

SHORT-FLASH BEZOLD-BRUCKE HUE SHIFTS*

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Abstract—Hue matching was used to obtain measures of Bezold-Brucke hue shifts with very brief flashes (17 msec) at ten wavelengths and several illuminance levels. Results were generally similar to those obtained by Purdy (1931) with uncontrolled stimulus duration, but there were also important differences. These were: the locations of invariant hues; the direction of shift for blue-green hues; and a reversal in shift direction at high intensities for yellowish stimuli. The results are compared with other measures of the hue shifts and discussed with respect to trichromatic and opponent-process models of color coding.

INTRODUCTION

Visual scientists have known for over a century that the perceived hue of a light of fixed wavelength is affected by varying its luminance or brightness. The effect is known as the Bezold-Brucke hue shift after two of its early discoverers. Using a hue matching procedure, Purdy (1931) found that most stimuli became bluer or yellower as stimulus intensity was increased. There were, however, four chromatic stimuli for which hue did not vary with changes of intensity. Purdy concluded that three of these invariant hues were the unique hues, yellow, blue, and green, but the fourth was a purplish-red hue that was not identical with unique red.

Since Purdy's early work there have been several other studies of intensity-dependent hue shifts. The results of many of these studies conflict in various ways with the results obtained by Purdy. Disagreements arise over the number of invariant hues, whether the unique hues are invariant, whether there are non-unique invariant hues, and whether all hues which do exhibit intensity-dependence become either bluer or yellower with increasing intensity (see Boynton and Gordon, 1965; Jacobs and Wascher, 1967; Larimer *et al.*, 1974 and 1975; Smith *et al.*, 1968; Savoie, 1973; Cohen, 1975; and Walraven, 1961). The stimuli used to measure the hue shifts in many of these studies differed considerably from those used by Purdy. It now appears that differences in stimulus parameters may be responsible for some of the conflicting results. In particular, Nagy and Zacks (1977) have shown that stimulus duration was a major fac-

tor in accounting for the differences in results obtained by Purdy and Savoie (1973). Purdy did not control viewing time while Savoie's stimuli were 5 msec flashes. Subsequently, Nagy (1979) found that stimulus duration has an effect on the invariance of unique hues. With very short stimulus duration, none of the unique hues was invariant. The nature of intensity-dependent hue shifts with brief stimulus durations is still largely undetermined, however, since measures have been obtained primarily from the yellowish region of the spectrum (Savoie, 1973; Nagy and Zacks, 1977). This paper presents further measures of the hue shifts obtained with short flashes at wavelengths and illuminance levels comparable to those used by Purdy. The results are compared to those obtained in other studies of the hue shifts and are discussed briefly with respect to explanations of the hue shifts.

METHODS

Apparatus

A conventional two-channel Maxwellian view optical system was used to present stimuli to the observers. A 150 W Xenon arc-lamp driven by a d.c. regulated power supply provided illumination for both channels. Schoeffel double monochromators positioned in each channel provided narrow-band spectral stimuli. Stimulus duration was controlled with Vincent Uniblitz shutters which provided nearly square-wave pulses of light 17 msec in duration. Wratten neutral density wedges were used to control luminance. Relative calibrations were done with a United Detector Technology photodiode (Pin-10) placed at the position of the observer's eye. Retinal illuminance levels at 580 nm were estimated with a MacBeth illuminometer using the method described by Westheimer (1966). Field stops provided two small circular fields 0.6° in diameter, separated by 0.5°.

Procedure

Procedures were similar to those used by Savoie

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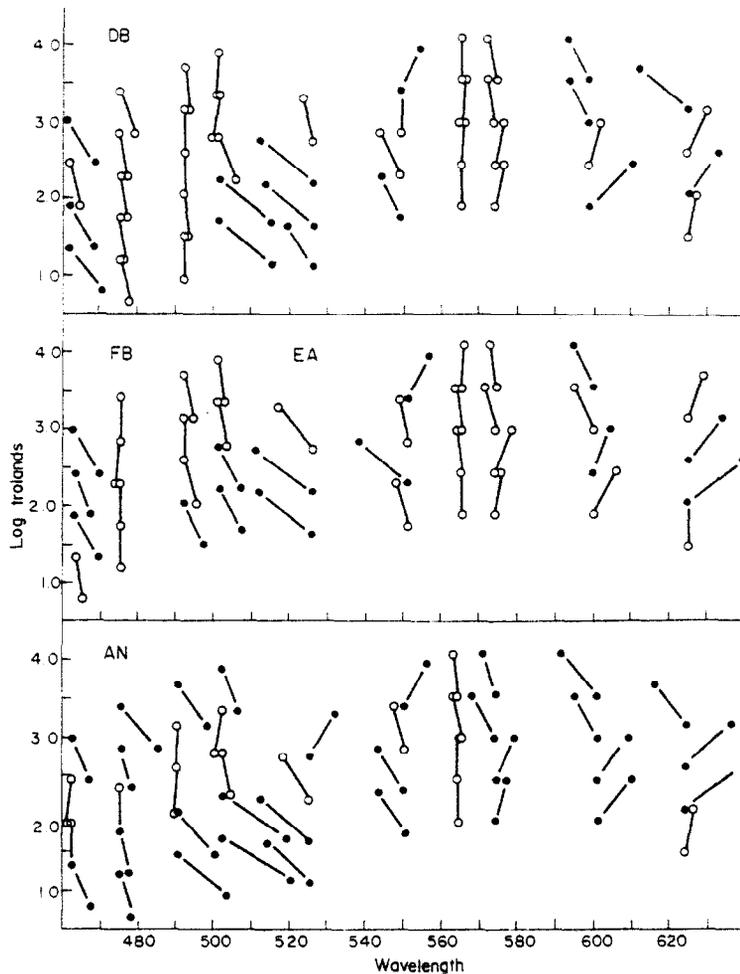


Fig. 1. Hue matches for individual observers. Each line segment connects two points of different illuminance that were matched in hue.

(1973). The observer sat in a darkened room with his head in a hood which shielded stray light. His eye position was maintained with a bite bar and four small dim fixation points arranged in a diamond shape were used to ensure that he was fixating the proper location when the flash occurred. The observer was forced to make a binary decision about the hue of a variable wavelength test stimulus relative to the hue

of a fixed standard stimulus on each trial. There were four possible judgments, "redder," "greener," "yellow," and "bluer," though only two were used for a given standard wavelength. For example, if the standard appeared orange, the observer was asked to judge whether the test appeared redder or yellow than the standard. The wavelength of the test was varied according to the rules of a double random staircase procedure (Cornsweet, 1962) with trials from two independent staircases randomly intermixed to prevent the observer from anticipating the next stimulus.*

* The starting points of the two staircases, generally 30–40 nm apart, were chosen to bracket the region containing the hue match. Each staircase independently followed the same rules for step sizes. The initial step size was 10 nm. After the first reversal the step size was 5 nm until a second reversal was made. After the second reversal the step size was fixed at either 2 or 3 nm. The staircase was terminated when 3 reversals were made with the smallest step size.

† The equal-brightness hue match was done at the beginning of each session for two reasons. Since it should also be a wavelength match, any large deviation would indicate that the observer or apparatus was not behaving properly. Second, it could be used as a control condition against which the difference-in-brightness matches could be compared. All data are plotted relative to mean equal-brightness hue matches, which were always within 2 nm of a nominal wavelength match.

To begin each session, the observer used a method of adjustment to match the brightness of the test to the standard with the two set at a nominal wavelength match. With the two matched in brightness the first pair of staircases was run to determine an equal-brightness hue match.† Then a 0.55 log unit illuminance difference between the test and standard was introduced and another pair of staircases was run to determine the hue shift induced by the illuminance difference. For following pairs of staircases the 0.55 log illuminance difference was maintained while the illuminance of both stimuli was varied in 0.55 log unit

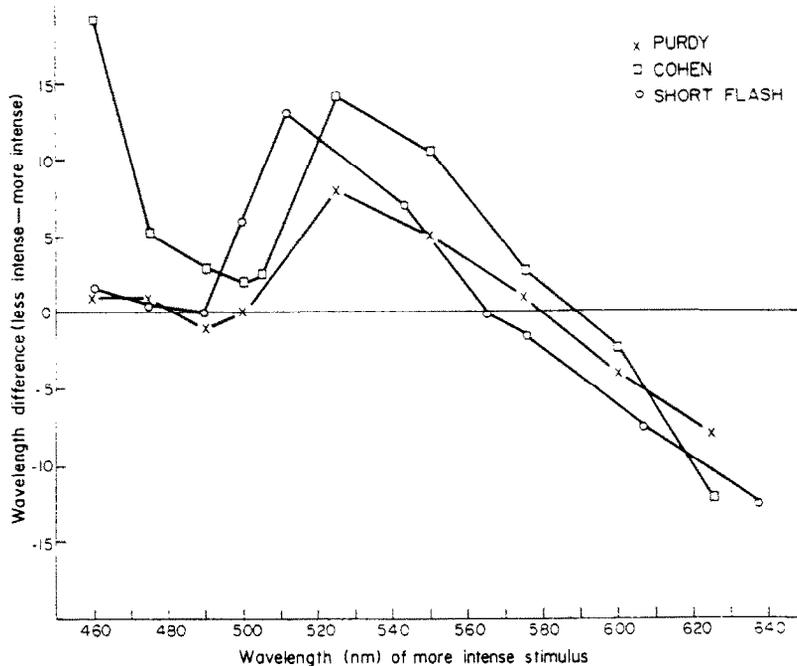


Fig. 2. The wavelength difference required for a hue match as a function of wavelength for a fixed illuminance difference. Each curve is from a different study described in the text.

steps over the available range, generally going from bright to dim or from dim to bright. The 0.55 log unit illuminance difference was chosen because it was large enough to produce a measurable hue shift but small enough so that the stimuli did not appear extremely different in brightness or saturation. The hue judgments were therefore relatively easy for the observers to make. The test and standard stimuli were presented simultaneously once every 10–20 sec until a pair of staircases was completed. The observer then had a brief rest period of 3–4 min while the experimenter set up the next pair of staircases. Generally, a series of intensity levels was run on one or two standard wavelengths in an experimental session which lasted about an hour. Each of 10 standard wavelengths was run on three different days for each observer.

Observers

The four observers were between the ages of 21 and 30 and had normal color vision. All four had extensive experience with the hue judgment before the data reported here were collected.

RESULTS

The last four reversal points from each pair of staircases (last two from each staircase of the pair) were

* Due to limitations in the apparatus the standard was the brighter stimulus for wavelengths less than 525 nm and the test was the brighter stimulus at 525 nm and longer wavelengths.

† Cohen's study was not done with a Maxwellian view system. The retinal illuminance levels given here were obtained from Cohen's measured luminances by using Figure 2.7 in Wyszecki and Stiles (1967, p. 214).

averaged to give a daily mean wavelength for each hue match at each illuminance level. The three daily means were then averaged to give an overall mean for each condition for each observer. These data are shown in Fig. 1. Note that data from two observers, FB and EA, are shown in the middle panel. Data from 460 to 500 nm were obtained from FB and data from 525 to 625 nm were obtained from EA. Each line segment in Fig. 1 connects two points at different illuminance levels. One end point is plotted at the wavelength required for a hue match to the standard stimulus in the equal-brightness condition.* The other end point is plotted at the wavelength required for a match when the test and standard stimulus differ in illuminance by 0.55 log trolands. 80% confidence intervals based on between-day variability were calculated for each match. In order to avoid cluttering the graph these were not plotted. Instead, each condition for which the confidence interval around the difference-in-brightness match does not overlap the confidence interval around the equal-brightness match is indicated by a solid symbol. This corresponds to a significant difference at the 0.01 level.

Inspection of Fig. 1 suggests that over much of the wavelength-intensity space hue shifts measured with short flashes are generally similar to those measured by Purdy with uncontrolled viewing times. The similarity is easily seen in Fig. 2 where the magnitude of the wavelength difference required for a hue match is plotted against wavelength for a fixed illuminance difference. Points above the zero-hue-shift line indicate that the wavelength of the dimmer stimulus must be increased for a hue match and points below the line indicate wavelength must be decreased for a hue match. The short flash data (O) are averaged across

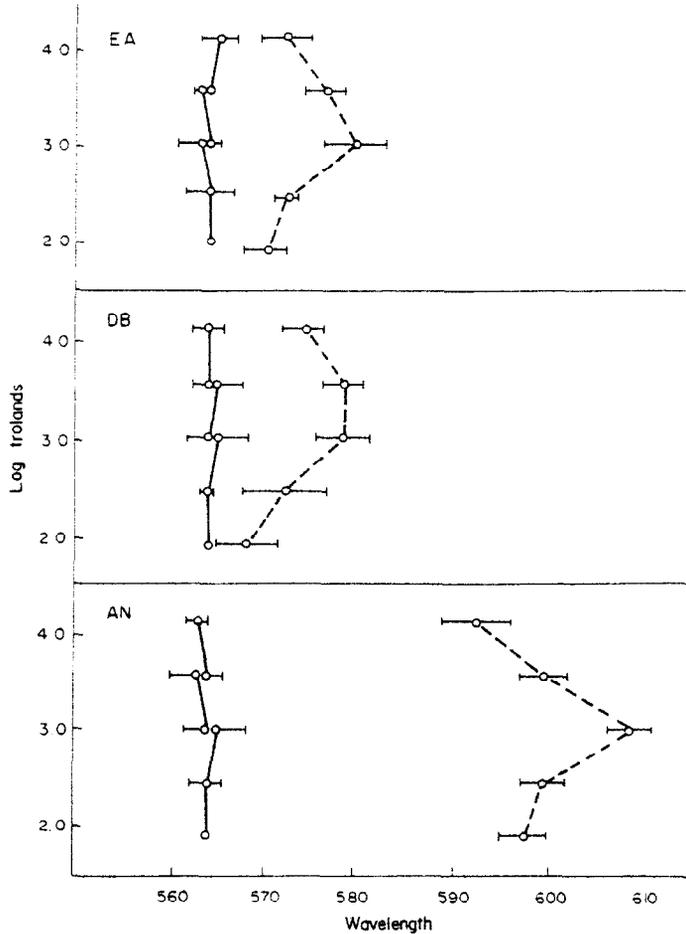


Fig. 3. Comparison of hue matches at 565 nm (continuous lines) with unique yellow locus (broken lines).

observers and are linearly interpolated from plots like those shown in Fig. 4 for an illuminance difference of 2.6–2.05 log td. The Purdy data (\times) are plotted from Table 1 of the 1937 paper for an illuminance difference of 2.6–2.0 log td. The third curve (\square) is the mean of data from two observers in a matching experiment done by Cohen (1975) with an illuminance difference of approximately 2.7–1.7 log td.† Cohen's data were obtained with a range of stimulus durations from 150 msec to 2 sec, a range over which stimulus duration had no effect on the hue shifts. The three curves have a similar characteristic shape. The largest hue shifts occur at the shortest and longest wavelengths and between 500 and 540 nm. There is an invariant hue, or wavelength at which there is zero shift, near 570 nm and a region of minimum shift between 475 and 505 nm. Note, however, that the curves from the three studies disagree in two important aspects: whether the curve touches or crosses the zero-shift line between 475 and 505 nm and on the exact location of the invariant hue near 570 nm.

Examination of the individual data in Fig. 1 indicates that the hue of the 565 nm stimulus is approximately invariant over the entire range of intensities tested for all three observers. The 565 nm stimuli appeared slightly greenish-yellow rather than unique

yellow. In order to determine the relationship between the hue matches at 565 nm and the unique yellow locus, each observer was asked to determine the location of unique yellow with similar staircase procedures. These data are shown in Fig. 3 along with the hue matches at 565 nm. The broken lines connect the unique yellow loci and the continuous lines indicate the hue matches at 565 nm. The horizontal lines indicate 80% confidence intervals based on between-day variability. The unique yellow loci are clearly at longer wavelengths and the locus is clearly not invariant with intensity.

Returning to the individual data in Fig. 1 there appear to be some individual differences in the results obtained between 460 and 500 nm. For observer AN there appears to be no invariant hue in this region of the spectrum. There are significant shifts at each standard wavelength which require the dimmer stimulus to be set at a longer wavelength for a hue match. For observer FB there appears to be no hue shift at 475, which is slightly purplish-blue for this observer, and a small shift at 490 nm which again requires that the dimmer stimulus be set at a longer wavelength for a hue match. For DB the 475 nm stimuli, which appear slightly purplish-blue to him, are nearly invariant in hue, but the small shifts in matching wavelength are

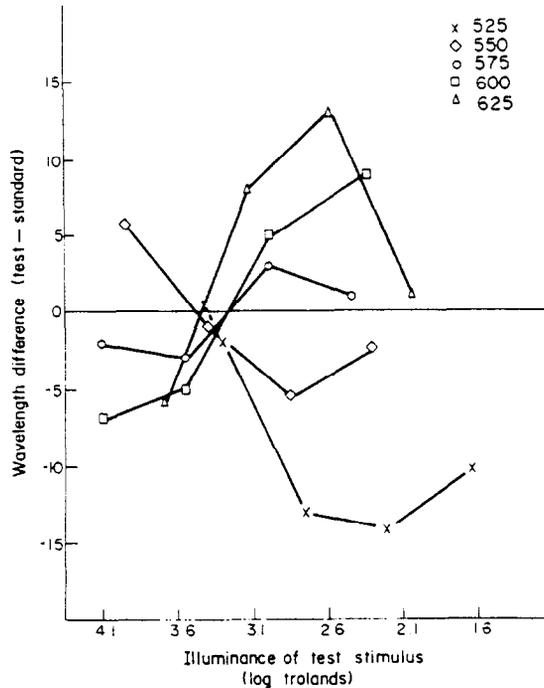


Fig. 4. The wavelength difference required for a hue match as a function of illuminance level. Each curve is a different standard wavelength. The illuminance difference between test and standard is fixed at 0.55 log units.

consistently in the same direction, suggesting that with a larger intensity difference a significant hue shift might be measured at 475 nm. The 490 nm stimuli, which appear blue-green, seem to be quite invariant in hue over the entire range of intensities. Thus, with short-flash stimuli, DB appears to have a second non-unique invariant hue in the blue-green region of the spectrum. It should be noted that the hue matches of AN and FB at 490 nm suggest that the hue of a blue-green stimulus shifts toward green rather than blue as intensity is increased. With a 1 sec stimulus duration the hue matches of all three observers at 490 nm suggest a shift toward green with increasing stimulus intensity, in agreement with results obtained by Cohen (1975) with 1 sec flashes.*

The third difference between the short-flash results and Purdy's results (see Fig. 1) is that the short-flash hue shifts reverse direction somewhere above 3 log td in the yellowish region of the spectrum (550–625 nm). Though the illuminance at which this reversal occurs cannot be determined precisely from these data, an estimate of its location can be obtained by estimating the midpoint of the illuminance difference at which zero hue shift would be measured. To obtain this estimate the data were plotted as in Fig. 4. The wavelength difference required to match the dimmer standard is plotted against the illuminance of the test stimulus, which is always 0.55 log units greater than

the standard. Data were averaged across observers since individual differences are small in this region of the spectrum. All of the curves cross the zero shift line within 0.25 log units of each other, suggesting that the illuminance at which the reversal occurs is approximately independent of wavelength. A rough estimate of the reversal point was obtained by determining the midpoint of the illuminance difference at which zero hue shift would be measured. Averaged across observers and wavelengths this procedure results in an estimate of 3.1 log td.

In order to determine whether the high-intensity reversal in hue shift direction was duration dependent, hue shifts were measured as a function of stimulus duration for a limited set of conditions. A standard wavelength of 600 nm and two test stimulus illuminances, one above and one below the illuminance at which the reversal occurs, were chosen. The standard stimulus was again always 0.55 log units less intense than the test stimulus. Procedures were as in earlier experiments except that stimulus duration, rather than illuminance, was varied from 17 msec to 1 sec over the course of a session. The results are shown in Fig. 5. Each point is again the mean of 3 or 4 daily means and 80% confidence intervals are based on between-day variability for individual observers. The results averaged over observers are shown in the lowest panel where 80% confidence intervals are based on between observer variability. The size and direction of hue shift at high intensity is clearly affected by stimulus duration while the direction of the hue shift at low intensity appears to be independent of duration.

* Partial data on hue shifts with one second flashes were obtained at five wavelengths (490, 525, 565, 575 and 600 nm) using the same observers and procedures. These data agree quite well with results obtained by Cohen (1975).

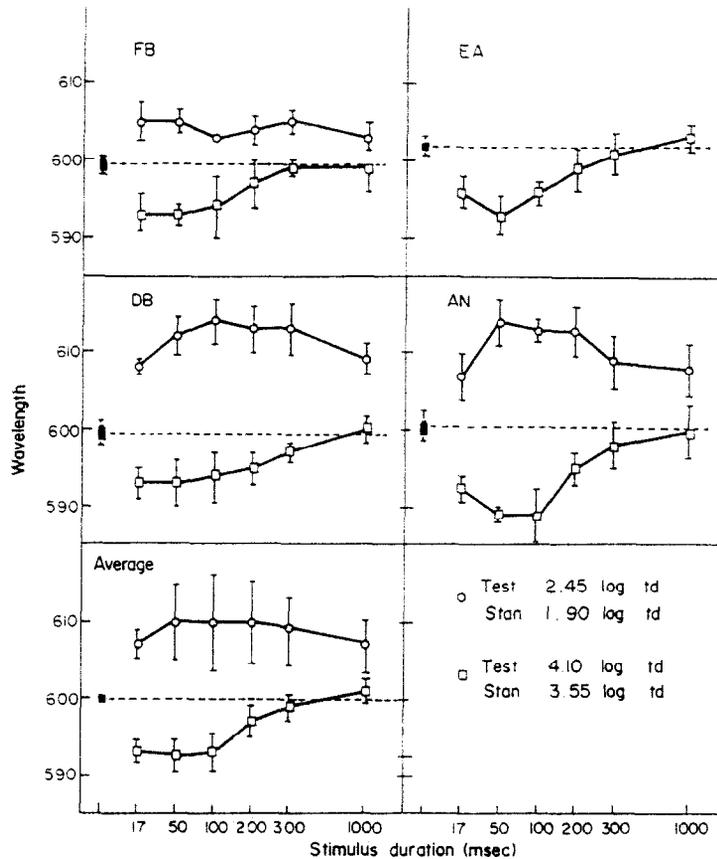


Fig. 5. Hue shift as a function of stimulus duration at 600 nm. The two curves in each panel are for different intensity levels. The illuminance difference between test and standard is 0.55 log units. The solid symbols at far left indicate the test wavelength for an equal-brightness hue match.

DISCUSSION

Over much of the wavelength-intensity space, Bezold-Brücke hue shifts measured with short flashes are similar to those measured by Purdy with uncontrolled viewing times. Most low illuminance stimuli tend to become bluer or yellower as illuminance is increased. However, it is clear that a substantial portion of the results obtained with short flashes do differ from those obtained by Purdy. With short flashes yellowish stimuli tend to become redder or greener as illuminance is increased above approximately 3.1 log td. There is one greenish yellow stimulus whose hue appears to be invariant over the entire range of illuminances for all three observers, but unique yellow is not invariant. Also, the hue of blue-green stimuli appears to become greener rather than bluer with increasing illuminance, or to be approximately invariant for one observer.

Hue shift of high intensity yellows

The reversal in hue shift direction of high intensity yellow stimuli apparently has been reported only with very short duration flashes (Savoie, 1973; Nagy and Zacks, 1977). The results of the duration experiment shown in Fig. 5 appear to confirm the hypothesis that

this reversal occurs only with very brief stimulus durations. Since response saturation has recently been demonstrated in cone mechanisms with high-intensity brief flashes (Alpern *et al.*, 1970; King-Smith and Webb, 1974; Shevell, 1977), it is plausible that the high-intensity hue shift reversal may also be due to response saturation. However, the nature of the hue shift reversal would suggest that the response saturation does not occur in the cones themselves. If response saturation were occurring in cones the appearance of yellowish-red and yellowish-green stimuli would become yellower with increasing intensity rather than redder or greener. However, if response saturation occurred in the signals of a yellow-blue opponent color mechanism (Jameson and Hurvich, 1955; Krantz, 1975), then high intensity yellowish-red or yellowish-green stimuli would be expected to become redder or greener with further increases in intensity as suggested by the data.

Hue shift of blue-green stimuli

The hue of blue-green stimuli appears to become greener with increasing intensity, or to be approximately invariant for one observer in this study. The shift toward green was obtained with both the 17 msec flash and a 1 sec flash, and thus does not

occur only with very brief flashes. Cohen (1975) and Jacobs and Wascher (1967) have also obtained shifts toward green for blue-green stimuli with stimulus durations ranging from 150 msec to 2 sec. However, Van der Wildt and Bouman (1967) obtained shifts toward blue with several different stimulus configurations and uncontrolled viewing times, leaving open the possibility that blue-green stimuli shift toward blue with increases in intensity only when very long observation times are allowed.

Invariant hues

Perhaps the most surprising aspect of the results obtained with short flashes is the occurrence of invariant hues that are not unique hues. For all three observers a greenish-yellow hue at 565 nm appears to be invariant over a 2.2 log unit range. For observer DB, a blue-green hue at 490 nm appears invariant over a 2.7 log unit range and for FB a purplish-blue hue at 475 nm appears to be invariant over a range of 2.2 log units. Savoie (1973) used a hue-matching procedure with 5 msec flashes and failed to find an invariant hue in the yellow region of the spectrum, though he collected data at 10 nm intervals from 560 to 610 nm. It might be pointed out, however, that the only major disagreement within the Savoie data occurs at 560 nm, where he found large hue shifts in opposite directions for his two observers. In the bluish region of the spectrum Smith *et al.* (1968) have reported a failure to detect a hue shift for blue-green hues with intensity differences as large as one log unit. The stimuli in their study were 1 sec flashes. In experiments with uncontrolled viewing times, Purdy (1931) and Walraven (1961) have reported invariant purple hues. The invariant purple found by Purdy was described as just slightly purplish-red, while the invariant purple found by Walraven appears to be nearer the violet corner of the chromaticity diagram.

Trichromatic and opponent-level theories

It appears that hue shifts obtained with short flashes may present problems for both trichromatic and opponent-process explanations of the hue shifts. Trichromatic theories of color coding have suggested that intensity-dependent hue shifts occur as a result of non-linearity in the coding of signals from the cone mechanisms (Pierce, 1877; Walraven, 1961; Savoie, 1973). Opponent theories of color coding have suggested that the signals input to the opponent mechanisms from the three cone mechanisms are linear with intensity, and that the hue shifts occur because the output signals of the yellow/blue opponent mechanisms grow with input at a greater rate than the output signals of the red/green opponent mechanism (Judd, 1951; Jameson and Hurvich, 1955). Within a trichromatic theory of the hue shifts, it is difficult to account for the reversal in hue shift direction of high intensity yellow stimuli and the hue shifts in the violet and blue-green hues, without proposing unusual response functions for the cone mechanisms (see, for example,

Savoie, 1973). On the other hand, it is difficult to account for the occurrence of non-unique invariant hues within an opponent-mechanism theory which proposes differential growth rates in the output signals of the yellow/blue and red/green opponent mechanisms (See Krantz, 1975).

Whether a model which incorporates non-linearities in input to the opponent-mechanisms as well as differential growth rates in their outputs, can account for the short-flash hue shifts is unclear. Within such a model the occurrence of non-unique invariant hues implies that non-linearities in input to the opponent mechanisms are just cancelled by the differential growth rates of the outputs. Though such a cancellation seems implausible, the non-linearities in input to the opponent mechanisms suggested by unique hue data do appear to be in the right direction to cancel the faster growth rate of the yellow/blue opponent-mechanism output (Larimer *et al.*, 1975; Nagy, 1979). Further study of this problem certainly seems worthwhile. A better understanding of the non-linearity in color coding implied by these hue shifts could provide interesting new evidence for models of the color coding mechanisms.

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