COMMUNICATIONS AND COMMENTS

Variability in Unique Hue Selection: A Surprising Phenomenon

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Abstract: Data from ten different experiments involving nearly 600 observers of determination of unique hues are compared. Six experiments involve determination using spectral lights; two use desaturated monitor colors, and the remaining two use color chip sets. Except for unique green, color chips result in narrower ranges of results than spectral lights. Unique green has a surprisingly large range of variation in both spectral light and color chip experiments, followed by red. Comparison of spectral light data indicates that one observer's unique blue can be another's unique green and vice versa, and the same for yellow and green. This finding raises significant questions for color appearance and color space/difference models, as well as philosophy of color. Col Res Appl, 29, 158–162, 2004; Published online in Wiley InterScience (www.interscience.wiley.com). DOI 10.1002/col.10237

Key words: color perception; unique hues

INTRODUCTION

Since the early eighteenth century hue circles involving spectral and extraspectral hues have been arranged in implicit or explicit continuous hue circles.[1] It has been of interest for a long time if among them there are hues with special properties. During the Renaissance period painters became aware that it is in principle possible to mix all other hues (if not at the same level of saturation) with three pigments, a yellow, a red and a blue. Glisson in the seventeenth century built a color specification system based on yellow, red, blue and gray scales. Some of the developers of hue circles and three-dimensional color order systems, such as Schiffermüller, Mayer and Lambert, began to describe their primary colorants as pure, such as pure red, neither with a yellowish nor a bluish cast. The hues from these pigments could not be matched with pigments resulting in intermediate hues while all other hues could be matched with binary combinations of the three primaries. In the late nineteenth century Ewald Hering described the results of his introspective psychological research as follows: "This description [of a hue circle] makes it clear that there are four outstanding loci in the series of hues . . . primary yellow and primary blue. Likewise we can name, third, the red and, fourth, the green that are neither bluish nor yellowish primary red and primary green."[2] Thus, he had concluded that there are in fact four primary or unique hue perceptions: aside from yellow, red and blue there is also green. For people with object color matching experience this is at first glance a strange claim because they know that most green colorations are obtained from yellow and blue colorants. However, just as it is possible to find a red hue that is neither yellowish nor bluish one can find a green hue that is neither yellowish nor bluish. It is not possible, however, to find, say, an orange hue that has neither a purplish nor a chartreuse component, and certainly not one that is neither yellowish nor reddish. We clearly discern in orange hues a yellowish and a reddish component.

As a constant hue page of the Munsell system shows, unique (and all other) hues can appear at many levels of lightness and chroma. It is evident that they occupy a special place in human color perception. As such they have been of great interest to vision and color scientists. They form the chromatic basis of the perceptual opponent color diagram, and much speculation has gone and is continuing to go into colorimetric or neural models for the generation of unique hue perception. In color space formulas such as CIELAB average unique hues do not fall on a^* and b^* axes. In fact it is impossible to linearly transform color-matching functions so that all four average unique hues fall on the axes, without seriously distorting constant chroma contours.[1] Similarly, there are no cone function based chromatic diagrams that make average unique hues fall on their axes without introducing strong distortion of contrast contours. Various other attempts at model building for unique hues have also failed.[3–5] It is fair to state that how the brain/mind generates unique hue perceptions remains a complete mystery.

During the last century many perceptual experiments to determine the location of unique hues have been made using many different experimental paradigms. The results have usually been expressed in the form of means and variability statistics. Means and variability have varied significantly between experiments without clear reasons. Experimental procedures range from sub-second exposures to spectral lights to indefinite exposures to arrays of color chips. The Swedish Natural Color System[6] is based on four unique hues deemed average representing the axes of the chromatic plane, and it is often used as basis of orientation in color appearance models. Constant hue lines in the CIE chromaticity diagram are generally curved because of nonlinear signal compression. For this reason for a given observer the dominant wavelengths of unique hues vary (within relatively narrow limits) as a function of saturation or chroma in case of video displays as well as color chips. Adaptation effects can be expected to make a difference in choice of unique hues when comparing sub-second and indefinite exposures. Similarly, surround conditions and illumination (in case of color chips) can be expected to affect the results. Variation in unique hue location as a function of illumination level has also been reported, presumably involving the Bezold-Brücke effect.[7,8] Unique hues have not been found to be related to age of observer[9,10] and to remain essentially constant through the life period.[9] On the other hand, wearing of colored spectacles for an extensive time period was found to cause distinct shifts in the location of unique yellow, a situation that reverses when no longer wearing the spectacles.[11]

This communication reports an analysis of several experimental sets of unique hue determination and its surprising results. Studies to determine unique hues have involved optical equipment creating the stimuli with spectral or with filtered light. Some studies employed video displays and others color chips, such as Munsell chips or specially produced chips at narrower hue intervals. All observers have been found to be color normal. The data sets included are briefly described as follows:

1. Ayama *et al.* (A)[7]: Ayama and co-workers report their own experiments (two observers) and those of eleven previous articles by other authors. All data relate to spectral lights, only data at or near 100 td of retinal illumination are included. Total number of observers: 19.
2. Schefrin and Werner (S)[9]: Spectral lights of 7.1 cd/m^2 projected onto rear-projection screen, 0.95° field, 50 cm distance, 1 sec exposure, surround: dim white (5500 K) light; unique hue wavelengths from logistics function; 50 dark adapted observers (25 F, 25 M), ages 13–74.
3. Nerger *et al.* (N)[12]: Foveal observations with 2° field only, spectral light, dark surround, 1 sec exposure at 250 Td, 4 dark adapted female observers (ages 23–35), forced binary decision.
4. Jordan and Mollon (JM)[13]: Three-channel Maxwellian view colorimeter, circular field, 9.6 deg with central 2.9 deg occluded, 2 sec exposure against black field, 20 td stimulus luminance, 97 male Caucasians, ages 19–30.
5. Volbrecht *et al.* (V)[14]: Spectral light in 1° field for unique green only; 1 sec exposure at 250 td; 5500 K white background at 250 Td data only, 3 min adaptation to background, 1 sec exposure; forced binary decision; 50 female and 50 male observers (ages 18–36).

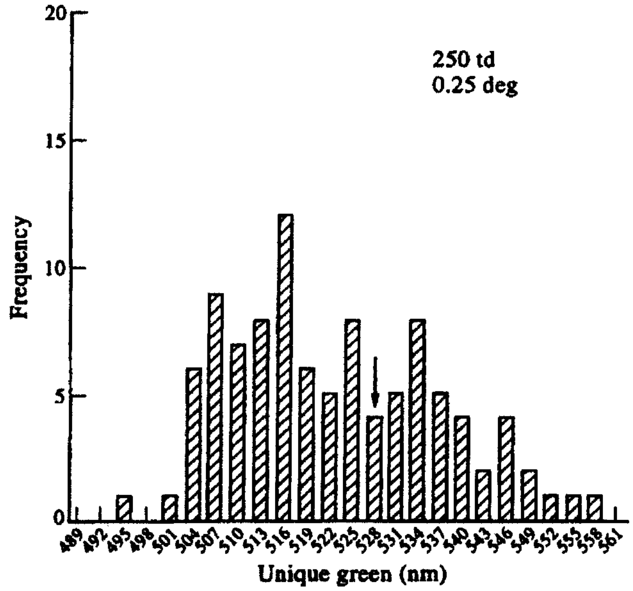

FIG. 1. Typical example of the distribution by spectral wavelength of unique green hue choices from Volbrecht *et al.,* Ref. 14.

6. Pridmore (P)[8]: Monochromatic spectral, Wratten filtered extraspectral lights; 4° field, D6500 surround data only, up to 10 sec exposure at 10 cd/m^2 only, wavelength adjustment; 7 observers (4 male, 3 female), ages 26–56.
7. Webster *et al.* I (W I)[3]: Monitor stimuli at 30 cd/m^2, 2° square field on neutral gray background at 30 cd/m^2 of illuminant C chromaticity; monitor at 250 cm distance in dark room, 280 ms exposure; 51 observers (45 students).
8. Kuehni (K)[10]: Munsell color chip series in hue sequence (identification obscured), viewed in light booth with artificial D7500 daylight (filtered fluorescent), on neutral gray cardboard of Y = 75, unlimited exposure (usually approximately 15 sec per color); 22 female and 18 male observers (ages 21–61), observers identified chip resulting in unique hue (UH) experience or position of UH between two chips. In a second, unpublished experiment 36 observers (students) assessed their unique green only in a comparable experimental set-up.
9. Webster *et al.* II (W II A and B)[15]: A) Hue palettes of 24 hues each produced on a computer printer, circular, 0.75 inch diameter, on bright white paper; shaded natural outdoor daylight data only, observers: 71 students from India (ages 17–23) and 110 students from USA (ages 18–64) only. B) Monitor stimuli as described under data set 6, 0.5 sec exposure, 105 student observers from India and Nevada only, forced binary choice.

In case of spectral lights results are expressed in terms of wavelength, in case of monitor lights or light chips in terms of dominant wavelengths. Hue angle data of the W I and W II A and B data have been converted to dominant wavelengths. In some cases observers made repeated determinations of their UHs. Some observers are able to repeat their results quite closely, others with an increased degree of

TABLE I. Experimental unique hue variability in 10 sets of data

Data set	Observers	Unique yellow Mean nm	Std. dev. nm	Range nm	Range nm	Unique green Mean nm	Std. dev. nm	Range nm	Range nm
Ayama	19	574	9.6	544–594	50	506	10.0	490–535	45
Schefrin	50	577	4.6	568–589	21	509	11.9	488–536	48
Nerger	4	575	1.7	573–577	4	510	9.0	502–518	16
Jordan and Mollon	97	ND				512	13.3	487–557	70
Volbrecht	100	ND				522	13.5	498–555	57
Pridmore	7	578	4.8	573–587	14	517	9.1	509–535	26
Webster I	51	576	2.0	572–580	6	544	16.0	491–565	74
Kuehnl	40 (76 UG)	578		575–581	6	505	15.6	488–555	67
Webster IIA	175	580	1.4	575–583	8	540	13.3	497–566	69
Webster IIB	105	576	1.7	571–581	10	539	20.8	493–567	74

variability. For most data sets the results represent the mean of five tests per observer. The distribution of mean UHs of highly reliable and less reliable observers is very similar, however.[3] Figure 1 illustrates a typical distribution for unique green (UG) selection of 50 observers.[14]

COMPARISON OF EXPERIMENTAL DATA

In the past unique hues have sometimes been interpreted as resulting from activity of the opponent color system where one of the systems is in equilibrium. In this manner unique hues can be defined for the CIE standard observers and they (UB, UG and UY) differ by about 5 nm. As yet no data have been reported that compare individual color matching functions (CMF) and the related UH of given observers, but estimates indicate that the UH range is much larger than one should expect from variation in CMF.[7] Nevertheless, the general tendency in color science and color technology has been to assume that a mean is a meaningful representation of UH variation.

Where information is available the unique hue data used in this comparison are numerically and graphically represented by mean, range and 1 standard deviation as shown in Table I and Figs. 2–4.

RESULTS AND DISCUSSION

The results can be summarized by hue as follows:

Unique yellow: with exception of the A data variability is quite narrow. There is no noticeable difference between desaturated spectral and object color (K and W IIA) data. A large excursion toward shorter wavelengths is noticeable in the A data.

Desaturated monitor and object color data have equally large ranges of a surprising 70 nm. The means of K and W IIA data differ significantly despite a similar range. The large panel spectral data (V) also show a nearly 60 nm range.

Unique blue: object color ranges are significantly narrower than spectral color ranges. Surprising is the large excursion toward shorter wavelengths of one set of monitor color data (W IIB).

Unique red: there are significantly less data here because of

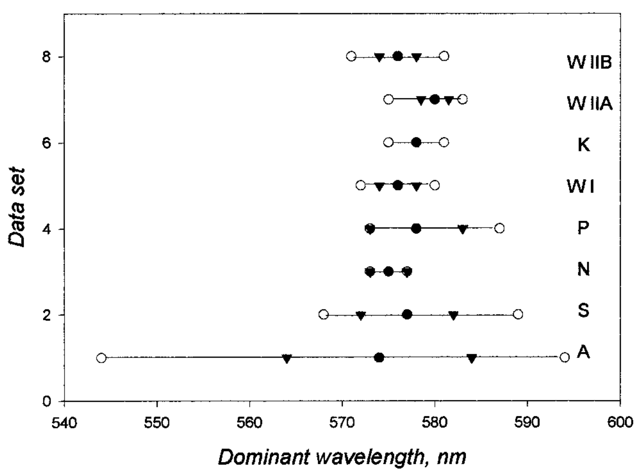

FIG. 2. Spectral or dominant wavelength of unique yellow selections from eight different experiments. The ranges are shown with open circles, the mean with a filled circle and the one standard deviation positions with triangles.

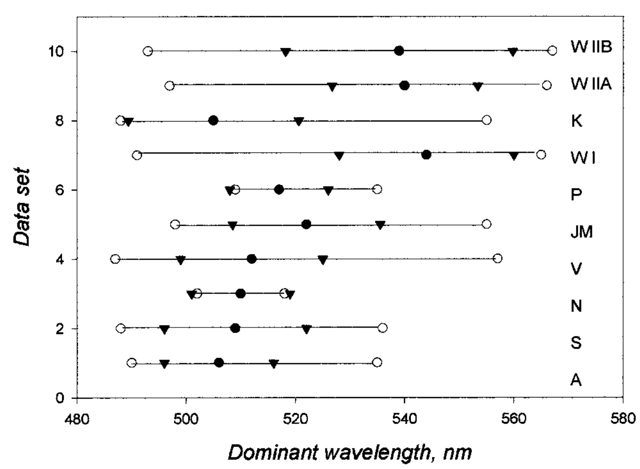

FIG. 3. Spectral or dominant wavelength of unique green selections from ten different experiments. The ranges are shown with open circles, the mean with a filled central circle and the one standard deviation positions with triangles.

Unique blue				Unique red			
Mean nm	Std. dev. nm	Range nm	Range nm	Mean nm	Std. dev. nm	Range nm	Range nm
474	6.7	465–489	25	497.5 c	2 obs. only		
480	7.0	465–495	30	ND			
471	6.6	461–475	14	ND			
ND				ND			
ND				ND			
479	11.6	458–495	37	494.6 c	0.7	493.2 c–495.5 c	2.3
477	4.2	467–485	18	EOS			
477		475–481	6	EOS		605–496 c	
479	2.3	474–485	11	605	10.3	596–700	
472	7.4	431–486	55	EOS			

ND indicates no data; EOS indicates end of spectrum; wavelength values followed by a c indicates complementary wavelength.

the overlap of unique hue results into the nonspectral color region. The ranges of spectral and filtered spectral colors are somewhat larger than those of object colors (the latter range falls within the former).

It is of interest to demonstrate the approximate object color ranges for unique hues in the perceptual Munsell chromatic diagram. For this purpose the dominant wavelengths of the range ends have been translated into Munsell hues using standard colorimetric tables and plots of Munsell colors in the CIE chromaticity diagram. Figure 5 illustrates approximate object color ranges for the four unique hues. The smaller yellow and blue ranges are approximately opposite, as are the red and green ranges. The green range surprises with its large range, spanning over some 10 Munsell 40 hues (25%). The unique hue ranges span more than 65% of the total range of the hue circle.

If the spectral light data of the experiments included here are taken as comparable there are overlaps in the maximal ranges of blue, green, and yellow: B 458–495 nm; G 490–555 nm; Y 544–594 nm. The implicit meaning is that one observer's unique blue is another observer's unique green and vice versa. The same applies at the green–yellow interface. This is a startling finding raising important questions.

To date there is no physiological model that can explain these large individual variations. Efforts to explain them on basis of variation in color matching functions have failed, as have other attempts, as mentioned.

Among the conclusions is that it is not justified, certainly not in case of green and red, to assume that a mean UH can be considered representative of humans. This raises questions about the degree of validity of color appearance models. While no explicit data have yet been published the impression is that for individual observers UH are not rotated one way or the other against the mean in a simple

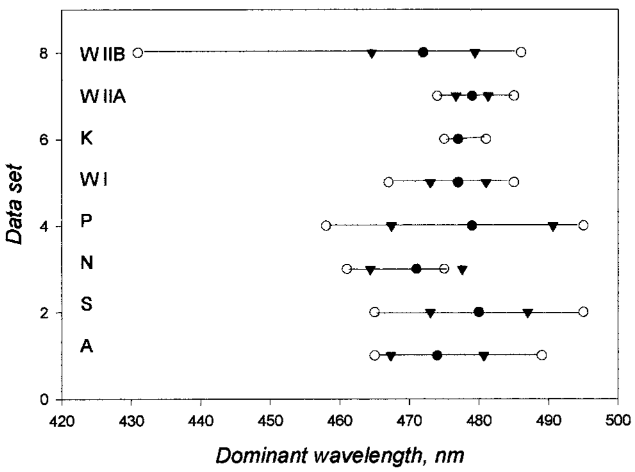

FIG. 4. Spectral or dominant wavelength of unique blue selections from eight different experiments. The ranges are shown with open circles, the mean with a filled central circle and the one standard deviation positions with triangles.

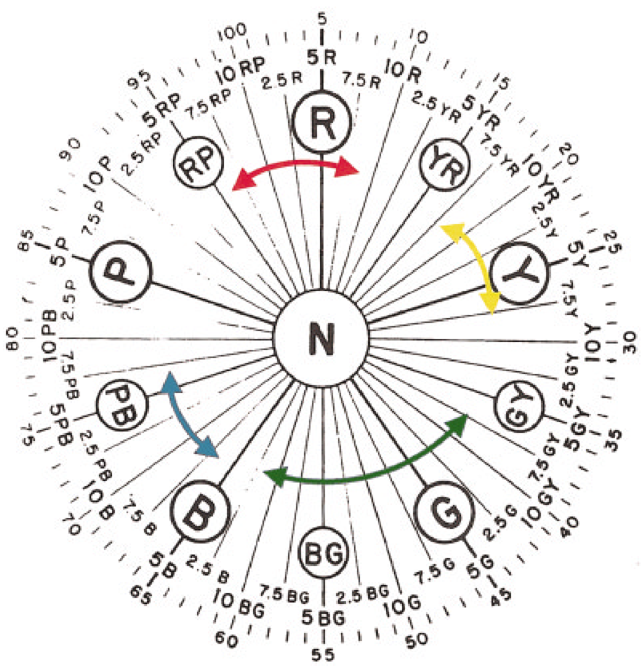

FIG. 5. Munsell system perceptual chromatic diagram with circle segments indicating the approximate unique hue ranges based on viewing object color chip ranges.

manner. It means that the perceptual distances between unique hues may vary to a smaller or larger extent by observer. This raises significant questions about color space scaling and color difference evaluation. If one observer experiences a pair of samples as reddish blue while an other sees them as near unique green judgments cannot be expected to agree. In a given quadrant one observer may be significantly more or less sensitive to hue differences than another.

The pervasive nature of green in the natural environment of many people, and certainly for our early ancestors, may offer an explanation for the large variability in UG. Perhaps different spectral signatures have been set for UG as a result of different experiences of early ancestor groups and are now genetically fixed or we may carry a kind of neural network in our brains that fixes unique hues as a result of infant experiences. It will be interesting to attempt to find the answer.

Most philosophers maintain a position of placing colors in objects.[16] The finding of large individual, repeatable variation in at least two of the four unique hues represents a serious obstacle to such a position. It appears more likely that the brain/mind constructs images of the world rather than reconstructing them from nature.

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