Experimental measures and theoretical account of hue scaling as a function of luminance^{1, 2}

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Functions relating the magnitude of chromatic response to stimulus luminance were determined at the unique green and yellow wavelengths. These measured functions were used to account for the shift from a preponderance of green at low stimulus luminances to a preponderance of yellow at higher luminances, for a stimulus wavelength of 550 nm. The two hue magnitude functions were found to have the same power-law exponents, and the hue shift was due to the difference in thresholds between the two opponent-color systems.

The change in the hue of a visual stimulus as luminance is varied is called the Bezold-Brücke phenomenon: A stimulus that appears red or green with a small amount of yellow or blue at low luminances becomes increasingly yellowish or bluish at higher luminances when the wavelength is held constant. For those wavelengths that are perceived as unitary hues (blue, green, and yellow), no shift is observed when the eye is neutrally adapted. One method of obtaining an index of this hue shift is to have an O adjust the wavelength of one-half of a bipartite field so that the two sides appear the same hue, with a constant luminance difference between the two halves of the field. This is the method used by Purdy (1931) in the best known investigation of this phenomenon. Note that this matching method does not provide a measure of the actual appearance of the stimulus, but just the wavelength changes required to maintain a constant, unspecified hue.

All hues can be described with four names, used singly or in pairs: blue, green, yellow, red, red-blue, green-blue, red-yellow, and green-yellow (red-greens and yellow-blues do not exist). This suggests an alternative method of measuring the Bezold-Brücke effect, i.e., to determine subjective hue scales as a function of luminance. In this procedure, the O simply reports, in response to a given test stimulus, the percentage (or coefficient) of each hue seen in the total hue percept. The hue scaling technique was first used by Jameson and Hurvich (1959) to quantify the appearance of spectral lights at different luminance levels, with chromatic surrounds. These investigators found that percentage hue scaling

judgments were a sensitive measure of hue as a function of wavelength, luminance, and adaptation. A related measure was later used by Boynton and Gordon (1965).

The Bezold-Brücke hue shift may be accounted for within the framework of the opponent-process theory of color vision if the assumptions are made that (1) the response of the red-green system grows at a slower rate as a function of stimulus luminance than does the response of the yellow-blue system, and/or (2) the threshold of the yellow-blue system is higher than that of the red-green. Computations may then be made to predict wavelength changes necessary to maintain a constant theoretical hue coefficient at different stimulus luminances (Hurvich & Jameson, 1957). The resulting theoretical constant-hue contours bear a striking similarity to Purdy's (1931) data.

The purpose of the present study was to test experimentally the assumptions of the Hurvich-Jameson model in accounting for the hue shift. In Experiment 1, measurements of hue as a function of luminance were made at a midspectral wavelength (550 nm) by the percentage hue scaling method, and the relative threshold luminances for green and yellow were determined. In Experiment 2, direct measures of hue growth functions were made at the unique yellow and green wavelengths by the method of magnitude estimation, and a yellow-green hue function was synthesized from these independent functions.

APPARATUS AND PROCEDURE

In all experiments, the stimulus was delivered through a circular aperture, 0.09 in. in diam, covered with translucent tracing paper, onto which was projected the grating image of a Bausch & Lomb high-intensity monochromator with a tungsten (quartz-iodine) source. At a viewing distance of 20 in., the aperture subtended a visual angle of 17 min. One degree to either side of the stimulus aperture were pinholes through which the light from miniature tungsten bulbs (Edmund Scientific) served as fixation points. The brightness of these fixation points was adjusted by the O so that they were just-easily visible. The left eye of the O was occluded, and he viewed the stimuli through a 4-mm artificial pupil in front of

his right eye. The O's head was stabilized with a chin and forehead rest.

Stimulus duration in the scaling experiments was controlled by an electromechanical shutter that was open for 1½ sec. The fixation lights were extinguished during stimulus presentation. There was a 28½-sec interstimulus interval, and 2 sec before each stimulus was presented, the O was given a warning click; this was a signal to fixate the center of the 2-deg imaginary line joining the two fixation points.

All experimental sessions lasted less than 1 h and were preceded by at least ½ h of dark adaptation to remove any effects of previous illumination.

Stimulus luminance was varied by means of calibrated neutral-density wedges and filters.

PRELIMINARY EXPERIMENT: DETERMINATION OF UNIQUE GREEN AND YELLOW WAVELENGTHS

The wavelengths giving rise to unitary yellow and green sensations were determined by two methods: (1) The O was given access to a knob, with which the wavelength drum of the monochromator could be turned, and was instructed to adjust the wavelength so that, for unique green, no blue or yellow was present and, for unique yellow, no green or red was present. In this procedure, the shutter was open continuously, and the fixation lamps were extinguished; the O blinked or looked away occasionally to avoid severe adaptation. Twelve determinations were made, six at about 1-mL stimulus luminance and six at 10 mL; there was no consistent difference between the values obtained at the two luminances. (2) A staircase procedure was used, with the E changing the wavelength drum in steps of 5 nm in the direction indicated by the O from trial to trial. Two separate runs were made, starting above and below the unique hue wavelength. In this procedure, the timing of stimuli was as described above in the general procedure section, with the fixation lights on between trials. Stimulus luminance was about 10 mL. Both procedures resulted in essentially the same estimate of unique hue wavelengths, and the mean unique green and yellow wavelengths for four Os are given in Table 1.

Table 1
Green and Yellow Unique Hue Wavelengths
for Four Subjects

Hue Subject	λ Green(nm)	λ Yellow(nm)
LA	512	572
ED	509	572
PH	512	565
JW	511	576

EXPERIMENT 1:

PERCENTAGE HUE SCALING

The yellow-green wavelength used for percentage hue scaling was chosen to produce a large Bezold-Brucke effect. This was accomplished by selecting 550 nm as the stimulus wavelength, since at very low luminances it appears pure green and at moderate and high luminances it appears more yellowish than green. Thus, a very large hue shift can be obtained in a short range of luminances.

Two Os, LA and PH, served in this experiment. First, specific relative energy thresholds for greenness and yellowness were determined by a staircase method. This was done for two purposes: (1) The hue scaling stimuli should be above the specific yellow threshold, or no hue shift occurs; (2) for later theoretical analysis, the log luminance difference between green and yellow thresholds was required. The results for the two Os showed that the mean threshold for greenness was 1.45 log units lower than that for yellowness at this wavelength, thus confirming one of the assumptions of the opponent-colors model.

Seven different stimulus luminances were used in the hue scaling procedure and covered the range from 0.30 log unit above the yellowness threshold to 2.10 log units above, in equal 0.30 log unit steps. Stimuli were presented in randomized blocks of the seven values, with 10 judgments at each level. The trials were separated into two daily sessions. In one of the sessions, the O judged the proportion of yellow in the hue mixture, and in the other judged the proportion of green. No systematic differences were observed between the two types of judgment, and the data from both sessions were combined into a mean (yellow)/(yellow + green) measure.

The data from both Os are shown in Fig. 1; the abscissa is in terms of log luminance units above the specific yellow threshold; the arrow denotes a measured luminance of about 1 mL. The data show

that there is a large shift in perceived hue in a small luminance range just above the yellow threshold, with the proportion of yellow rising to more than 0.75 at about 10 mL. Both Purdy (1931) and Boynton and Gordon (1965) used stimuli in a higher range of luminances. Boynton and Gordon's 100-troland stimulus would be about 3 mL with this size of artificial pupil, and the 1,000-troland stimulus would be 30 mL. In the hue scaling data of the present experiment there is actually a very small change of hue in that stimulus range, and most of the effect occurs at lower luminances.

EXPERIMENT 2: MAGNITUDE ESTIMATION OF CHROMATIC RESPONSE

The second assumption of the opponent-process theoretical analysis of the hue shift is that the response of the yellow-blue system increases with luminance at a faster rate than the red-green system. If the assumption is made that hue magnitude grows as a power function of luminance, or $\psi = a\phi^b$, then one way that this difference could be accomplished is for the exponents (b) for the two systems to be significantly different: $b_{r-g} \ll b_{y-b}$. Then, at 550 nm, the hue coefficient of the stimulus is predicted by the expression

$$H.C. = \frac{a_y \phi^{b_y}}{a_y \phi^{b_y} + a_g \phi^{b_g}} \quad (1)$$

where a_y and a_g are modulus adjustments, b_y and b_g are the power function exponents for the two systems and ϕ is the radiance of the stimulus. Of course, this simple power-law expression is inadequate to account for events near threshold, and

the appropriate modifications will be considered later.

Judgments relating yellow and green magnitudes to stimulus luminance were made by each of the four Os at their own unique yellow and green wavelengths, determined in the preliminary experiment. Stimuli were presented in a 3.5 log unit range above the specific chromatic thresholds determined by the staircase method, for each O individually. Thus, the data from the four Os could be combined despite the fact that they were obtained at different wavelengths and different absolute energies. The instructions to the Os were as follows:

"In this experiment you will judge the amount of (green; yellow) in a series of 1½-sec flashes by the method of magnitude estimation, with no prescribed standard. I will set the intensity of the light, you will hear a warning click, and the light will flash on every 30 sec.

"Your task is to assign to each stimulus a number which you feel is an appropriate description of the amount of hue present. The judgments you give should feel right. You may use whole numbers, fractions, or a combination of the two, as long as each number seems to match each sensation. Try to make the numbers directly proportional to your subjective impression of the amount of hue. Try not to worry too much about being consistent. Try to judge each sensation more or less independently, and try to ignore the brightness, or achromatic, part of your impression, and to given each one a number which you feel describes the amount of hue most aptly.

"Try as far as possible to make your judgments throughout the entire experimental session satisfy two criteria: direct proportionality to amount of hue

Fig. 1. Hue scale for 550 nm as a function of luminance. 0.0 log relative luminance is the yellow threshold. The arrow indicates a luminance of 1 mL. Means of 10 judgments per O. Os LA and PH.

Fig. 2. Log magnitude estimation functions for yellow and green at the unique hue wavelengths. Points are the geometric means of 10 judgments for each of four Os. 0.0 log relative luminance indicates the thresholds for yellow and green. The straight line is a least-squares fit to the linear portion of the data. The curved line is a power function of the form $\psi = a(\phi^b - c)$ (see text).

were chosen for the yellowness and greenness functions such that $a(\phi^b - c) = 0$ at a log relative luminance of 0.0; this satisfies the condition of no hue at the chromatic threshold. The curved lines in Fig. 2 are plots of these corrected functions, and it is obvious that they provide a quite adequate description of the experimental data. The entire theoretical function has been lowered by this procedure, with a greater effect at lower response levels, and an adjustment must be made of the multiplicative constant, a , to bring the theoretical curve into best coincidence again with the data.

THEORETICAL ACCOUNT OF THE HUE SHIFT AND DISCUSSION

It was assumed that the separate magnitude functions were the same at intermediate wavelengths as they were at the unique hue wavelengths, if an adjustment was made for the sensitivity of the green and yellow hue systems at the different wavelengths; this is true of the brightness system (Ekman et al, 1960; Wilson, 1964). The two hue systems were further assumed to be independent of each other.

To generate a theoretical hue coefficient function, Eq. 1 must be modified to the following form:

H.C.

$$= \frac{a_y \left[\left(\frac{\phi}{\phi_{ty}} \right)^{b_y} - c_y \right]}{a_y \left[\left(\frac{\phi}{\phi_{ty}} \right)^{b_y} - c_y \right] + a_g \left[\left(\frac{\phi}{\phi_{tg}} \right)^{b_g} - c_g \right]} \quad (3)$$

In this expression, ϕ is the energy of the 550-nm stimulus; ϕ_{ty} and ϕ_{tg} are the energy thresholds for yellow and green; b_y and b_g are the power-law exponents for yellow and green; c_y and c_g are the decremental constants described above,⁵ and a_y and a_g are multiplicative constants which express the relative amplifications in the two hue systems

and appropriate absolute size. Don't feel constrained to use the same or different set of numbers at all times in the experiment. Use whatever number seems fit. If you don't see any (green; yellow) when you hear the sound of the shutter, tell me so. Otherwise your magnitude estimates should be greater than zero. Make your judgments only on the specified hue (green; yellow), and ignore brightness. Do not judge the *saturation* of the lights."

The geometric means of 10 judgments from each O for each stimulus were converted to logarithms and plotted as a function of log luminance relative to the specific chromatic threshold (Fig. 2). Since no specified modulus and standard stimulus were used, the data were corrected for inter-O modulus differences before being plotted.

It is obvious that both the yellowness and greenness functions are well described by a simple power function in the upper two-log-unit range of luminances. A least-squares linear fit to the data in this region gives estimates of $b_y = 0.29$ and $b_g = 0.27$, or essentially identical slopes. These simple power functions are shown as straight lines in Fig. 2. Both functions are markedly nonlinear up to about 1.5 log units above threshold, confirming that the

judgments were not being made on the basis of brightness, since the brightness magnitude-estimation function is still quite linear at this luminance level.

The simple power law model cannot, of course, describe the whole range of these measured functions; some adjustment must be made for the departure from linearity in the vicinity of threshold. The fact that $b < 1$ and the fact that the curvature of the function is quite gradual and extends far above threshold imply that a response correction is a more appropriate model than is a stimulus correction (Marks & Stevens, 1968). This form of the magnitude estimation function for brightness, i.e.,

$$\psi = a(\phi^b - c) \quad (2)$$

has been confirmed experimentally to give a more satisfactory fit to the data than the stimulus correction alternative (Fagot & Stewart, 1968).

In the present analysis, the exponents, b_g and b_y (Eq. 1), were estimated by least-squares fits to the data, in the range of 1.5-3.5 log units above threshold, as described above. The constants c_g and c_y

Fig. 3. (A) Fitted hue magnitude estimation functions adjusted for the difference in thresholds between green and yellow at 550 nm and translated vertically to cross at the luminance that has a hue scale value of 0.50. Same abscissa as in Fig. 1. (B) Mean hue scale for 550 nm as a function of luminance. Os LA and PH. The curved line is a plot of Eq. 3, with the appropriate parameter values (see text).

following the power-law transform. The values for a_y and a_g are chosen such that

$$a_y \left[\left(\frac{\phi}{\phi_{t_y}} \right)^{b_y} - c_y \right] = a_g \left[\left(\frac{\phi}{\phi_{t_g}} \right)^{b_g} - c_g \right] \quad (4)$$

at the luminance where the judged hue coefficient (Fig. 1) is 0.50. This occurred at a luminance 0.80 log unit above the yellow threshold. Figure 3A shows both of the fitted hue magnitude functions plotted on the same abscissa as Fig. 1, crossing at the 0.50 hue coefficient point. The two hue magnitude functions are separated along the abscissa by the log luminance difference between the green and yellow thresholds.

Figure 3B is a plot of Eq. 3, with the parameters as described above. The theoretical hue coefficient function computed in this way bears a close resemblance to the average experimental hue coefficient function. This theoretical function changes rapidly from pure green to increasingly yellowish-green and begins to level off at about 0.65 yellow. In the theoretical model, since $b_y \cong b_g$, no further hue change would occur at high luminances where the hue magnitude functions are no longer significantly affected by the response correction. As was pointed out above, the failure of the theoretical function to cover as wide a range of hues as was found experimentally may be due to an interaction between the two hue processes; specifically, the finding could be accounted for if the hue function that had a greater magnitude of excitation masked the other function in proportion to the difference in their excitations. This would lead to the result that the theoretical function would be above the empirical function at hues below 0.50, and they would cross at that point; this is the case in the present analysis.

In conclusion, the power function

Fig. 4. Theoretical yellow-green hue scales as a function of luminance. The parameter is log luminance difference between green and yellow thresholds.

exponents for greenness and yellowness, as measured by magnitude estimation, are nearly identical. The Bezold-Brücke hue shift occurs because the separate hue magnitude functions increase more rapidly near threshold, and then gradually approach a power function. Because of the threshold differences between the two

systems, the green response is nearing its power-law segment just as the yellow system comes into play (see Fig. 3A). A family of hue coefficient functions may be derived from Eq. 3, with the parameter being the threshold difference between the green and yellow systems; a_y and a_g are specified by the analysis at 550 nm given

above. Then, for a series of yellow-green wavelengths, the predicted hue coefficient functions are given in Fig. 4, the only measurement necessary being the two specific chromatic thresholds; the amount of hue shift is inversely related to the threshold difference. This analysis may, of course, be generalized to other regions of the spectrum.

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NOTES

1. Pilot studies for this experiment were conducted in collaboration with James Pomerantz.
2. Portions of this paper were presented by the first author at the 1968 meeting of the Psychonomic Society in St. Louis.
3. Address: Department of Psychology, Brown University, Providence, Rhode Island 02912.
4. Parts of this study were conducted while E. Taylor and J. Pomerantz were participants in the NSF-URP program at Brown University. The authors thank Lynn Aikin, David Krantz, Sylvia Thorpe, and Billy Wooten for their critical reading of the manuscript.
5. Since

$$\left(\frac{\phi}{\phi_t}\right)^b = 1$$

at the specific chromatic threshold, $C_y = C_g = 1$ in this analysis.

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