Psychophysical estimates of opponent-process response functions*

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A technique is described that uses scaling judgments of the hue, saturation, and brightness of chromatic stimuli to estimate the response vs luminance functions of the three paired neural systems postulated by the opponent-colors theory. Derived response functions based on the experimental data for one O are presented to illustrate the technique.

The opponent-colors theory postulates that perceived hue and saturation of visual stimuli are based on ratios of neural responses. These ratios represent the relative outputs of the red-green (r-g), yellow-blue (y-b), and white-black (w-bk) neural systems (Jameson & Hurvich, 1955; Hurvich & Jameson, 1955). Hue is specified by a hue coefficient (HC), and for binary hues there are two such coefficients: one specifies the redness or greenness of the chromatic component of the sensation, and the other specifies the yellowness or blueness. The two coefficients add to 100%, and take the form:

$$HC_{(r-g)} = \frac{|r-g|}{|r-g| + |y-b|} \quad (1a)$$

and,

$$HC_{(y-b)} = \frac{|y-b|}{|r-g| + |y-b|} \quad (1b)$$

where the quantities on the right-hand side of the equations are the outputs of the opponent systems in absolute values. For example, $|y-b|$ is the absolute value of the output of the yellow-blue system and it can be either positive or negative. The convention adopted is yellow if positive, blue if negative. A saturation coefficient (SC) is also used in the model and is assumed to represent the proportion of the total sensation that appears chromatic. It is defined as the ratio of the sum of the outputs of the two chromatic systems to the sum of the outputs of all three systems (chromatic and achromatic):

$$SC = \frac{|r-g| + |y-b|}{|r-g| + |y-b| + |w-bk|} \quad (2)$$

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In addition, brightness is postulated to follow the output of the achromatic (w-bk) system:

$$B \cong |w-bk| \quad (3)$$

Thus, the theory defines quantitative measures of hue, saturation, and brightness that specify the three dimensions of the appearance of simple visual stimuli.

These three perceptual dimensions can be directly scaled by human Os using relatively simple techniques. This report presents a method for using scaling judgments of the hue, saturation, and brightness of several chromatic stimuli and, by introducing the three theoretical equations (1a, 1b, 2, and 3), a method to solve for the relative responses of the (w-bk), (r-g), and (y-b) systems to these stimuli.

METHOD

Apparatus

The O was presented with 1-sec exposures of a centrally fixated 2-deg 22-min circular field through a 1.4-mm-diam artificial pupil. The stimuli were derived from an 18-A ribbon-filament tungsten source that was viewed through one of several Balzers, B-40, interference filters with appropriate cutoff filters and through neutral density filters and a wedge. A beam splitter was interposed to reflect the image of the filament of a grain-of-wheat bulb into the optical path for fixation control. All lenses were achromatic, and the stimulus was presented to the O in Maxwellian view.

The relative energy distributions of the four spectral stimuli (454, 490, 598, and 654 peak nm) were determined, using an ISCO spectroradiometer, and are plotted in Fig. 1. To measure the luminances of the stimuli, haploscopic matches were first made between the annulus of a MacBeth illuminometer and a broadband stimulus projected through the apparatus. Then a successive heterochromatic technique was used to equate the broadband stimulus to the various spectral stimuli. Different luminance levels of the spectral stimuli were produced by the use of the calibrated neutral density filters and appropriate wedge positions. These luminance values are given in Table 1.

Observer

One male O (21 years) was used in this experiment. His color vision had been extensively tested and established as normal with a Nagel anomaloscope, pseudoisochromatic plates, and the Farnsworth 14-hue test. The O had extensive experience in scaling experiments and was aware of the basic design of this experiment.

Fig. 1. Relative spectral energy distributions of chromatic stimuli.

Table 1
Luminances of Stimuli

Peak Wavelength of Spectral Distribution (nm)	Luminance (in mL)				
454	3.4	10.8	34.0	340	6000
490	3.4	10.8	34.0	340	6800
598	3.4	10.8	34.0	340	6800
654	3.4	10.8	34.0	340	7400

Procedure

This experiment was conducted as part of a study on chromatic adaptation (Eichengreen, 1971), and the data presented here are only part of those collected in each experimental session.

Ten brightness scaling sessions were conducted. Each consisted of 30 stimulus presentations of 1 sec duration with a

30-sec interstimulus interval. Each session was preceded by 10 min of light exclusion. At the end of this period, the O positioned himself in a chinrest with the fixation light serving as a guide to correct head position. (To avoid "fixation-light bias," the fixation light was extinguished during the stimulus presentation.) To scale brightness, a method of magnitude estimation was used. The O was instructed to estimate the brightness magnitudes of the stimuli. He was told to use any number he wished to estimate the brightness of the first stimulus presented to him, and that the brightnesses of subsequent stimuli were to be expressed as magnitudes based on multiples, or ratios, of the first judgment.

The 30 stimuli in the brightness scaling experiment included the 20 narrowband chromatic stimuli listed in Table 1 (four chromaticities at each of five luminances) and 10 additional stimuli. The latter included four luminance levels of a broadband stimulus (5,100°K). In each session, the 5,100°K stimulus was presented at 34 mL and at three other luminances randomly selected from a set of eight luminance levels, ranging from 2.0 log units above to 2.0 log units below 34 mL. The remaining 6 additional stimuli differed from one session to another and were selected for each session from a set of 26 luminances of the 4

Fig. 2. Mean log brightness scaling judgments (N = 10).

Fig. 3. Median hue and saturation judgments for the 454- and 490-nm peak stimuli ($N = 10$).

narrowband chromatic stimuli. These stimuli ranged from 2.6 log units above to 2.5 log units below 34 mL. Thus, 9 added stimuli varied from session to session to guard against the possibility that the O might memorize numbers to be assigned to particular, recurring, easily identifiable stimuli.

Hue and saturation scales were determined in separate series of experimental sessions. In individual sessions, following 10 min of light exclusion, the O was presented with a single 1-sec exposure of one chromatic stimulus at a single luminance level. Individual sessions of this sort would not normally be required and were used here because each brief exposure was followed by a long-duration presentation of the stimulus to observe adaptation effects that are beyond the concerns of the present report.

As soon as the stimulus appeared, the O reported the color that he saw and the percentage that each hue component contributed to the total chromatic sensation (e.g., 90% red, 10% yellow) (Jameson & Hurvich, 1959). He also judged saturation by reporting the percent of the total sensation that was chromatic rather than achromatic (e.g., 40% color, 60% white, gray or achromatic). Ten separate sessions were conducted with each of the 20 chromatic stimuli. The sessions were conducted in a mixed order, except those with the 454-nm peak stimuli which were introduced after all of the other sessions had been completed.

RESULTS

Brightness

No standard stimulus was used in the brightness scaling sessions, and the correction procedure proposed

by Lane, Catania, and Stevens (1961) was adopted to reduce all estimates to a common scaling modulus. The mean of the logarithms of each of the brightness estimates obtained for the 21 stimuli repeated in each session was subtracted from the grand mean of the logarithms of all of the judgments made to these stimuli in all of the sessions. The deviation, thus obtained, for each session was then added to each judgment obtained in that session (all in logarithmic units). The corrected logarithms were then averaged across sessions for each stimulus. These values were taken as the mean log brightnesses of the stimuli. These values are presented as a function of log luminance in Fig. 2.

Hue and Saturation

The median hue and saturation judgments are presented in Figs. 3 and 4. The left-hand set of graphs in each figure shows the hue percentages plotted as a function of log luminance. The right-hand graphs show the saturation percentages for the same stimuli also as a function of log luminance.

The hue judgments of each of the chromatic stimuli show a Bezold-Brücke hue shift toward increased yellow or blue (decreased red or green) with increased luminance. The saturation judgments tended to vary only slightly with the luminance of the chromatic

Fig. 4. Median hue and saturation judgments for the 598- and 654-nm peak stimuli ($N = 10$).

Fig. 5. Derived achromatic and chromatic responses for each of the spectral distributions.

stimuli, but there is evidence of a systematic decrease in saturation at the higher luminance levels that is most apparent with the 454- and 490-nm stimuli (Fig. 3).

DISCUSSION

Solution of Eqs. 1, 2, and 3 provides estimates of the response values of the three opponent systems to each of these stimuli as follows. The brightness scaling values were assumed to represent and be equal to the response of the (w-bk) system. Therefore, the numerical response values depend directly on the scaling modulus that the O chose. The hue percentages were assumed to be equal to the appropriate hue coefficients and the saturation percentages equal to the value of the saturation coefficient. For any stimulus, the scaled brightness value (see Eq. 3) was substituted for the $|w-bk|$ quantity in Eq. 2. Then, taking the scaled saturation judgment as the value of the saturation coefficient, algebraic manipulations yielded a numerical value for the total chromatic response ($|r-g| + |y-b|$).

The hue reports were then substituted into Eq. 1 to divide the total chromatic response into its component responses from each of the chromatic response systems. The calculated response values for each of the 20 chromatic stimuli are presented in Fig. 5 for each of the four spectral distributions.

In another experiment (Eichengreen, 1971), chromatic thresholds for each of these spectral distributions were determined for this O. That is, the least energy which produced a reliable chromatic response (red, blue, green, or yellow) was determined for each of the stimuli. Because each of these stimuli produced two hue reports, separate threshold values were determined for each of the hue components. The derived responses of the chromatic systems to each of the chromatic stimuli are plotted relative to these values in Figs. 6 and 7. Thus, the response functions obtained for the four spectral distributions are adjusted for the

Fig. 6. Derived responses of the red-green response system to each of the spectral distributions.

Fig. 7. Derived responses of the yellow-blue response system to each of the spectral distributions.

sensitivity of the response systems to these stimuli and the growth functions for each system can be compared.

The derived responses of the achromatic system (the brightness magnitude estimates from Fig. 2 and repeated in Fig. 5) grow rather rapidly at low luminance levels, while the rate of growth decreases at higher luminance. The responses of the chromatic systems also grow more rapidly at low luminance levels than at higher luminance levels. However, the derived chromatic responses tend to flatten out at the higher levels. In addition, there are certain differences in the shapes of the red and green response functions, on the one hand, and the blue and yellow, on the other. That is, the red and green responses seemed to reach a "ceiling" at lower luminances and stayed "flat" thereafter to a greater extent than did the blue- and yellow-derived response magnitudes.

It is also possible to compare the red to the green responses and the blue to the yellow responses (Figs. 6 and 7). Whereas the red and green responses to each of the spectral distributions seemed to grow at similar rates with changes in luminance (see Fig. 6), there are noteworthy differences. The green response to the 490-nm peak stimuli and the red response to the 598-nm peak stimuli reached essentially the same ceiling; the red response to the 454-nm peak stimuli, on the other hand, reached a much lower ceiling and the red response to the 654-nm peak stimuli reached a much higher ceiling than did the red response to the 598-nm peak stimulus. Figure 7 shows that the yellow and the blue response functions to the 454-, 490-, 598-, and 654-nm peak stimuli all seem to fall fairly close to one another, although it is less certain that the yellow function is leveling off at the higher luminances in all cases.

Thus, the derived response functions indicate a similarity within the paired chromatic systems in regard to rate of growth with luminance, i.e., the red and green

growth curves resemble each other and so do the yellow and blue ones. However, within the red-green system, there appears to be an asymmetry with respect to the ceiling reached; the red chromatic response component behaves differently in different regions of the spectrum.

The tapering off, or the ceiling effect, of the (r-g) derived response with luminance fits well with the Bezold-Brücke hue shift, which previously had been explained as being due to differential, but constant, growth rates of the red-green and yellow-blue response systems (Hurvich & Jameson, 1958). In addition, the slower growth rates for the responses of both chromatic systems at high luminances is consistent with the decrease in perceived saturation at very high luminance levels; the achromatic system seems to continue to increase in output, while the chromatic systems remain nearly constant at the higher luminance levels. With the luminances used in the present experiment, this effect is apparent with the two shortwave spectral distributions and would probably be apparent at higher luminances of the longwave spectral distributions.

Neither the brightness magnitude function measured by the magnitude estimation technique nor the chromatic response magnitude functions derived from the scaling data are simple power functions. None of these measures plots as a straight line in log-log coordinates (see Figs. 2, 5, 6, and 7). Nor are these functions linear in semilog coordinates. And thus, the response magnitudes are not simply a log transform of the stimulus energy. The opponent-colors theory posits (a) all positive outputs from photoreceptor activity and (b) bimodal plus/minus responses at the neural level that depend on interaction between the photoreceptor activities (Jameson & Hurvich, 1968) and neighboring retinal areas (neural interaction). Nonlinear transformation could occur at (a) or at (b) or at both. The results obtained in the present preliminary study on

one O should be extended to a number of Os to determine their generality before a more extensive and rigorous analysis of the data can be made.

REFERENCES

- Eichengreen, J. M. Time dependent chromatic adaptation. (Doctoral dissertation, University of Pennsylvania) Ann Arbor, Mich: University Microfilms, 1971. No. 71-26005.
- Hurvich, L. M., & Jameson, D. Some quantitative aspects of an opponent-colors theory. II. Brightness, saturation, and hue in normal and dichromatic vision. *Journal of the Optical Society of America*, 1955, 45, 602-616.
- Hurvich, L. M., & Jameson, D. Further development of quantified opponent-colour theory. In *Visual problems of colour, II*. London: Her Majesty's Stationery Office, 1958. Pp. 691-723.
- Jameson, D., & Hurvich, L. M. Some quantitative aspects of an opponent-colors theory. I. Chromatic responses and spectral saturation. *Journal of the Optical Society of America*, 1955, 45, 546-552.
- Jameson, D., & Hurvich, L. M. Perceived color and its dependence on focal, surrounding, and preceding stimulus variables. *Journal of the Optical Society of America*, 1959, 49, 890-898.
- Jameson, D., & Hurvich, L. M. Opponent response functions related to measured cone photopigments. *Journal of the Optical Society of America*, 1968, 58, 429-430.
- Lane, H. L., Catania, A. C., & Stevens, S. S. Voice level: Autophonic scale, perceived loudness, and effects of side tone. *Journal of the Acoustical Society of America*, 1961, 33, 160-167.

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