors within the fovea. In most cases, we compare two colors by viewing one color and then another color with some delay between these successive views. It should be noted that successive comparison necessarily involves memory, and if color information stored in memory is less accurate than that in appearance we can expect deterioration in color discrimination and variation in color information in memory.

Several investigations on memory for color were conducted in various fields of color perception.[2–7] Among these investigations the experiments using successive comparison showed that successive color discrimination thresholds were larger than those of the simultaneous color discrimination in the dimensions of hue[2,3,8] and saturation[9] and combined dimensions of hue and saturation.[10,11] These results indicated that the color discrimination deteriorated in memory. It was also reported that saturation in memory was shifted toward increased saturation,[9,10] but no systematic hue shifts were observed.[8,10]

Memory for brightness, however, has been studied in only a few investigations,[10,12] despite the fact that brightness is one of the fundamental dimensions of color. Therefore, in the research reported below, we investigated, first, how accurately brightness of colored lights was discriminated and, second, whether any shift in brightness of colored lights was observed when the successive comparison method was used. We performed two experiments. The first experiment compared matching accuracy obtained with successive and simultaneous brightness comparisons. The second experiment studied more precisely wavelength effect and influence of interference stimuli that were presented between test and comparison stimuli on variability and shift in brightness in memory.

GENERAL METHOD

Apparatus

We used a conventional two-channel Maxwellian-view optical system. The source was a 500-W xenon-arc lamp. The first channel produced a chromatic light by means of a grating monochromator with a half-bandwidth of 6 nm, constituting the test field. The second channel produced a white light, providing the comparison field. The CIE 1931 chromaticity coordinates of the white light in the second channel were $x = 0.398$, $y = 0.439$. When a white test stimulus was required in the first channel, we used the zero-order diffraction light having a broadband spectrum from the monochromator. The spectral radiance of the zero-order diffraction light was adjusted by putting Wratten color-compensating filters in the first channel so that chromaticity of the white test light was visually matched with that of the comparison white in the second channel.

Two electromagnetic shutters in the two channels presented test and comparison stimuli for a certain duration and with a certain stimulus-onset asynchrony (SOA) between the test and comparison stimuli. Two circular neutral-density wedges could vary luminances of both channels. These shutters and wedges and the monochromator were controlled by a microcomputer.

The circular test and comparison fields subtended a 45′ visual angle and were separated horizontally by 30′. The test stimuli were presented on the left field, and the comparison stimuli on the right field. The observers fixated a small dim-red point continuously presented at the center of the gap between the two fields.

Observers

Two males, KU and SS, 32 and 25 years of age, respectively, served as observers in the experiments. Both had normal color vision and were experienced in psychophysical experiments.

EXPERIMENT I

Stimulus

Seven colors, six monochromatic lights of 450, 490, 530, 570, 610, and 650 nm, and a white light were used as test stimuli. The comparison stimulus was a white light that had the same chromaticity as the test white light. Ten luminances separated in about 0.05 log luminance steps were provided for each test monochromatic light and the white light. The luminance level of each set of ten luminances was determined so that the stimulus of the sixth luminance from the highest luminance in a set was matched in brightness to the comparison white light of 220 Td. This brightness matching was carried out for each observer as a preparatory experiment in which the test and the comparison stimuli were simultaneously presented for 1 sec.

Procedure

Experiment I consisted of two brightness comparison modes: simultaneous brightness matching and successive brightness matching. In simultaneous brightness matching, test and comparison stimuli were presented simultaneously for 1 sec with 2-sec intervals. The observers adjusted intensity of the comparison white stimulus to obtain a brightness match to a test stimulus. In successive brightness matching, only a test stimulus was first presented for 1 sec, and then, with a SOA of 11 sec, the comparison white stimulus began to appear for 1 sec with 2-sec intervals until the observers completed brightness matching to the test stimulus. The duration of the comparison white stimulus was set the same in both comparison modes to compare directly the results of the two matching modes without considering any brightness difference possibly caused by duration effects.

As some time is needed to complete brightness matching in a trial, the observers had to see the comparison white several times. We measured matching time in the successive matching for each observer in order to show how much of a delay occurred between presentation of a test stimulus and the last presentation of the comparison white when the observers made final judgment of a brightness match. Since the observers could see a test stimulus only once, they had to use their memory for brightness of the test stimulus in order to perform the successive brightness matching.

In a session, only one test color was used, and ten different luminances of that test color were randomly presented to avoid any possible learning effect that might occur when repeatedly using only one luminance. The simultaneous and the successive matching trials were alternated in a session so that the results obtained with the two matching modes could be directly compared without considering any error caused by sessional difference. A session consisted of 20 trials. Ten test stimuli of different luminances were presented twice, once for simultaneous matching and once for successive matching. Several sessions for one or two colors were run in a day. The observers performed 16 sessions for each wavelength to make a total of 16 matches for each test luminance of a test color in each matching mode. Altogether 112 sessions were required to obtain matches for all the colors tested.

It should be noted that we employed heterochromatic brightness matching, that is, the same white light was used as a comparison stimulus to be matched in brightness with test colored lights. This is because it would be better to employ a single scale, that is, luminance of the same white in this experiment, to compare directly variability and shifts in brightness of different colors in memory.

Results and Discussion

Figure 1 shows examples of standard deviations (SD's) as a function of test-stimulus luminance of 530 nm obtained with the simultaneous (filled circles) and the successive (open circles) matchings for the two observers. We used log relative luminances of the comparison white to calculate the standard deviation (SD) for each test stimulus. The posi-

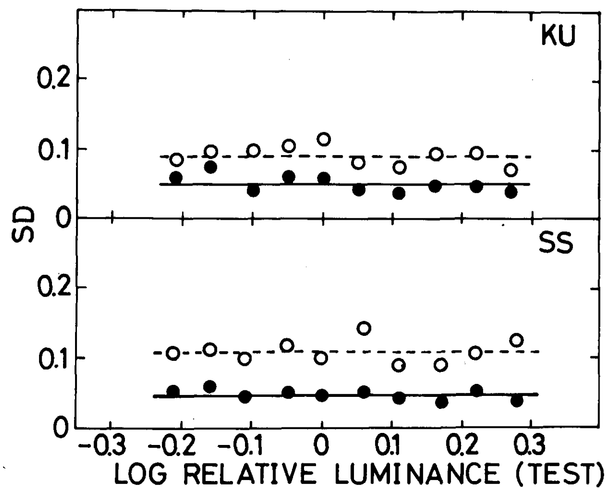

Fig. 1. Examples of standard deviation (SD) of simultaneous matching (●) and successive matching (○) as a function of log relative luminance of 530-nm test stimulus. Observers: KU (top), SS (bottom).

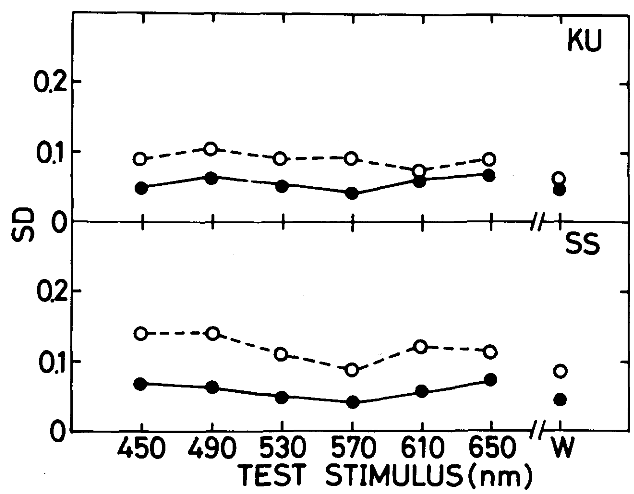

Fig. 2. Mean SD's for test wavelengths and white: ● simultaneous matching, ○ successive matching. Observers: KU (top), SS (bottom).

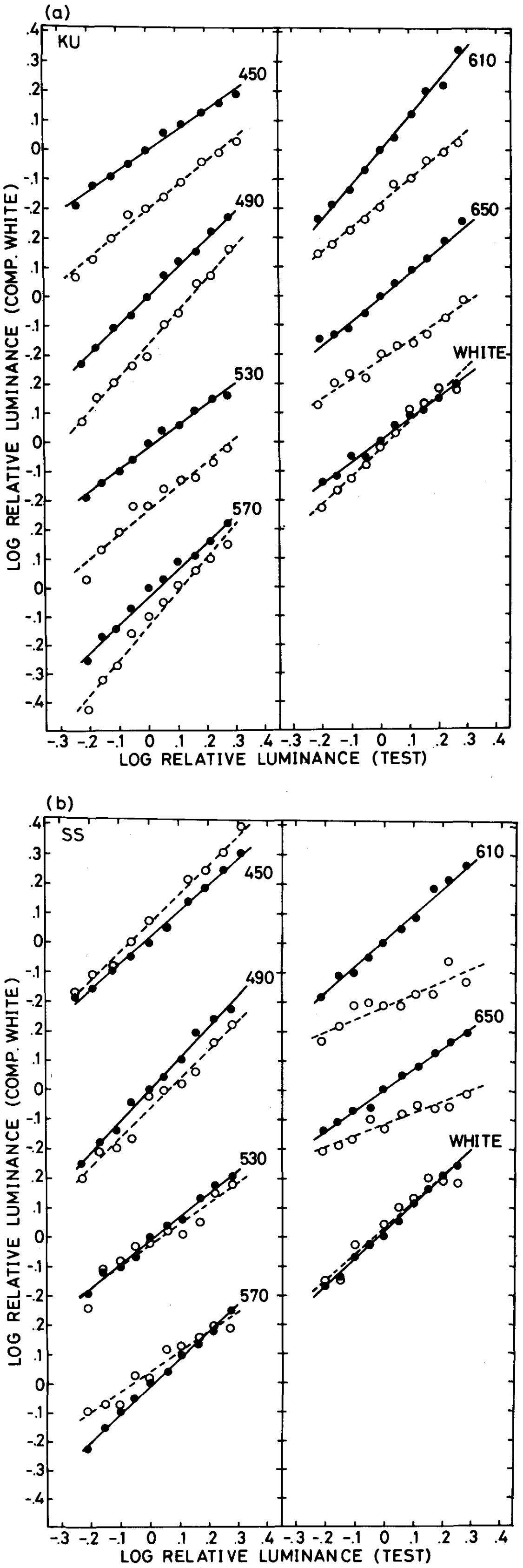

Fig. 3. Means of log relative matching luminance of the comparison white with the simultaneous matching (filled symbols) and the successive matching (open symbols). Observers: (a) KU; (b) SS. Test wavelengths are shown on the upper right of each set of data. Solid and dashed lines give the best fit to the respective points.

tion of zero value on the abscissa indicates luminance of the test stimulus that was matched in brightness to the white of 220 Td. Solid and dashed lines represent means of SD with the simultaneous and the successive matching, respectively.

It is shown in Fig. 1 that SD's of all test stimuli are greater with the successive matching than those with the simultaneous matching and that there are no systematic deviations from means for both matching modes. Since these characteristics hold for all test colors, we can simply take the mean of SD's for each test color to see any chromatic effect on the amount of SD.

Figure 2 shows means of SD's for all test colors. No systematic differences are evident among SD's of different colors for both simultaneous (filled circles) and successive (open circles) comparisons. We took the ratio of the successive SD to the simultaneous SD for each color in order to show the degree of deterioration by the successive comparison. It is found that all ratios are in the range of 1.2 to 2.3, and the means are 1.6 for KU and 2.1 for SS. This means that the brightness in memory is less accurate than the brightness in appearance. The values of the ratio between 1.5 and 2.0 agree well with those values obtained in the successive hue and the saturation discriminations previously reported.[3,9]

In Figs. 3(a) and 3(b), we show means of log relative matching luminance of the comparison white with the simultaneous (filled symbols) and the successive (open symbols) matchings for KU and SS. Solid and dashed lines in these figures were obtained by the least-squares method to make the best fit of the respective data points. In simultaneous matching, as expected, log relative luminance of the comparison white increases linearly with increasing log relative luminance of the test stimulus. But it may be surprising that, in the successive matching, log relative luminance of the comparison white also increases linearly as log relative luminance of the test stimulus increases. This suggests that, regarding the order of its relative magnitude, the brightness of test stimuli can be reproduced well from memory. As can be seen in Figs. 3(a) and 3(b), however, the matching luminances determined by successive matching tend to have less value than those by simultaneous matching for some colors. It is likely that brightness information in memory varies from brightness in actual appearance.

In Experiment I, we used the method of adjustment to obtain the matching luminance of the comparison white with both the successive and simultaneous modes. As described earlier, in successive matching, the memory time during which brightness of a test stimulus had to be stored in memory was measured. The mean stimulus-onset asynchronies between a test and the last comparison stimuli were found to be approximately 25 sec on the average for the two observers. But this memory time was not the same among test colors. Moreover, the observers saw the comparison white stimuli with various brightnesses while they adjusted its brightness. There might be an influence of memory time and stimuli presented between test and comparison stimuli on memory for brightness of colored lights. In Experiment II, we further investigated possible influences of these variables using the method of constant stimuli in order to set only one SOA between test and comparison stimuli and presenting interference stimuli between test and comparison stimuli.

EXPERIMENT II

Stimulus

Fourteen monochromatic lights chosen from 410 to 670 nm in 10-nm steps were employed as test stimuli in Experiment II. The chromaticity of the comparison white stimulus was the same as that used in Experiment I. Five stimuli of different luminances in about 0.1 log step were used for each test wavelength. As in Experiment I, the middle luminance, i.e., the third luminance from the highest luminance, for each test wavelength was determined so that the stimulus with the third luminance was matched in brightness to the white comparison of 220 Td by the simultaneous matching method.

Procedure

Experiment II consisted of three temporal modes of brightness comparison. The first mode was simultaneous comparison, in which test and comparison stimuli were presented simultaneously for a 1-sec duration. The second mode was successive comparison without interference stimuli. Test stimuli that appeared for 1 sec were followed by comparison stimuli with a SOA of 11 sec. The comparison stimuli were also presented for 1 sec. The third mode used interference stimuli, presented for 1 sec between test and comparison stimuli. A SOA between test and interference stimuli was 6 sec. These interference stimuli were of the same wavelength as the test stimuli but two different luminances of about 0.25 log luminance higher and lower than the test stimuli.

The method of constant stimuli was used in Experiment II to determine matching points of brightness between a test color and the comparison white and variability of brightness comparison. The observers' task was to judge whether a comparison stimulus was brighter than a test stimulus at every trial. For the successive comparison modes with and without interference stimuli, the observers were allowed to respond with "unable to judge" when they had completely forgotten brightness of the test stimulus.

Seven comparison luminances were provided for each test luminance so that the comparison stimuli of two extreme luminances were clearly perceived to be brighter and darker than the test stimulus. Only one test color was used in a session. The first, second, and third comparison modes were chosen trial by trial in this order in a session. Five different luminances of a test color varied in a random order in a block to avoid a possible learning effect. When we obtained a frequency curve of response "brighter," we combined frequency curves of the middle three luminances of the test color to make up one frequency curve as a function of comparison luminance. Fifteen trials were carried out as a total for each comparison luminance in all three comparison modes.

Results and Discussion

Figure 4(a) shows examples of percent "brighter" responses obtained by the simultaneous comparison (filled circles), the successive comparison without interference stimuli (open circles), and the successive comparison with interference stimuli (open squares) with 610-nm wavelength for observer KU. The absicssa represents log relative luminance of the comparison white. Solid, dashed, and dotted ogives were derived by probit analysis[13] to give the best fit to the respective points. Although the response "unable to judge" was permitted, the total percentage of this response was very small, 1.9% for KU and 1.3% for SS on the average of all pairs of test and comparison stimuli.

It is shown in Fig. 4(a) that, for any comparison mode, the responses "brighter" increase with increasing luminance of the comparison white. But two curves of the successive comparison were found to be shifted in the negative direction relative to the simultaneous comparison curve, indicating that the test stimulus was observed as darker with successive comparisons. Moreover, the response curves of two successive modes were slightly more inclined than the simultaneous comparison curve, which means poorer discrimination in brightness with successive comparison modes.

The matching point between the test stimulus and the comparison white was defined as log relative luminance having a 50% point of the ogive. M1, M2, and M3 in Fig. 4(b) represent the matching luminances of the comparison white with the simultaneous and two successive modes, respectively. The differences between the successive and the simultaneous matching luminances, i.e., M2–M1 and M3–M1, may be considered as indexes of brightness shift with the successive comparisons. The scale on the abscissa in Fig. 4 represents this difference. The SD of the response curve is equal to the distance on the abscissa between 50% and 84% points of the ogive. In Fig. 4(b), SD's for the simultaneous and two successive modes are shown as SD1, SD2, and SD3, respectively.

In Fig. 5 SD1, SD2, and SD3 are plotted as functions of test wavelength for the two observers. It is shown in Fig. 5

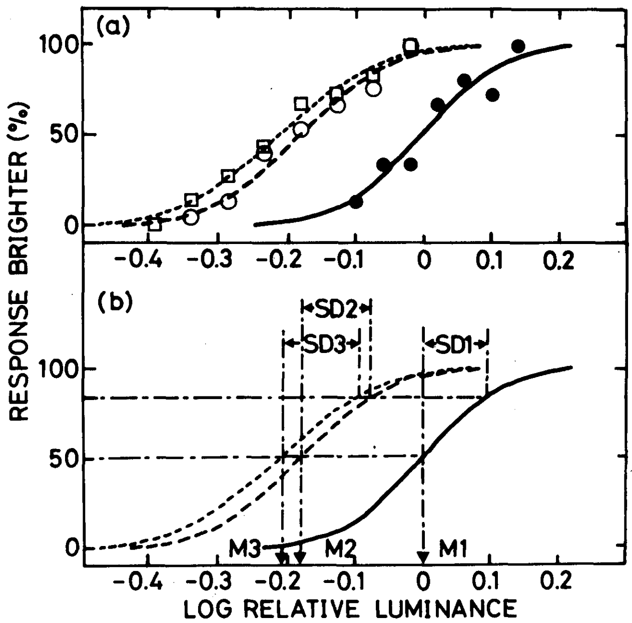

Fig. 4. (a) Examples of percent "brighter" response with 610-nm test stimulus for observer KU: ● the simultaneous comparison; ○ the successive comparison without interference stimuli; and □ the successive comparison with interference stimuli. Solid, dashed, and dotted ogives give the best fit to the respective points. (b) Matching luminance M1, M2, and M3 of the comparison white to a test stimulus (50% point) and SD's SD1, SD2, and SD3 (distance between 84% and 50% points) with simultaneous comparison, successive comparison without interference stimuli, and successive comparison with interference stimuli, respectively.

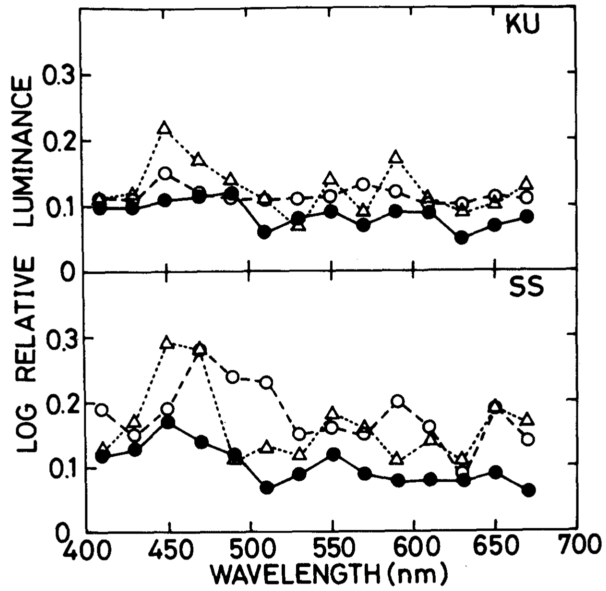

Fig. 5. Standard deviations with simultaneous comparison SD1 (●); successive comparison without interference stimuli SD2 (○); and successive comparison with interference stimuli SD3 (Δ) as functions of test wavelength. Observers: (top) KU; (bottom) SS.

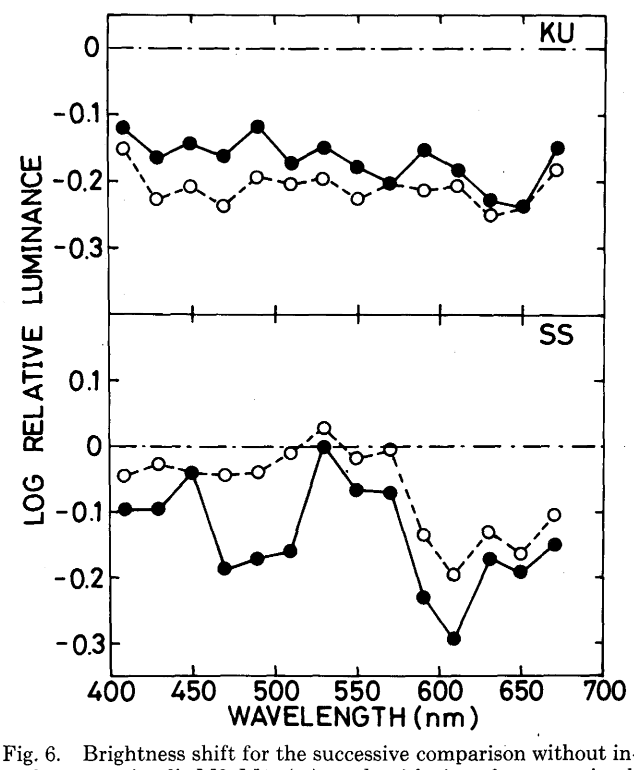

Fig. 6. Brightness shift for the successive comparison without interference stimuli M2–M1 (●) and with interference stimuli M3–M1 (○) as functions of test wavelength. Observers: (top) KU; (bottom) SS. Zero value on the ordinate indicates no brightness shift.

that the values of SD1 are smallest for all wavelengths except at a few points, indicating that the most precise discrimination of brightness occurred with the simultaneous comparison. SD2 and SD3, having higher values than SD1 for both observers, do not differ from each other in a systematic way. The ratios of SD2 to SD1 turned out to be 1.3 for KU and 1.9 for SS on the average of all wavelengths, which confirms the results of Experiment I. This implies two things about variability of brightness discrimination in memory: First, the interference stimuli do not have any appreciable influence. Second, memory time of 25 sec on the average used in Experiment I has the same effect as that of 11 sec used in Experiment II.

In Fig. 6 we show brightness shifts M2–M1 (filled circles) and M3–M1 (open circles) as functions of test wavelength for both observers. The zero value on the ordinate indicates the position of no brightness shift. The values of M2–M1 were found to be negative for both observers, which indicates that brightness of test color was recalled from memory as darker than it really appeared. The brightness shifts for the successive comparison with interference stimuli (M3–M1) are different from M2–M1; they are always lower for KU and higher for SS than M2–M1 across all wavelengths. These brightness shifts appear quite systematic, although the brightness shifts occurred in opposite directions between the two observers. Since we made two brightness levels of interference stimuli, brighter and darker than a test stimulus, it might be interesting to see whether these two interference stimuli have any different effect on brightness shifts.

Figure 7 shows the brightness shifts for the successive comparison with brighter interference stimuli [M3 (B)–M1] and those with darker interference stimuli [M3 (D)–M1] represented by open squares and open triangles, respective-

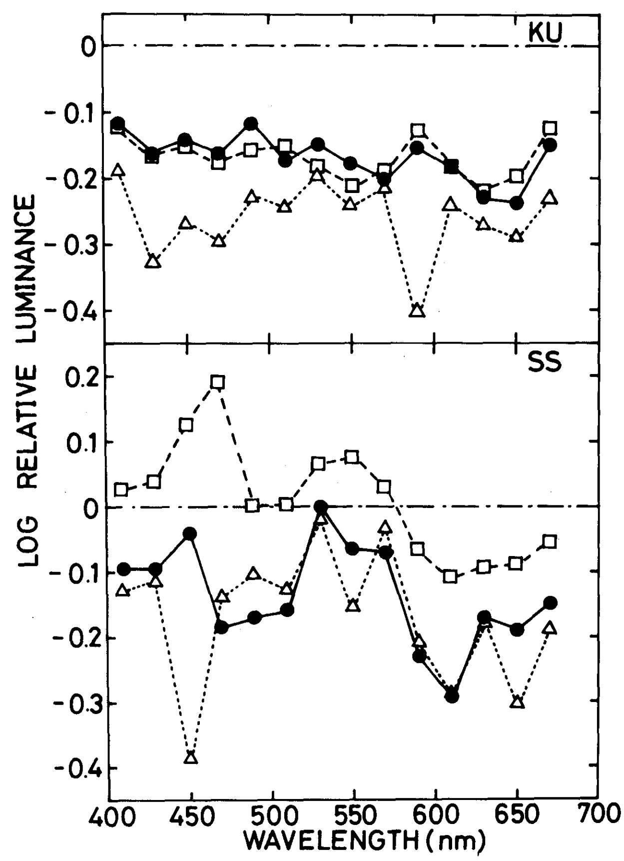

Fig. 7. Same as Fig. 6 but for successive comparison with brighter interference stimuli M3 (B)–M1 (□) and with darker interference stimuli M3 (D)–M1 (Δ). M2–M1 (●) is replotted from Fig. 6 for comparison.

ly. For comparison, M2–M1 is also shown in Fig. 7 (filled circles). It was found that M3 (B)–M1 and M3 (D)–M1 were clearly separated across all test wavelengths for both observers. When the interference stimulus was brighter, the brightness shifts were in the brighter direction, but when the interference stimulus was darker, the brightess shifts were in the darker direction. This suggests that the observers confused test and interference stimuli, and thus brightness shifts of a test stimulus by memory might be affected by stimuli that followed the test stimulus.

However, it turned out that M3 (B)–M1 for KU and M3 (D)–M1 for SS were almost coincident M2–M1, implying that brighter interference stimuli for KU and darker interference stimuli for SS had no effect on brightness shifts. This explains the total brightness shifts of M3–M1 in Fig. 6, although it is still unknown why brighter and darker interference stimuli had different effects on brightness shifts between the two observers. We should say for the moment that further experiments need to be done to show clearly how test and interference stimuli interact with each other.

GENERAL DISCUSSION

It was shown in both Experiments I and II that brightness discrimination deteriorated by the successive comparison compared with the simultaneous comparison. The degree of deterioration, that is, that ratio of SD with successive comparison to that with simultaneous comparison, was between 1.5 and 2.0, consistent with those in the hue and saturation discrimination.[3,9] Therefore, it can be concluded that color-discrimination ability of the visual system uniformly degrades with the successive comparison in any dimension of a color.

It was observed in the present experiments that brightness shifts by successive comparison were in the darker direction. These brightness shifts were also reported in the previous investigation by Newhall *et al.*[10] However, they showed increased brightness shifts in memory. In their memory-matching experiments, the mean SOA between presentation of test stimulus and termination of matching stimulus was about 35 sec, which was quite similar to those of the present experiments. But their experiments and our experiments are mainly different in that (1) we used a white comparison stimulus and did heterochromatic brightness matching, whereas they used a colored comparison stimulus to perform color matching in which the observers could control hue and saturation as well as brightness, and (2) we presented the white comparison stimulus for the same duration as a test stimulus (1 sec) with a 2-sec intervals, whereas in their experiments a matching stimulus was continuously presented until the observers completed color matching, although a test stimulus was presented for 5 sec. The comparison white stimulus used in our experiments may also produce its own adaptation effects, but differences (1) and (2) may produce stronger adaptation effect on chromaticness and brightness of matching stimuli in their experiments. It might be due to the predominant adaptation effect that the matching stimuli required more luminance to obtain color match by their memory-matching experiments.

We showed in Experiment II that interference stimuli presented between test and comparison stimuli had some effects on brightness shifts, that is, that brighter and darker interference stimuli could produce brightness shifts of a test stimulus in opposite directions when compared with those shifts without interference stimuli. While the results shown in the experiment were not always consistent between observers, it might be a useful technique to utilize interference stimuli in order to study brightness of colors in memory.

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