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Variations in normal color vision. III. Unique hues in Indian and United States observers

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Basic color categories are thought to share a common pattern across linguistic groups, yet the focal colors defining those categories can vary substantially within any single group. We asked whether focal colors can also differ systematically across different groups of individuals living in potentially different color environments, by measuring focal and unique hues for observers in India and the United States. Differences between groups were generally small relative to the within-group variations, consistent with a strong common basis for color naming across diverse contexts. However, for most hues the average settings differed significantly across sub-populations. These differences persisted across testing conditions and thus probably reflect longer-term contextual influences on color appearance judgments. They suggest that while color categories may be qualitatively similar, precisely how the hue spectrum is parsed may differ quantitatively across different populations of observers. Both the between-group and the within-group differences are inconsistent with the differences predicted by common peripheral sources of variation in color vision (e.g., in lens or macular pigment) and may reflect an influence of environmental or cultural differences in focal color choices. © 2002 Optical Society of America

OCIS codes: 330.1690, 330.1710, 330.1720, 330.5020, 330.5510, 330.7310, 330.7320.

1. INTRODUCTION

Studies of color perception suggest that humans perceive color in terms of three dimensions that represent sensations of “black versus white,” “red versus green,” or “blue versus yellow.”¹ Any aperture color can be described as a combination of these perceptual axes. Thus “orange” is perceived as a combination of red and yellow. Alternatively, stimuli confined to a single axis appear pure or “unique” (e.g., a “unique yellow” is a pure yellow that is not tinged by red or green). The perceptual salience of the unique hues suggests that they reflect fundamental characteristics of the neural representation of color. In fact, observations on the opponent nature of color appearance (e.g., that no light appears both red and green or both blue and yellow²) foreshadowed the color-opponent processing that was subsequently revealed in single-cell studies of postreceptoral neurons in the visual system.³ Yet the actual substrate of the unique-hue axes has yet to be identified. And why our experience of color is organized in terms of these specific dimensions remains an enigma.⁴ In this study we asked to what extent—and in what ways—these axes are malleable, by exploring whether they vary across observers drawn from very different populations and environments.

In a highly influential study, Berlin and Kay⁵ argued that color experience is similar across a diverse range of cultures and thus reflects “universal” principles that are independent of an individual’s personal experience. Specifically, they found that all cultures studied describe color by using a similar set of basic color terms. Though

the number of basic terms varied for different languages, the presence of particular terms followed a consistent order across languages. Thus all languages had words to describe black and white, while languages with three or more terms always included red, with four or more green or yellow, and so on. Moreover, Berlin and Kay found that these terms are assigned to similar regions of color space, and the foci for these regions were subsequently shown to correspond closely to observers’ choices for unique hues (for red, green, blue and yellow⁶). A number of authors have pointed to exceptions to this scheme and have seriously questioned its interpretation (e.g., Refs. 7–12). Yet in general, the linguistic patterns revealed by Berlin and Kay’s work and the many studies it inspired have been taken to confirm a common basis for human color experience.^{13,14} Further, this common basis has been interpreted in terms of a common and specific physiological organization of the visual system.^{6,15,16}

The basic color terms revealed by Berlin and Kay’s analyses reflect qualitative categories along which hue and lightness sensations are parsed. At a quantitative level, individuals in fact vary widely in the stimuli they choose as unique hues. For example, the wavelength that appears unique yellow can differ by 20 nm across observers, while for unique green the range may span 80 nm (i.e., a large fraction of the 300-nm range of visible wavelengths).^{17,18} Inter-observer differences are as large for the desaturated colors characteristic of natural objects.¹⁹ Indeed, Berlin and Kay⁵ found less agreement in color foci among multiple respondents from a single

language (Tzeltal) than they did between respondents drawn from different languages. The presence of such large within-group differences led us to ask whether there might also be quantitative differences in the color categories across different populations. The bases for normal variations in color appearance are unknown, as are the bases for the unique hues themselves. However, individual differences could plausibly arise from a number of sources, including physiological, environmental, and cultural differences, and many of these factors are likely to vary across groups. To explore this possibility, we measured the unique hues and focal colors for a large number of observers in different settings in India and the United States (U.S.). We chose these contexts because it allowed us to compare color judgments across groups that differed along many dimensions, including ethnicity, language, culture, and visual environment (e.g., rural or urban). Our results support a strong common source of individual variation for the populations we tested, but they also reveal consistent differences in hue loci across different populations.

2. METHODS

A. Participants

Color judgments were collected for a total of 349 observers in India and the U.S. Respondents were administered the tests in Tamil, Marathi, or English (see Table 1), at the following locations:

1. *Elite School of Optometry, Chennai, India.* This group included 70 undergraduate optometry students residing in Chennai, India, who were tested both outdoors in a shaded corridor illuminated by natural daylight and indoors in a room illuminated by an incandescent source. The students ranged in age from 17 to 23 (mean age 19) and were tested in English.

2. *Silk merchants, Chennai, India.* We also tested a second population of urban residents in Chennai. This group consisted of 70 employees of a large silk shop, who were of interest to examine because they spend several hours a day judging and working with a broad spectrum of colored sari fabrics. The employees ranged in age from 18 to 70 (mean age 42), and by tradition were all male. Testing was conducted in Tamil on the premises of the shop, again with an incandescent source.

3. *Rural Tamil Nadu, India.* Color settings were collected for 26 subjects at a farming village outside Chennai. These observers varied from 18 to 60 years in age (mean age 35) and viewed the stimuli under shaded outdoor lighting. Testing was conducted in Tamil in October, near the beginning of the second regional Monsoon.

4. *Rural Maharashtra, India.* We also collected settings from 73 observers in rural agricultural areas in the

Nasik district of the state of Maharashtra, India. These subjects were all farmers and ranged from adolescents to elders (though we do not have specific ages for these observers). In this case testing was conducted in Marathi. To explore the influence of seasonal changes in the outdoor color environment—which are pronounced for this region because of the monsoon rain pattern—we further subdivided these individuals into two groups, who were tested in either September or early October (near the end of the monsoon season; 38 subjects) or in late December and January (during the dry winter season; 42 subjects, including 7 who were tested at both time intervals).

5. *University of Nevada, Reno, Nevada.* For comparison, equivalent measurements were made for 110 students in Reno, Nevada, in the U.S., aged 18–64 (mean age 25). Like the Elite School of Optometry (ESO) students noted above, the University of Nevada, Reno (UNR) students made settings under both shaded outdoor lighting and indoor incandescent lighting.

6. *Controls.* Finally, two of the authors (MW and SW) made repeated settings during the course of the study and at each of the test sites in order to assess variations that might arise from specific testing environments.

B. Stimuli

Subjects included were all screened for normal color vision with the Neitz color test.²⁰ This recently developed test is a printed variant of pseudoisochromatic plates in which subjects must identify simple shapes rather than numbers and was thus ideally suited to testing across different linguistic groups. Somewhat surprisingly, less than 1% percent of our sample was classified as color deficient by this test. The low incidence among observers in India could reflect variations in the geographical distribution of color deficiencies.²¹ Moreover, among the optometry students, known color deficient were excluded on the basis of prior tests, and groups such as the silk merchants may not have included color deficient because of the requirements of their trade.

After the subjects had been screened, color judgments were assessed with three different stimulus sets:

1. *Munsell Chips.* In order to include a standardized stimulus consistent with those of previous studies, we first measured color appearance using a palette of Munsell chips. The palette was equivalent to the original stimulus set used by Berlin and Kay in hue and lightness, though some of the chips that we used had a higher saturation. The palette consisted of 320 glossy chips of the maximum available saturation, spanning 40 hue steps and 8 lightness levels. The specific array is illustrated in Fig. 1. The full array was mounted on five pages from the Munsell Color Book and shown together. The observer was asked to select the one chip from the array

Table 1. Color Terms Used During Testing

English	Red	Green	Blue	Yellow	Orange	Purple
Tamil	segappu	pachai	neelam	manchal	orange ^a	oodha
Marathi	lal	hirva	neela	pivla	shendra	jambala

^aThere is no Tamil term for “orange,” and the English term has instead been adopted

Munsell Palette

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40			
9		2	2	2	2	2	2	2	4	4	6	6	6	6	4	4	4	4	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2		
8		6	6	6	6	6	8	10	14	16	14	12	12	12	10	10	8	8	6	6	6	6	4	4	4	4	4	4	6	6	6	4	4	4	4	6	6	6	6	6	6	6	
7		8	10	10	10	10	14	16	14	12	12	12	12	12	10	10	10	10	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	10	10	8	8
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2		8	8	8	6	4	4	4	2	2	2	2	2	2	4	4	4	6	6	6	6	6	6	6	6	6	6	6	6	6	8	10	10	10	8	6	6	8	8	8	8		
	R	R	R	R	YR	YR	YR	YR	Y	Y	Y	Y	GY	GY	GY	GY	G	G	G	G	BG	BG	BG	BG	B	B	B	B	PB	PB	PB	PB	P	P	P	P	RP	RP	RP	RP			
	2.5	5	7.5	10	2.5	5	7.5	10	2.5	5	7.5	10	2.5	5	7.5	10	2.5	5	7.5	10	2.5	5	7.5	10	2.5	5	7.5	10	2.5	5	7.5	10	2.5	5	7.5	10	2.5	5	7.5	10			

Fig. 1. The Munsell palette. The array of chips varied in 8 levels of lightness and 40 hue steps. The number in each cell gives the chroma of the chip.

that best represented a particular color (e.g., the chip that was the best example of the color “red”). Chips were selected in order for the colors red, yellow, green, blue, purple, and orange.

2. *Unique-hue palettes.* In the second test, we focused on identifying the stimuli that appeared as unique hues for the observer, by testing settings for red, green, blue, or yellow. In this case we generated palettes displaying a graded series of hues that were printed on bright white paper, using an HP1220C printer. (Our stimuli thus differed substantially from the monochromatic aperture colors typically used to measure unique hues.) For each unique-hue series the palettes were chosen to span a range of hues at high saturation. To maintain consistency, sheets for each hue palette were printed from a single cartridge, with the reflectances calibrated with a Photo Research PR650 spectroradiometer and subsequently with a GretagMachbeth Spectrolino Spectrophotometer (for palettes sent for measurement to the Center for Imaging Science at Rochester Institute of Technology). Figure 2 shows the chromaticities of each hue series within a scaled version of the MacLeod–Boynton²² chromaticity diagram, which we have used previously to characterize unique hues.¹⁹ Coordinates within this space are related to the MacLeod–Boynton r, b values by

$$\begin{aligned} \text{LvsM contrast} &= (r_{mb} - 0.6568) * 2754, \\ \text{SvsLM contrast} &= (b_{mb} - 0.01825) * 4099, \end{aligned} \tag{1}$$

where 0.6568 and 0.01825 are the r, b values of Illuminant C (our reference Illuminant) and 2754 and 4099 are factors that scale contrasts along the axes for roughly equal multiples of detection threshold. The palettes were displayed as 24 uniformly colored circles (~0.75-in. diameter) arranged along a circular path, and the range of colors was chosen so that it clearly spanned the hue in question. For example, for unique yellow the palette ranged in incremental steps from greenish to reddish. Subjects were instructed that the palette contained a graded series of a particular hue (e.g., yellow) and were asked to select the one circle that appeared untinged by either of the secondary colors (i.e., neither reddish nor greenish). Three palettes were shown for each hue.

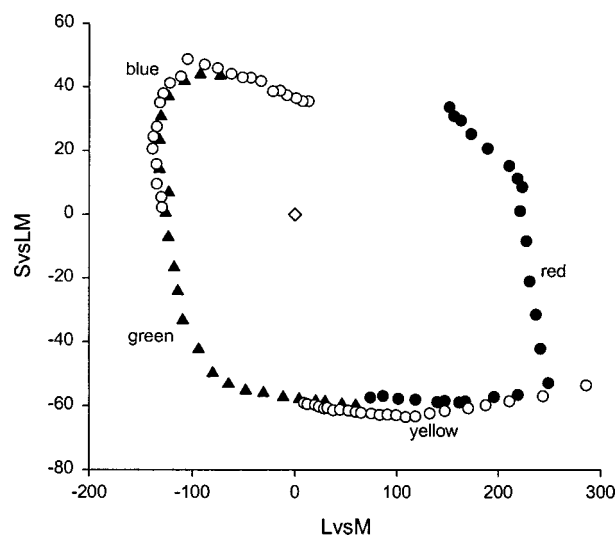


Fig. 2. Chromaticity coordinates for the printed hue palettes, plotted in the scaled LvsM and SvsLM color plane [see Eq. (1)]. Palettes for individual hues were composed of 24 colors drawn from regions around the nominal unique hue.

These differed by three or six palette steps in the range displayed, so that specific colors were not tied to specific locations on the page, and thus allowed us to check the reliability of subjects’ choices.

3. *Computer test.* Both the Munsell chips and the hue palettes were composed of highly saturated colors. For a small subset of subjects we also measured unique hues for desaturated stimuli presented on a color monitor. These stimuli allowed us to control more carefully the observers’ state of adaptation and allowed us to compare settings with our previous measures of individual variations in unique hues.¹⁹ Stimuli were presented for 0.5 s in a uniform 2-deg square, centered on the 6 × 8-deg background of 30 c/m² and a chromaticity equivalent to Illuminant C. The room was otherwise dark. Subjects initially adapted to the background for 30 s before testing began and for 2-s between presentations. For each stimulus a button box was used to indicate how the presented color deviated from the unique point (e.g., responding “too green” or “too red” for unique yellow or blue).

surprisingly, however, the differences between the indoor and outdoor illuminants are much larger than differences between the two sets of illuminants measured in India and the U.S. Thus differences in hue settings between the ESO and UNR students that persist across the two testing conditions are unlikely to reflect differences in the ambient illuminant.

2. As a second test, authors MW and SW were re-tested during the different screening sessions, as noted above. We used these measurements to examine whether their hue judgments covaried with the different test groups. Such covariations might suggest that group differences were the result of ambient factors during testing (e.g., the lighting or sets of surfaces in the scene) or changes in the test materials (e.g., which conceivably could have varied or faded over time).

3. RESULTS

In the following sections we consider the hue settings estimated by each of the three different measures that we used.

A. Munsell Chips

Figure 4 shows an example of the distributions of focal color choices from the Munsell array. The two tables show settings for the ESO or the UNR students tested under the incandescent source; the two groups were reasonably matched for age, educational background, and testing environment, and both consisted of respondents fluent in and tested in English. The numbers in each table indicate the number of respondents who chose a particular chip as the best example of red, orange, yellow, green, blue, or purple. To a first approximation, the foci for the color terms are very similar across the groups and are also similar to the foci obtained originally for individual observers by Berlin and Kay⁵ (shown by the shaded cells in the table). Nevertheless, there are consistent differences in the mean focal colors across the groups. Relative to the UNR observers, blue is shifted toward greener values and red and yellow are both shifted to a lesser extent toward orange for the ESO observers.

To better compare the settings for the different groups we collapsed the foci across lightness levels in order to plot the distributions as a function of the single dimension of hue. Histograms for these hue foci are shown in Fig. 5. Again, although the distributions of focal stimuli are qualitatively similar, small but significant differences are apparent in the mean foci across the groups. For example, consider again the groups tested under common incandescent lighting (ESO-in, SM-in, and UNR-in). For the UNR students the focal yellow had an average Munsell hue of 3.6Y, while for the two Chennai groups the mean was 2.3Y (ESO) or 0.8Y (for the group of silk merchants). Thus pure yellow differed by a full Munsell chip (2.5 hue steps), a difference that is visually salient and is large relative to the variations within the groups (which had standard deviations ranging from 1.5 to 2.1 hue steps). This difference can also be seen within the histograms of Fig. 5. For example, for all groups the modal yellow was 2.5Y, but 37% of the UNR students chose chips greener than this value, whereas only 3% selected more-

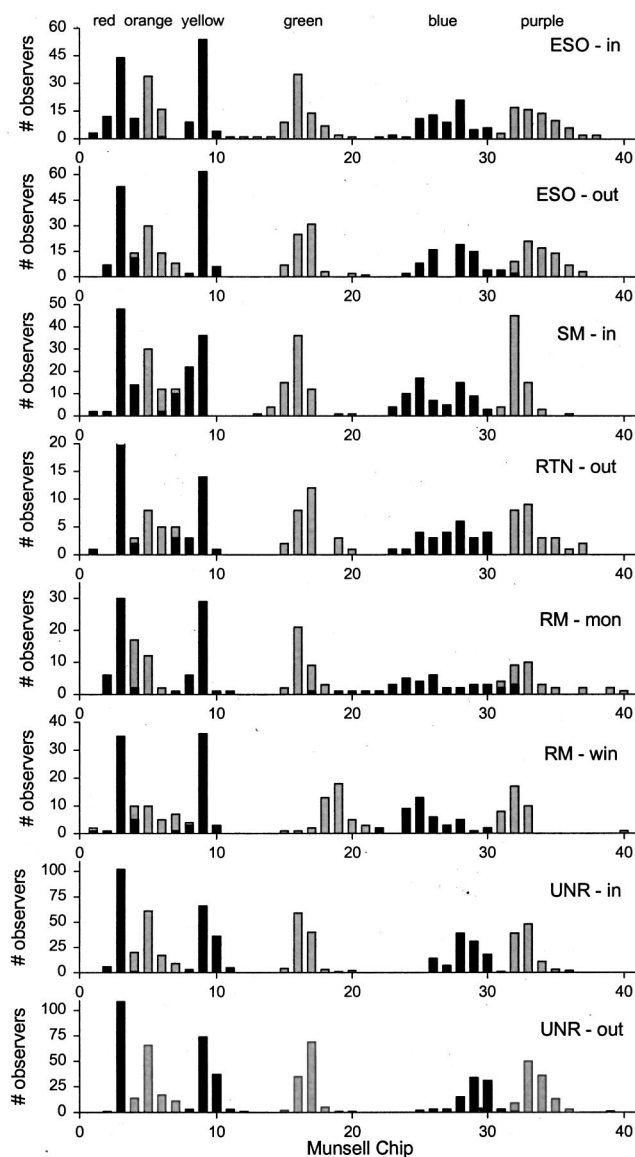


Fig. 5. Distribution of focal hues, based on averaging Munsell selections across lightness levels. Histograms successively plot the distributions for red, orange, yellow, green, blue, or purple for each of the eight test groups and conditions. Values correspond to the position of the hue (1–40) in the palette shown in Fig. 1.

orange chips. Conversely, among the silk merchants, 49% selected chips shifted toward orange, whereas none of the 70 observers chose greener chips. Moreover, within the ESO and UNR groups, similar differences in focal yellow persisted when the same students were re-tested under outdoor lighting. Mean differences were even larger in the focal blue values, which varied from 5.9B to 10.9B for the same three groups, with the UNR students' mean settings shifted toward purple by either one or two chips relative to the two Chennai groups. And again, these differences remained under outdoor lighting. In contrast, settings for focal green showed less difference across the populations, with the exception of the rural Maharashtran subjects tested in winter, whose choices were strongly shifted toward blue.

We also asked subjects to choose focal orange and purple from the Munsell array. These were included because they do not have the same primary status as the unique hues and thus could conceivably show different patterns of variation both across and within groups. There are also differences in the group means for these stimuli. However, since we did not include a second measure to evaluate these (and since they were problematic terms for some respondents) we can be less confident about these differences, and we do not consider them further here.

B. Hue Palettes

Figure 6 plots comparable histograms for the unique-hue loci based on selections from the printed palettes. Again we used these palettes to try to provide a stimulus set that more directly facilitated judging the unique point, by displaying a single hue series bracketing each unique hue. The histograms were constructed by converting the chromaticities of each selected chip into a chromatic angle within the color space defined by Eq. (1). In this representation an angle of 0 deg corresponds to the +L pole of the LvsM axis, and a value of 90 deg represents the +S

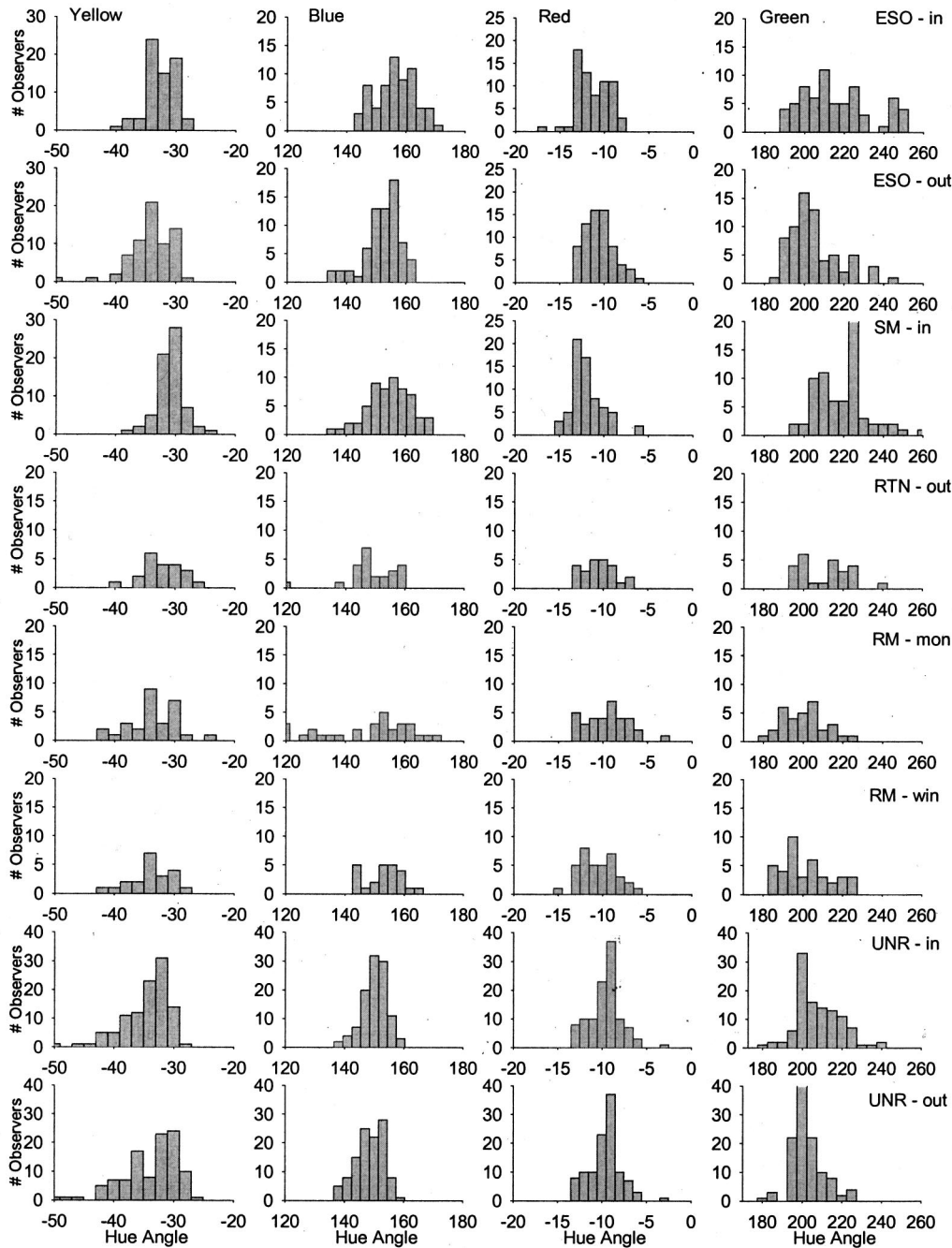


Fig. 6. Distribution of unique hues selected from hue palettes. Each histogram plots the hue angle that was selected for unique yellow, blue, red, or green for each of the eight test groups and conditions. Hue angles correspond to the directions in the LvsM and SvsLM space shown in Fig. 2.

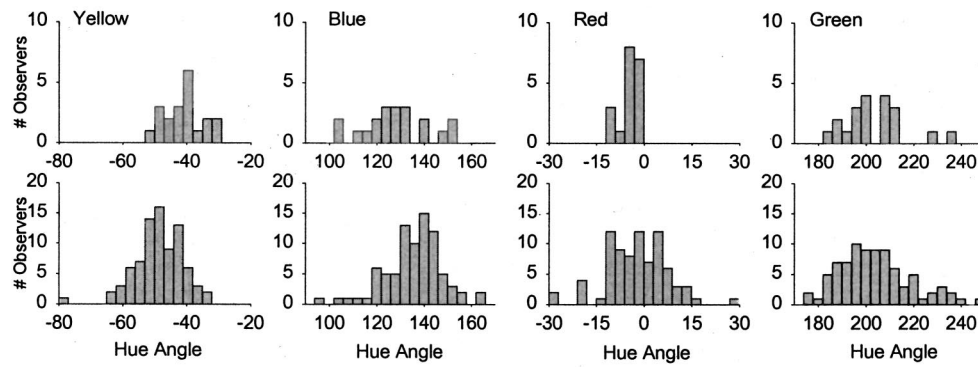


Fig. 7. Distribution of unique hues for desaturated stimuli presented on the computer. Each histogram plots the hue angle that was selected for unique yellow, blue, red, or green for either the ESO students (upper row) or the UNR students (lower row). Hue angles correspond to the directions in the LvsM and SvsLM space shown in Fig. 2.

pole of the SvsLM axis. These angles were then averaged for the three different settings made by each individual for each hue. As noted, the three palettes used to judge each hue differed by three stimulus steps in the range displayed. For example, an observer who selected the same chip location (rather than the same hue) would thus have a setting range of six steps. The average range was between one and two steps for red and yellow, and between two and three steps for green and blue. To exclude the least reliable settings, we omitted selections with ranges greater than three in red or yellow or five in blue or green (eliminating roughly 7% of the responses).

Differences in the mean hue settings across the groups are again evident and follow a pattern similar to those found with the Munsell chips. As before, relative to the UNR subjects the observers in Chennai chose for unique yellow and unique red stimuli that were on average shifted toward oranger values. Although these mean differences are small relative to the within-group differences, they are again perceptually clear and significant (e.g., $p < 0.01$ for UNR versus ESO yellow or red under either illuminant, with stronger differences between UNR-in and SM-in, as assessed by t tests). Blue was also again shifted in directions that paralleled the differences in the selections for the Munsell chips.

In characterizing these differences, we have focused on the Chennai and Reno groups, because the differences between these groups were the largest and most reliable (because of both the larger number of observers and the lower variability in their settings). Settings for the rural respondents whom we tested were fewer in number and were generally more variable, and thus we are less certain about trends in the color choices. However, it is notable that the Maharashtra respondents tended to be more similar in their hue settings to the UNR students than to respondents in Tamil Nadu.

C. Computer Test

In the third test, we used a computer display to measure the unique hues for desaturated stimuli, with a chromatic contrast of 30 as defined by the scaling of Eq. (1). This test provided more careful control over short-term chromatic adaptation and more directly required a unique-hue criterion in the responses (by requiring a forced-

choice response between the two complementary colors bracketing the primary hue). Because we had used a similar test previously, the present settings also allowed us to test whether we could actually replicate the distributions for a given population. In this case the two groups tested included the UNR students and 20 of the ESO students.

Figure 7 shows the histograms of the hue choices for these groups. The mean hue angles for the UNR observers were very similar to those for the settings that we reported previously for a different population of UNR observers measured with a different psychophysical system,¹⁹ and t tests of these means confirmed that none of the differences were significant. Unique red for these weak chromatic stimuli are again centered along the LvsM axis, though variations around this mean were large. Alternatively, the yellow and red settings for the ESO students were again biased on average toward orange relative to the means for the UNR students. The mean differences between the ESO and the UNR observers were significant for all but the green hues. However, for unique blue they are in the direction opposite to those that we found with the previous tests—for the ESO students, the average is now biased toward a purpler hue angle. The blue settings for the ESO students were variable and were based on only a small sample, and as the flat histogram in Fig. 7 suggests, they do not have a well-defined modal value.

D. Controls

The mean foci for each of the groups that we tested are summarized in Fig. 8. For this figure we have converted the hue values for the Munsell chips into chromatic angles within our space in order to express the three measures with a common metric. It is evident from this figure that within any group of observers the chromatic angle defining the focal colors varied depending on the test condition. In particular, the chromatic angles for the red, blue, and yellow were similar for the Munsell chips and the hue palettes but were different from those in the computer test. We do not know the basis for this difference, but it may result in part because the paper versus monitor stimuli varied widely in both lightness and saturation and were presented on backgrounds of slightly different chromaticity. What is important, however, is that

the rank ordering of the group differences was generally replicated when each of the different color tests was used (with the exception of the blue settings for the computer test, as we discussed in the preceding paragraph). This suggests that the differences between the groups are unlikely to reflect an artifact of the specific testing procedures or color samples.

A second potential source of between-group variation was the ambient lighting, and as pointed out above we specifically included testing under very different lighting to assess the influence of this factor. Not surprisingly, to a first approximation observers showed a high degree of color constancy, in that the shifts in the distributions are very small relative to the large shifts in chromaticity under the outdoor and the indoor illuminants. However, Fig. 8 and the preceding histograms show that settings did systematically vary when observers changed from outdoor to indoor lighting. It is also noteworthy that the correlations between the individual settings across the two illuminants were often weak, suggesting that errors in constancy and/or individual settings were comparable in magnitude to the individual differences within groups. Yet despite this, the between-group differences remained similar across the two lighting conditions. Thus it is unlikely that the differences can be attributed to differences in the illuminant during testing.

A third factor that could have introduced group differences (among populations that might otherwise be the

same) could be uncontrolled—and unknown—differences in properties of the scene in which observers made their settings. In fact we made relatively little effort to equate or constrain the scenes within which the stimuli were presented. Thus different groups viewed the stimulus arrays within a context that often included very different surrounding surfaces and colors. To assess whether these potential variables might have influenced the settings, two of the authors made settings during the different screening sessions, in the same contexts as each of the participants tested. Even though we made these settings under diverse viewing conditions, the settings remained relatively stable across the different contexts and across the six months of the study, and they did not covary with the settings for the different test groups. For SW there was no correlation between her settings and the group means. For MW there was a weak but significant correlation across the eight conditions of Fig. 6, but this was found to be due to the shifts in settings between the incandescent versus outside illuminants (which as noted above, cannot account for the group differences). Thus it is unlikely that the differences that we observed across the different populations are an artifact of contingencies specific to particular testing conditions.

4. DISCUSSION

As we noted in Section 1, studies of color naming have tended to emphasize the similarities in color judgments across different groups, while studies of individual differences have pointed to the large variations in focal and unique hues within groups. In this study we have partly merged these two approaches by asking to what extent individual differences in color naming exhibit a similar pattern across different populations of observers. A large number of factors could potentially contribute to normal variations in color perception and could vary in ways that could bias color appearance across different sample groups. The relevance and relative importance of these potential factors are important but unanswered questions. To explore them, we asked how judgments of color might vary quantitatively across individuals living in different contexts. The groups that we tested were drawn from very different ethnic, environmental, and cultural backgrounds. Consistent with many previous reports, the range of unique hues within individual groups was large, implying that the hue loci are very malleable. Yet—also consistent with the basic findings of Berlin and Kay⁵—the differences between groups were by comparison small. Thus to a large extent, the factors leading to individual variation may be universal or common across different natural contexts.

At a finer level, the populations that we tested did show consistent differences in the stimuli that they selected as unique hues. Again, these differences persisted across different stimuli and different illuminants and were largely unaffected by the specific context in which the stimuli were presented (since the groups varied in ways in which the control subjects did not). This suggests that the factors biasing the average hue settings reflected longer-term contextual influences on color appearance rather than factors that were specific to individual scenes.

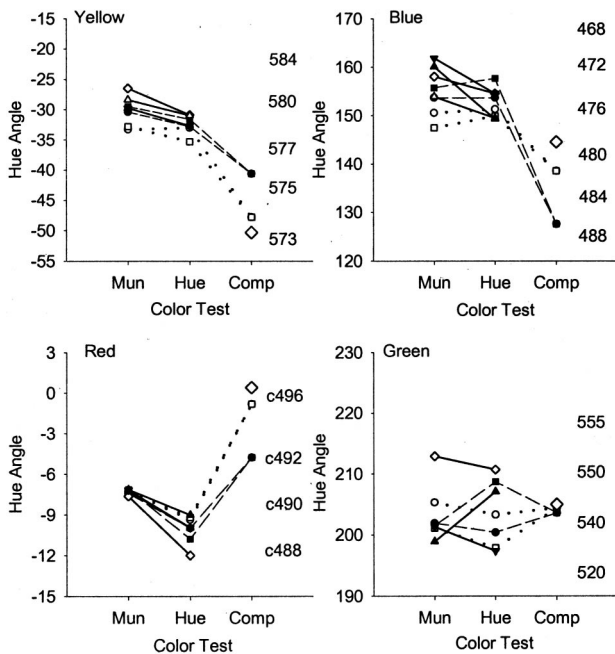


Fig. 8. Mean hue settings for each of the eight tested groups and conditions based on the Munsell palette (Mun), the printed hue palette (Hue), or the computer test (Comp). ESO-in (solid squares, dashed line), ESO-out (solid-circles, dashed line), SM-in (small diamonds), RTN-out (open triangle), RM-mon (solid upward triangle), RM-win (solid downward triangle), UNR-in (open circles, dotted line), UNR-out (open squares, dotted line). Large, unconnected diamonds plot the mean unique hue angles estimated previously with the computer test by Webster *et al.*¹⁹ Numbers to the right in each panel indicate the dominant wavelength corresponding to different hue angles, or the complementary wavelength in the case of the “red” settings.

Our results thus also support a limited degree of “relativity” in color naming and are consistent with analyses of color-similarity judgments in showing both a strong, common component to color judgments and a much weaker, population-specific component.²³

Identifying the possible bases for the differences both within and between groups is of interest because it could help elucidate how and to what extent human color perception can be modulated by variations in observers or their world. But what are these factors? We have previously discussed possible bases for individual differences in unique hues within a population.¹⁹ In the following subsections we consider three potential sources of differences in color naming across populations.

A. Physiological Factors

Normal variations in visual sensitivity arise at multiple levels of the visual system, from differences in preretinal filtering (e.g., lens and macular pigment), the photopigment spectra (e.g., optical density and spectral peak), the relative numbers of L, M, and S cones, and how the cones are combined in postreceptoral pathways.^{19,24} Such differences could bias color appearance across different populations. For example, unique green has been found to correlate with eye pigmentation and could thus vary across different ethnic groups.¹⁷ Moreover, Brown and Lindsay²⁵ recently suggested that differences in lens density could underlie population differences in the number of basic color categories.

However, variations in such peripheral factors generally fail to predict the pattern of unique hues that we observed. First, commonly known variations in factors such as lens and macular density predict strong correlations across different unique hues (e.g., in the stimuli that observers choose for blue and yellow), whereas the observed variations in the unique hues are conspicuously independent.¹⁹ This independence was also observed in the present experiments. For none of the groups did we find a consistent correlation among their selections for different hues. Second, mean differences across the groups are not in the direction predicted by a pigmentation difference. For example, Fig. 9(a) shows the changes in hue angle predicted by an increase in lens or macular pigment density and compares these with the observed difference between the ESO and the UNR subjects for the unique hues measured with the computer test. The predictions were calculated by finding the color angle in the space of Eq. (1) that would be required to maintain a constant ratio of the cone signals after the change in pigment screening. Clearly, no relative density difference can account for the pattern of differences across the four hues. Moreover, the shift in yellow is toward a lower predicted pigment density for the ESO students, even though they would be expected to have a higher average density. Although we cannot rule out a density variation or other source of sensitivity difference for the hue differences, the foregoing results suggest that this variation would have to affect the different hues independently, and this rules out the simplest interpretations of a peripheral visual change.

It should be noted that physiological variations across our groups might also be expected from factors such as

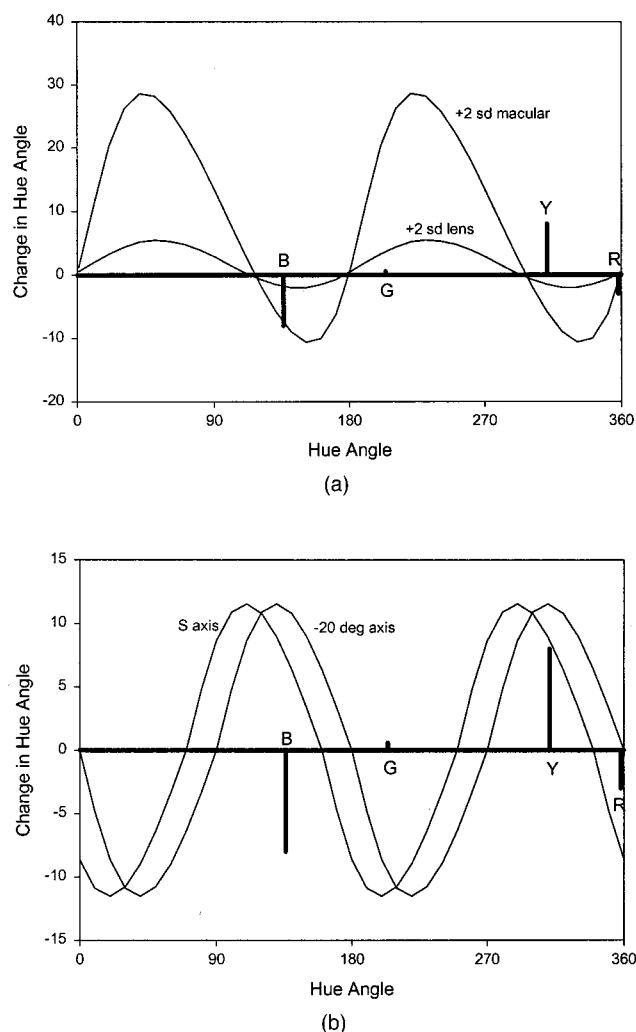


Fig. 9. (a) Hue shifts predicted by an increase in macular or lens density compared with the mean differences between the unique hues for the ESO and the UNR subjects. Predictions are based on the Smith–Pokorny fundamentals adjusted for a lens or macular density increase of 0.36 at peak density (equivalent to 2 standard deviations for the density variations estimated by Webster and MacLeod).⁴⁰ (b) Hue shifts predicted by a relative change in contrast sensitivity along the SvsLM and LvsM axes or to an intermediate axis of -20 and $+70$ deg, again compared with the mean differences between the ESO and the UNR subjects. Predictions are based on a relative difference of 1.5 between the adapted and the unadapted sensitivities. Both sets of predictions plot the change in color angles required to maintain a constant ratio of LvsM and SvsLM excitation relative to a standard observer.

subject age. For example, the silk merchants that we tested had the most clearly shifted hue settings (relative to the UNR students). Yet they differed from the ESO and the UNR students in being much older on average and in being all male. However, despite the large changes in visual sensitivity with age, color appearance remains comparatively stable across the life span, suggesting substantial compensation for these sensitivity changes.^{18,26,27} In our sample there was little evidence for a correlation between hue settings and age in the group of silk merchants. We also found no differences between the mean settings for males and females among the ESO or the UNR students (who were comparably

matched for gender and age but still differed significantly in their hue settings). And finally, the red-shift in the unique yellow settings for the silk merchants was again opposite to the direction predicted by their presumed higher average pigment densities. Thus neither gender nor age is likely to account for the pattern of color-appearance differences across our groups.

B. Environmental Factors

The lack of an obvious connection between color appearance and visual sensitivity has led some authors to suggest that the unique hues more directly reflect properties of the environment, which may or may not be represented explicitly in the physiological organization of the visual system. For example, a number of authors have suggested that the blue–yellow axis corresponds to the principal chromatic variation in natural daylight (owing to direct yellow sunlight versus indirect blue light from Rayleigh scattering in the sky.^{28–31}) By such accounts, human observers share a common color experience because they are exposed to a common pattern of stimulation in the terrestrial environment.

In this case, color differences among observers could arise because of differences in the specific environmental stimuli to which they have been exposed. Natural environments may vary widely in average color both because of differences in illumination and because the set of surfaces within the scene may have strong biases in their reflectance spectra.^{32,33} For example, in lush environments the average reflectance and illumination may both be strongly shifted toward “green” because of the presence of foliage.³⁴ Moreover, color in different environments can also show biases in the range of contrasts along different axes of color space. For example, in arid scenes color signals vary primarily along bluish–yellowish axes, whereas in scenes dominated by foliage the principal chromatic variation lies closer to the tritanopic axis.^{33,35,36}

One way that differences in the average color or the gamut of colors in scenes might alter unique-hue settings is through adaptation. For example, Yamauchi *et al.*³⁷ found long-lasting shifts in unique yellow after observers were exposed for extended periods to a change in the average color of their world. Similarly, contrast adaptation to the biases in the color contrasts of scenes can distort color appearance by selectively reducing sensitivity to the axes along which color varies in the image,³⁸ and contrast biases in natural color distributions are large and variable enough to induce scene-specific changes in the state of contrast adaptation.³³ For example, Fig. 9(b) shows the hue shifts predicted by a relative increase in sensitivity to the SvsLM axis. This would rotate the perceived color of all hue angles toward the SvsLM axis, and thus an observer adapted to this environment would need to rotate hue angles toward the LvsM axis in order to maintain the same pattern of excitation experienced under neutral adaptation.

However, a problem with such accounts is that they again have a general influence on color sensitivity and thus predict that changes across different unique hues should be correlated. Moreover, our control settings (for MW and SW) did not appear to vary with specific testing

environments, even though we often made these settings after being immersed in those environments for several hours. Thus if contrast adaptation does play a role, it is not of the rapid form we have examined in previous measures of color appearance,³⁹ or the environments we tested in were not in fact substantially different with regard to the adaptation effects they induced. Finally, the differences between the hue loci for the Indian and the U.S. groups are not consistent with a simple common shift in color space (which might result from differences in light adaptation) or compression along a particular axis (which might result from selective contrast adaptation). For example, a different choice of adapting axis (e.g., -20 deg) could provide a better fit to the observed shifts in red and yellow, but this would again predict the wrong changes in blue and green.

An alternative way that color vision might be altered by specific environments is through “adaptation” to the higher-order statistics of the color distributions. Yendrikhovskij⁴¹ found that the general location and number of basic color terms could be predicted from the local clusters of color signals in the color distributions of images, and he suggested that observers may learn color categories through experiencing these stimulus categories. Within different environments color clusters are likely to occupy different regions of color space. An observer exposed to images from these environments might therefore form different prototypes for the different color categories. A model like this has the advantage that the color clusters and thus the color categories could in principle vary independently, though it is not currently known how the fine structure of color distributions varies across environments or whether observers can in fact adjust to these.

C. Cultural Factors

Although the consistency of color terms across languages argues for a common basis for human color vision, this does not rule out influences that are specific to the individual’s culture, an influence that in some cases may be much more pronounced than for the groups that we tested.¹² For example, several authors have noted that even the basic color terms adopted by a language often have specific referents.^{9,10} Thus they may often be tied to the specific spectral characteristics of the referent. In that case, it is possible that the purest or even most unique form of a particular hue could be biased by knowledge about or experience with specific stimuli, particularly in highly specialized and color-rich environments such as a sari shop. In this regard, it should also be noted that the unique hues involve inherently subjective judgments and that it is possible to adopt different perceptual criteria for selecting them (e.g., by focusing on the points at which different secondary hues become visible). Such effects may be more likely to be manifest in regions of color space that change only gradually in hue as the physical spectrum is varied (e.g., in the region perceived as “green”). This account again has the advantage that it could modulate judgments of different colors in independent and potentially arbitrary ways, and we cannot exclude such criteria or cultural effects as the basis for the differences.

Clearly, the different factors that we have considered are not independent. For example, the distribution of colors characterizing the observer's environment will depend strongly on the colors available and utilized by their culture. Similarly, the environment and how observers live within it can affect their exposure to daylight, which can in turn markedly affect the rate and degree of age-related physiological changes in the visual system.^{25,27} Given the potential for variation in both the observers and their environments and the large range of unique hues exhibited across individuals, it is striking and surprising that the distributions of hue loci remain as stable as they do across such diverse populations. Thus again—whatever factors are shaping the unique hues—our results suggest that they are to a large extent common to many contexts.

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