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PURITY DISCRIMINATION: SUCCESSIVE VS SIMULTANEOUS COMPARISON METHOD

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Abstract—Purity discrimination thresholds (Δp) were measured with successive (SOA = 3 sec) and simultaneous (SOA = 0 sec) comparison methods for seven dominant wavelengths; 410, 480, 500, 530, 570, 600 and 650 nm. The stimulus duration was 1 sec. The Δp values with the successive comparison method were found to be about 1.5–2.0 times larger than those obtained in the simultaneous case. The degree of purity discrimination deterioration shown in this study is similar to that of wavelength discrimination deterioration previously reported (Uchikawa and Ikeda, 1981, *Vision Res.* **21,** 591–595). Saturation shifts of stimuli with the successive comparison method were also observed; these were toward increased saturation direction for most dominant wavelengths.

INTRODUCTION

Human color discrimination has been extensively investigated with simultaneously viewed, closely juxtaposed comparison fields. Successive color comparison, on the other hand, is a more common task than the simultaneously viewed case (Burnham and Clark, 1955). Two colors can never be compared simultaneously unless closely juxtaposed stimuli are observed with foveal vision. Because temporal delays normally occur between fixations of two colors, successive color comparison involves color memory and thus may depend on a higher level of color processing in the visual system than do juxtaposed fields.

Some previous investigations indicate that successive color matching yields greater valiability than simultaneous color matching (Hamwi and Landis, 1955; Burnham and Clark, 1955; Newhall *et al.*, 1957; Nilsson and Nelson, 1981), suggesting that color discrimination deteriorates in memory. Newhall *et al.* (1957) also showed substantial increases in remembered saturation with successive color matching, although Hanawalt and Post (1942) reported no significant saturation shift in memory.

Uchikawa and Ikeda (1981) measured wavelength discrimination deterioration as a function of temporal delay between short presentations (0.1 sec) of two stimuli. They showed that with a stimulus onset asynchrony (SOA) of 0.2 sec wavelength discrimination thresholds reached asymptotes, which were 1.5–3.0 times greater than for simultaneous discrimination thresholds. Despite differences in their experimental conditions, results obtained by Uchikawa and Ikeda (1981) and Nilsson and Nelson (1981) are in good agreement that successive wavelength discrimination thresholds are about twice greater than those for the simultaneous case.

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It is interesting and important also to study successive color discrimination using non-spectral colors. Therefore the present investigation compares successive and simultaneous comparisons in *purity* discrimination.

METHOD

Apparatus

A conventional five channel Maxwellian view system was used [Fig. 1(a)]. The light source, XL, was a 1000 W xenon arc lamp.

Two chromatic lights were produced by means of grating monochromators, M1 and M2, in channels 1 and 3, respectively. M1 and M2 were set to half bandwidths of 8 nm. Channels 2, 4 and 5 produced white lights. The CIE 1931 (x, y) chromaticity coordinates of the white lights from channels 2, 4 and 5 were $x = 0.345 \pm 0.003$, $y = 0.355 \pm 0.003$ measured with an EG&G spectroradiometer. Two circular stimulus fields, surrounded by a white adaptation field, were presented to the observer [Fig. 1(b)]. The left field came from channels 1 and 2 and the right field was produced by channels 3 and 4. These stimulus fields could vary in purity from 0.0 to 1.0. The surrounding adaptation field came from channel 5.

Neutral density wedges W1, W2, W3 and W4 were driven by stepping motors controlled by a microcomputer. The maximum resolution of these wedges were 0.0013 log density unit. The observer could control any wedge with a switch, SW, connected to the computer. SW also transmitted the observer's responses to the computer. The shutter, S1 and S2, also controlled by the computer, were used to deliver the stimuli. The observer viewed stimulus and adaptation fields through an achromatizing lens, AL. An ophthalmic lens, OL, was used as required to provide a sharp image of the fields.

Each stimulus field subtended 45′ visual angle and was separated from the other one by 30′ as shown Fig. 1(b). The surrounding white adaptation field sub-

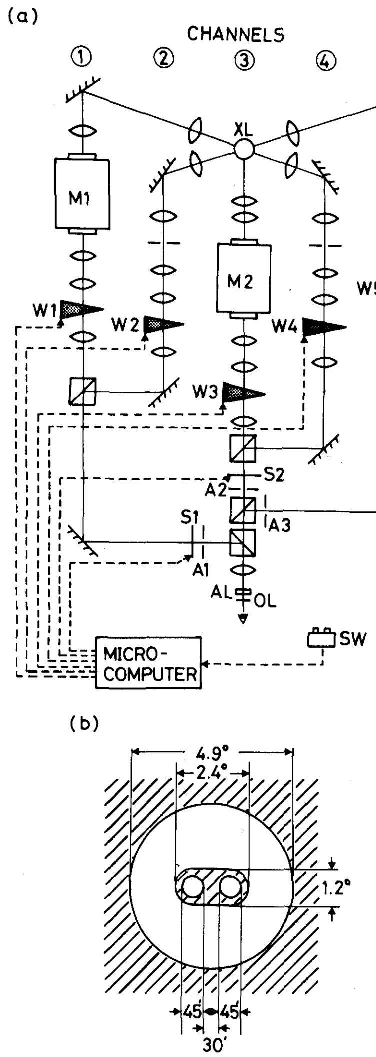

Fig. 1. (a) Schematic diagram of the apparatus. (b) The test stimulus field (right), the comparison stimulus field (left) and the surrounding adaptation field. See text for details.

tended 4.9° with a centre part occluded. The luminance of the surrounding white field was kept constant at 170 td throughout all experimental sessions.

Observers

Two observers, a male, K.U. and a female, H.U., 30 and 29 years of age respectively, participated in all experiments. They had normal color vision as tested by the Farnsworth–Munsell 100 Hue Test and the AO-HRR plates.

Procedure

Seven wavelengths; 410, 480, 500, 530, 570, 600 and 650 nm, were chosen as dominant wavelengths for test and comparison stimuli. Purity of these stimuli were varied between 0.0 and 1.0 by adding white light to spectral lights. Purity is expressed here as excitation purity in the CIE 1931 (x, y) chromaticity diagram.

The stimuli used in the main experiment were first equated for brightness with excitation purities of 0.1–0.9 in 0.1 steps plus 0.05 and 0.95. The light from channel 4 was set in the right stimulus field (see Fig. 1) as a reference white. Direct heterochromatic brightness matching was performed between the stimuli in the left field and the reference white for all dominant wavelengths. The luminance level of the reference was 150 td. Then direct homochromatic brightness matching was conducted between the stimuli in the right field and those in the left field, which had been equated for brightness. Each stimulus in the right field had the corresponding stimulus in the left field as a reference with the same dominant wavelength and purity. The stimuli were simultaneously presented for 1 sec. In the main experiment the microcomputer adjusted positions of wedges W1, W2, W3 and W4 so that stimuli in both fields were presented at equal brightness as previously determined. Linear interpolation for wedge positions was used when necessary.

Each observer made saturation estimates for the equally bright stimuli in both right and left fields obtained above (Uchikawa *et al.*, 1982). The observer estimated the percent chromatic content in each stimulus by the method of constant sum. The stimuli were presented for 1 sec. The surrounding white field was always present to provide the observer with a baseline for their responses. The aim of the saturation estimation experiment was to choose test stimulus purities in a linear range of saturation which was a function of test stimulus excitation purity. Moreover, some results may be better described in terms of saturation estimates than excitation purity.

Figure 2 shows the test stimulus purities used in the main experiment for each observer. Five test purities for each dominant wavelength were selected for both observers, except that only three test purities for 570 nm were chosen for observer H.U. Numbers shown along the lines describing tests stimuli in Fig. 2 indicate mean saturation estimates (percent chromatic content) of two observers for each dominant wavelength. The test stimuli were in a range of about 10–50% of saturation estimates. The test stimuli with 410 and 570 nm as dominant wavelengths lay on a tritanopic confusion line, and those with 500 nm on one of the deuteranopic confusion loci. (The significance of choosing these two theoretically critical axes, which was fully discussed by Boynton and Kambe (1980), will be mentioned again later in this paper.)

In the main experiment, the method of constant stimuli was used to determine purity discrimination thresholds and points of subjective equality, relative to fixed test stimuli, for comparison stimuli. Seven comparison stimuli were chosen for each test stimulus so that the two extreme comparison stimuli clearly appeared to be more and less saturated than the test stimulus. The test stimuli were always presented in the right field and the comparison stimuli in the left field.

At each trial, the observer pressed one of two switches indicating whether a comparison stimulus was "more saturated" or "less saturated" than a test

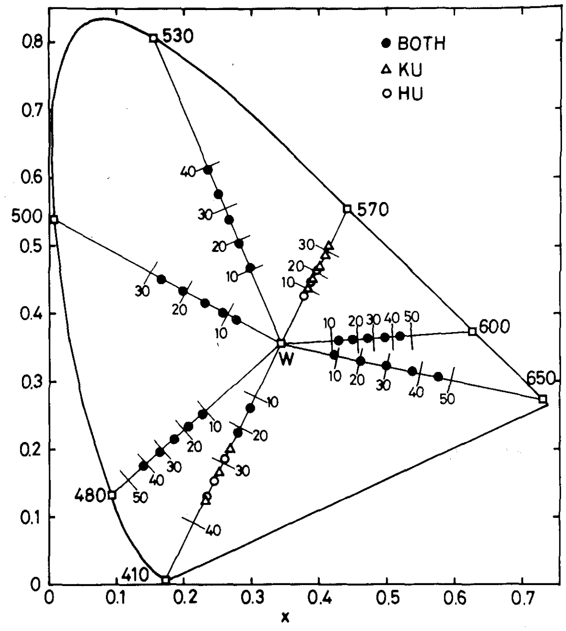

Fig. 2. Chromaticity points of test stimuli in the CIE 1931 chromaticity diagram. ●: for both observers K.U. and H.U., Δ: for K.U., O: for H.U. W indicates the position of the white light. Numbers shown along the lines describing test stimuli represent mean saturation estimates of two observers for each dominant wavelength.

stimulus*. For the stimuli with the dominant wavelength of 410 nm some hue change occurred as well as saturation change as excitation purity of the stimuli was varied. In this case the observer responded in which direction (i.e. toward white or the 410 nm spectral light) a color change had appeared†.

In each session, only one dominant wavelength was used. A session consisted of six blocks; three blocks for simultaneous condition and the other three for successive condition. Blocks for simultaneous and successive conditions were alternated within a session. All test stimuli with different purities were chosen in a random order in each block in order to avoid possible learning effects by presenting repeatedly only one test stimulus throughout a block. Each pair of test and comparison stimuli was presented randomly four times in each block. The purity range of comparison stimuli was checked at end of each block to maintain comparison stimuli in the proper purity region; that is, two comparison stimuli were seen as clearly more or less saturated than the test and these were shifted when necessary.

The duration of both test and comparison stimuli was 1 sec. In the successive comparison condition the SOA between presentations of test and comparison stimuli was set to 3 sec (i.e. an inter-stimulus interval of 2 sec). In the simultaneous condition SOA was 0 sec. The observer was not required to fixate at a particular point during the test exposure, but fixated in the surrounding adaptation white field between trials to reduce chromatic adaptation effects of the test and comparison stimuli.

*It is known that most of the constant hue loci are not straight in the chromaticity space (Wyszecki and Stiles, 1967). In the present experiment, however, except for 410 nm, the observer did not perceive any hue difference between each test stimulus and its comparison stimuli probably because there were only small purity differences between test stimuli and their corresponding comparison stimuli.

†This criterion was similar to that used by Boynton and Kambe (1980). It was not difficult for both observers to respond using this criterion.

RESULTS AND DISCUSSION

Figure 3 shows two examples of percent "more saturated" responses with dominant wavelength of 650 nm [Fig. 3(a)] and 530 nm [Fig. 3(b)] for observer K.U. The abscissa represents excitation purity of the comparison stimulus, P_c, in the CIE 1931 (x, y) chromaticity diagram. The solid and open circles show responses with simultaneous (SOA = 0 sec) and successive (SOA = 3 sec) comparisons, respectively. The test stimulus purity, P_t, which was used for both simultaneous and successive conditions, is indicated by an arrow in the figures. Solid and dashed ogives were derived by the probit analysis (Finney, 1971) to give the best fit to the data points.

It is shown in both Fig. 3(a) and (b) that the linear portion of solid ogives have greater slopes than the dashed ogives, indicating better discrimination in purity with simultaneous than successive comparison in both examples. In Fig. 3(a), on the other hand, the dashed ogive was found to be shifted in a positive direction in purity when compared with the solid ogive, indicating that the test stimulus was perceived as more saturated with successive than for simultaneous presentation. The dashed ogive in Fig. 3(b) is

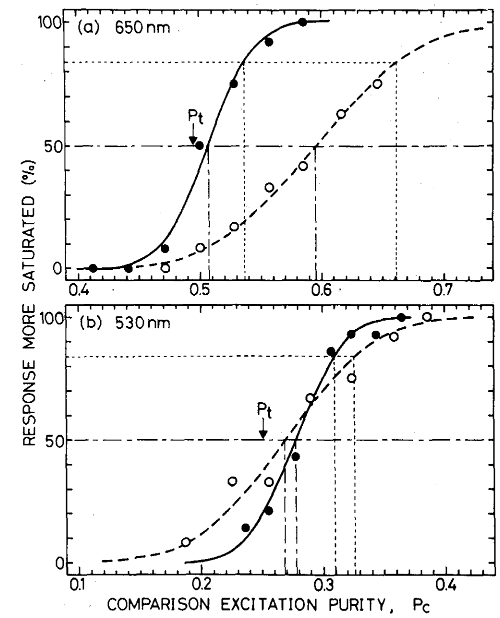

Fig. 3. Two examples of percent "more saturated" responses with dominant wavelength of 650 nm (a) and 530 nm (b) for K.U. ●: simultaneous condition (SOA = 0 sec), ○: successive condition (SOA = 3 sec). The test stimulus purity, P_t, is indicated by an arrow in each figure. Solid and dashed ogives give the best fit to the solid and open symbols, respectively.

only slightly shifted in a negative purity direction, which means that the test stimulus appeared to be almost equally saturated in simultaneous and successive conditions.

The discrimination threshold of purity, Δp, was defined as the distance in purity between 50 and 84% points of the ogive, which is equivalent to the standard deviation of the ogive curve. In Fig. 3(a), for example, the discrimination thresholds are 0.030 and 0.066, respectively, as shown by dotted lines in the figure. The simultaneous purity discrimination thresholds, obtained by this definition, can be compared with previous data (Wright, 1941; McAdam, 1942) and for the average of all test stimuli, they turn out to be about five times larger for K.U. and eight times for H.U., than those of MacAdam. This difference is probably due to methodological differences in determining purity discrimination threshold; MacAdam employed variability in color-matching as the discrimination threshold, whereas in the present experiment the discrimination threshold was defined as the slope of a probability function of discrimination.

The point of subjective equality, PSE, of the responses was also defined as purity of 50% point of the ogive. PSEs with simultaneous and successive comparison in Fig. 3(a) were determined to be 0.507 and 0.595, respectively. The difference between successive and simultaneous PSEs may be considered as an index of saturation shift with the successive comparison method.

It is noticed in Fig. 3 [particularly 3(b)] that there is a small discrepancy between the test purity P_t and the simultaneous PSE. For all test stimuli of the experiment, this discrepancy, the average constant error, turned out to be 0.044 for K.U. and 0.045 for H.U. Besides response validity, this discrepancy is probably due to two different optical paths of test and comparison stimulus fields (see Fig. 1), since two perfectly perceptually identical stimulus fields are rarely obtained even when an attempt is made to make them physically match.

Successive and simultaneous discrimination thresholds

In Fig. 4 the discrimination threshold values, Δp, for simultaneous comparison (solid symbols) and successive comparison (open symbols) are shown as a function of excitation purity of test stimuli P_t for observers K.U. and H.U. The discrimination thresholds Δp for both cases tend to decrease as the test excitation purity P_t increases for dominant wavelengths of 480 and 410 nm (K.U.), and increases for the other dominant wavelengths. The successive discrimination thresholds are greater than the simultaneous discrimination thresholds for most test purities, which indicates deterioration of purity discrimination with the successive comparison method. The difference between the successive and simultaneous discrimination thresholds clearly depend on dominant wavelengths tested.

In order to determine the relative degree of deterioration with the successive comparison method, the

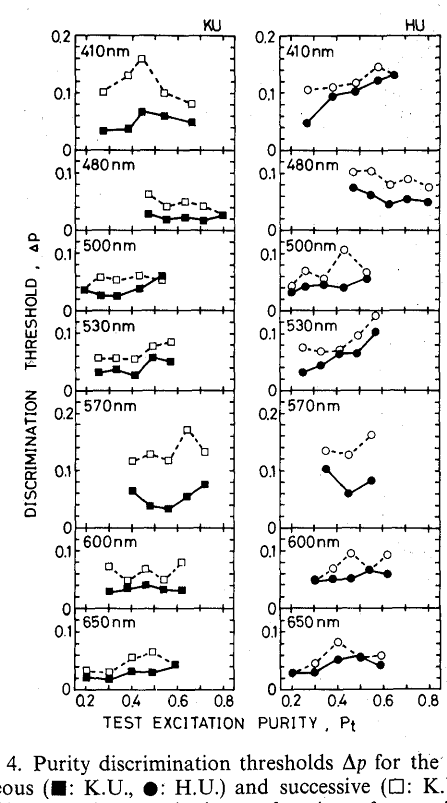

Fig. 4. Purity discrimination thresholds Δp for the simultaneous (■: K.U., ●: H.U.) and successive (□: K.U., ○: H.U.) comparison method as a function of test stimulus excitation purity, P_t. Dominant wavelengths are shown in each section of the figure.

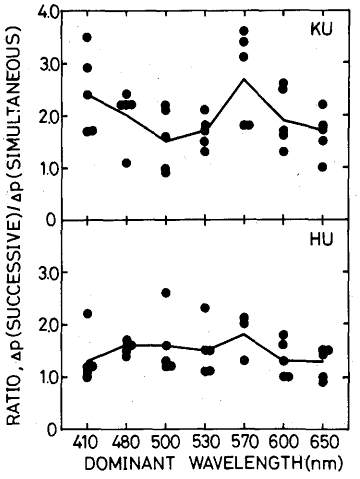

Fig. 5. The ratios of successive to simultaneous discrimination thresholds shown at each dominant wavelength. Solid line represents arithmetic means of ratios at each dominant wavelength. Observers: K.U. (top), H.U. (bottom).

ratio of successive to simultaneous discrimination thresholds was calculated and is plotted as a function of dominant wavelength in Fig. 5. These data points, at each dominant wavelength, were derived from the successive and simultaneous thresholds in Fig. 4. Solid lines in the figure represent arithmetic means of ratios at each dominant wavelength. The discrimination threshold with the successive comparison is, on the average, 2.0 times greater than that with the simultaneous comparison for K.U. and 1.5 times for H.U. This amount of deterioration is quite similar to those obtained by previous investigations on wavelength discrimination (Uchikawa and Ikeda, 1981; Nilsson and Nelson, 1981). This consistency suggests that color discrimination processing in memory works for saturation similarly as for hue.

For observer K.U. the ratios of 410 and 570 nm (wavelengths which lie on the tritanopic axis) tend to be higher than those of other dominant wavelengths, whereas for H.U. the ratios are almost constant across all dominant wavelengths. It is generally accepted that color discrimination along tritanopic confusion loci are mediated by y-b opponent system, whereas color discrimination along deuteranopic confusion loci are mediated by r-g opponent system (Boynton and Kambe, 1980). Therefore there seems to be greater discrimination loss in the former system than the latter system for K.U., but two systems for H.U. almost the same discriminability in memory for color.

Individual differences in wavelength discrimination were found to be greater below 460 nm than other parts of the spectrum (Wright and Pitt, 1934). Boynton and Kambe (1980) have reported that there are larger differences between observers in color discrimination steps along the tritanopic than the deuteranopic confusion loci. Therefore the present results suggest that greater individual variability in color discrimination along the tritanopic axes may also exist in deterioration of color discrimination in memory.

Saturation shifts with the successive comparison method

Figure 6 shows the differences between successive and simultaneous PSEs, D_{pse} = PSE(successive) − PSE(simultaneous), as a function of test stimulus excitation purity P_t for observers K.U. and H.U.* Arrows in the figure indicate means of the simultaneous discrimination thresholds for each dominant wavelength. PSE differences turned out to be of similar magnitude to the simultaneous discrimination thresholds, and for all dominant wavelengths except 650 nm, most differences are positive; that is the purities of comparison stimuli, that appeared equally saturated as their corresponding test stimuli, are greater with the successive comparison than those with the simultaneous comparison. However, a few test stimuli with low purities for K.U., and all test stimuli of 650 nm for H.U., show the opposite tendency; i.e. negative differences.

Figure 7 shows saturation estimates (percent chromatic content) of PSEs using the simultaneous vs successive comparison methods, in each case for the same dominant wavelength and purity of test stimuli. The diagonal line in each figure indicates no PSE difference.

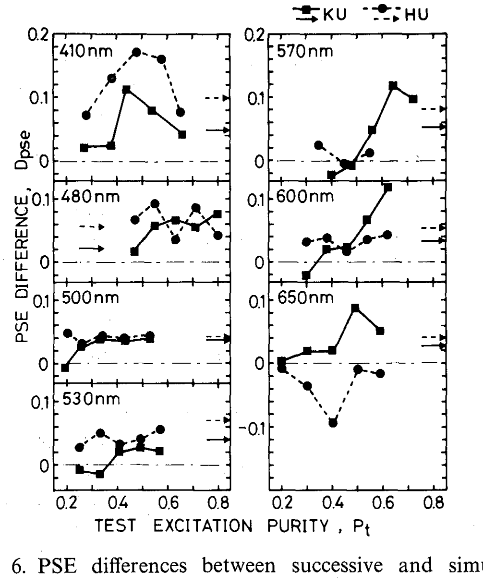

Fig. 6. PSE differences between successive and simultaneous PSEs, D_{pse} = PSE (successive) − PSE(simultaneous), as a function of test stimulus excitation purity, P_t. Observers: K.U. (■), H.U. (●). Dominant wavelengths are shown in each section of the figure. Arrows in the figure show mean values of simultaneous discrimination thresholds Δp for each dominant wavelength; solid for K.U., dashed for H.U.

*As mentioned before, there was a small constant error between the test purity P_t and the simultaneous PSE. However this constant error has no effect on determining the difference between the successive and simultaneous PSEs, because the same test stimulus was used for both cases and both PSEs were expressed using the same purity scale (comparison excitation purity).

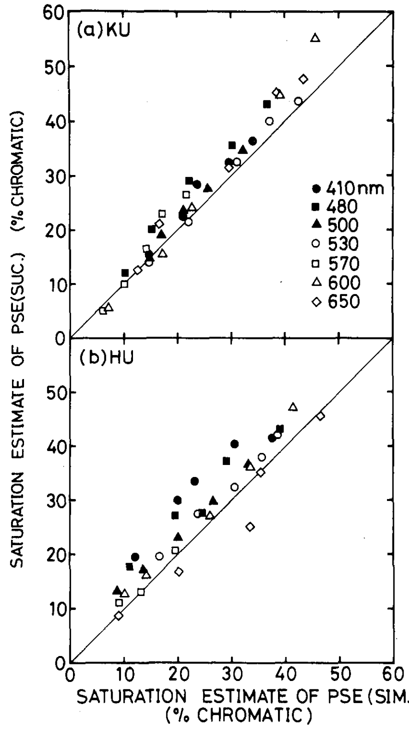

Fig. 7. Saturation estimates (percent chromatic content) of PSEs with simultaneous (in the abscissa) and successive (in the ordinate) comparison methods for the same dominant wavelength and purity of test stimuli. Each type of symbol indicates each dominant wavelength as shown in the figure. Observers: (a) K.U., (b) H.U.

Test stimuli with positive PSE differences shown in Fig. 6 plot here above the diagonal, and those with negative PSE differences, below. Saturation estimates of PSE obtained by the successive comparison method were larger for most stimuli than those of PSE made in the simultaneous condition, meaning that saturation usually increases in memory; the opposite is the case for only a few test stimuli below the diagonal. However, most stimuli are placed near the diagonal (within 10% difference for both sides of the line); that is, saturation shifts in memory are not more than 10% of saturation estimates for both observers.

Figure 7 also indicates that for K.U. more saturated stimuli tend to have greater saturation shifts; but for H.U. all stimuli except those of 650 nm (diamonds) show similar shifts to more saturated direction, regardless of their initial saturation values. These results are generally consistent with those of Newhall *et al.* (1957), who showed systematic increases in purity for the successive matches as compared with the simultaneous matches using the same test colors.

Finally, the present investigation used only one temporal delay; that is, a SOA between test and comparison stimuli of 3 sec. Since the amount of purity discrimination deterioration and purity shifts are similar to previous results obtained by using longer time delays (Newhall *et al.*, 1957; Uchikawa and Ikeda, 1981; Nilsson and Nelson, 1981), it is probable that no further deterioration or shift would occur with SOAs longer than 3 sec.

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