

Unique-hue stimulus selection using Munsell color chips

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Presented are intra- and inter-observer variability data comparing the unique-hue (UH) selections of sets of males and females, using two different visual experimental procedures incorporating Munsell color chips of varying hue but identical chroma and value. Although 34 of the 40 Munsell hue chips were selected by at least one observer as a UH, selections were generally repeatable. In addition, intra-observer variability represented approximately 15% of inter-observer variability. Also, when only three consecutive Munsell chips were viewed at a time, females showed significantly larger intra-observer variability than males, especially when making unique green selections. However, variability in UH selections was statistically insignificant between males and females when all Munsell chips were viewed simultaneously. No correlation was found between UH selections or intra-observer variability and hue ordering ability. © 2007 Optical Society of America

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1. INTRODUCTION

Humans are autonomous agents. Our feelings and sensory experiences are private, and we can describe them to others only in simplistic, metaphorical terms. This is particularly the case when attempting to describe the nature of colors, tastes, smells, and sounds, or of feelings. In an absolute sense these experiences are indescribable: We do not know how to phrase an absolute description of, say, red. We can offer only a description in relative terms: How one object we agree on as red compares to another. The implicit assumption is that we have the same color experience when looking at a given object.

An individually varying response to color stimuli was noticed as long ago as the second half of the 19th century when studies of the appearance of the spectrum led to comparison of the wavelengths individuals selected as representing for them the pure yellow, green, blue, and red hues, or the spectral ranges representing one of these hues. Many observers could not find the pure red in the spectrum. In the late 19th century the physiologist Ewald Hering offered an experiential theory of color vision in considerable contrast to the psychophysical theory that Maxwell and Helmholtz developed, based on Palmer and Young's suggestions of three cone types in our visual system [1,2]. Hering posited three perceptual opponent pairs of primary colors (*Urfarben*): white and black, yellow and blue, and green and red, in terms of which any color experience can be described. The hues of these colors are usually referred to as unique hues (UHs). Hering himself at first identified the UHs with four wavelengths of light, 470, 500, 570, and an extra-spectral red, an identification he later abandoned [3].

Since that time a number of studies have been performed to identify the location of UHs in the psychophysical color solid. UH definitions are utilized in modeling

uniform color space as well as color appearance models (CAM) that incorporate UHs to predict a correlate of hue quadrature and hue composition [4]. Investigations have been performed in the intervening years with growing sophistication, involving adaptation control, very short exposure to the stimulus, staircase methods of honing in on the stimulus experienced as having a UH, etc. [5–13]. In some experiments, more natural methods involving color chips have also been applied [11,14]. Kuehni recently prepared a meta-analysis of a number of these investigations [15]. The results showed a surprisingly large inter-observer variability in stimuli selected as representing the UHs, demonstrating that the visual experience of individuals varies considerably when viewing a given physically defined stimulus under controlled conditions. The cause of the variability found in the data is as yet unknown. Wuerger *et al.* recently confirmed that the lateral geniculate nucleus (LGN) neurons tuned to $L-M$ and $S-(L+M)$ are not the basis of UH perception [16]. They stipulate that three higher-order postreceptoral chromatic cone input mechanisms are required to account for the UHs [one for unique red (uR), one for unique green (uG), and one for both unique yellow (uY) and blue (uB)]. Results of various studies indicate that in given circumstances the hues consciously experienced from given stimuli can vary widely and presumably are determined by high-level neural mechanisms [17,18]. The output of such mechanisms may reflect in part the past visual experiences of the observer [16,17]. In the work reported here, consisting in three separate experiments, we test the following three hypotheses pertaining to the UH selection of object colors in relatively natural viewing environments in order to test factors leading to variability in UH stimuli selection:

- (1) Restricting the visual scene to a small number of

stimuli with stepwise changes in hue will result in a statistically smaller inter-observer variability in UH selections (experiments I and III, described below).

(2) Intra-observer variability (individual repeatability) in UH selections is small in comparison with inter-observer variability (all three experiments).

(3) Assuming a causal relationship between UH stimulus choice and the ability to sequentially order a series of samples with small hue differences, the average angles between UH stimulus choices in an approximately uniform perceptual space will influence hue ordering and discrimination ability (experiment II).

In addition, we assessed the individual observer “signatures” of UH stimulus selections to gain insight into possible patterns in selecting the four UHs.

2. EXPERIMENT

A. General

Three experiments were conducted at separate times and with different sets of observers, all with essentially the same basic test method (described below). Experiment I was an initial study to test the effect of significantly restricting the viewing of Munsell chips when selecting UHs arranged in a hue circle. Experiment II was identical to experiment I except that no viewing restriction was applied and the errors in hue ordering, as determined using a modification of the Farnsworth–Munsell 100 Hue Test (FM100) [19], were compared to the hue angles between UH selections for each observer. Experiment III was a repeat of experiment I with a larger observer set in order to substantiate some of the surprising data obtained for females in the previous experiment.

B. Test Method and Experiments

The test method was devised to enable color normal observers to make UH selections under comparatively natural, but controlled, conditions using an ordered set of 40 color chips, without time limitation. The color chips selected for the purpose represent a complete hue circle at (approximately) constant luminous reflectance (Munsell value 6) and constant Munsell chroma (Munsell chroma 8). The chips were mounted uniformly and in Munsell hue

sequence on a large circular rotating tray, as shown in Fig. 1(a). The tray was painted standard neutral gray (N7.25) and placed in a Macbeth Spectralight III light box (also painted to neutral gray, N7), and the samples were diffusely illuminated with a calibrated filtered incandescent daylight simulator (6533 K, 1424 lx). The daylight simulator was used throughout and was allowed to equilibrate for at least 20 min prior to commencement of all visual judgments. The spectral power distribution of the light source was measured during the testing. The location of the Munsell chips in a CIE a^* , b^* diagram (2° standard observer, illuminant D65) is shown in Fig. 2. All extraneous light was eliminated. Observers were adapted to the visual scene for at least 2 min prior to commencement of the experiment, during which time the test method was explained. Chips were labeled numerically (different for each experiment) by a number from 1 to 40 in a way that prevented biasing observer judgments. In all three experiments, observers determined their UH choices two times, with at least 24 h of time between the judgments.

In experiments I and III a stationary mask, painted in standard neutral gray (N7.25), was mounted over the chip circle so that the observer could view only a hue range comprising three chips at any given time, as shown in Fig. 1(b). Each observer was allowed to move the rotating tray underneath the mask in order to make a UH selection. The mask was placed randomly at the beginning of the test. Observers were instructed to select the yellow chip that appeared neither greenish nor reddish, and comparably for the other three UHs. The code numbers for each selection were recorded.

In experiment II, a comparison was made between UH stimulus selections and hue ordering errors recorded using a nonstandard test that employed all the FM100 test caps for assessment of just noticeable differences. In this test the FM100 caps, identified by a randomized sequential number, were randomly placed on the rotating tray. After visual adaptation to the scene for at least 2 min, the observer was asked to place all the caps in correct hue sequence in a circle, using a rotating tray similar to the one employed for the UH selections (Fig. 1). Then the hue location for each transposition error was recorded for each observer in the conventional manner, and the errors were

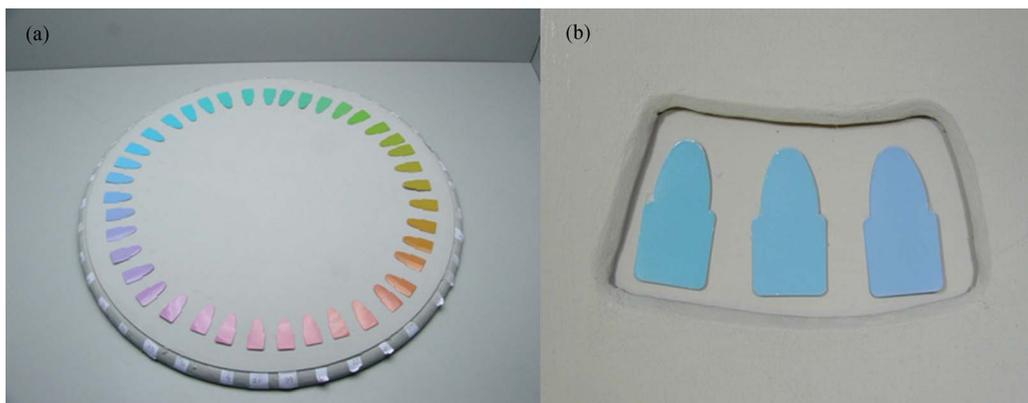


Fig. 1. (Color online) Rotating tray exhibiting the 40 Munsell chips of value 6 and chroma 8 in the standard viewing booth, (a) without and (b) with a stationary mask (close up view).

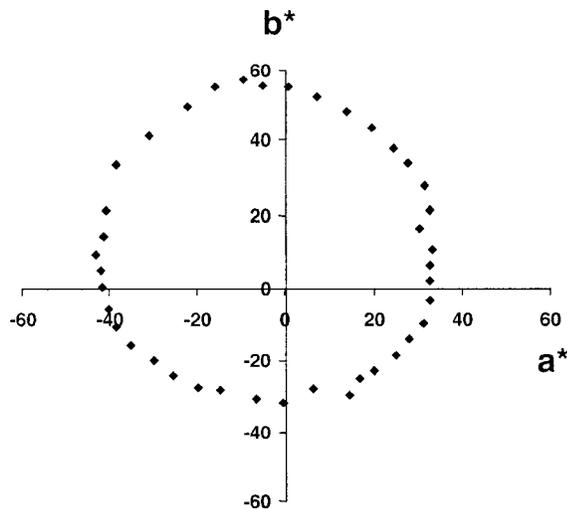


Fig. 2. Plot of the 40 Munsell chips in the CIE a^* , b^* plane using D_{65} daylight simulator and CIE 2° standard observer.

compared to their UH selections to determine possible correlations.

C. Observers

A total of 102 observers participated in the three experiments. No observer participated in more than one experiment. Almost all observers were university students between 18 and 49 years of age and from a variety of ethnic extractions. The color vision of observers was tested using the Ishihara pseudoisochromatic plates test [20] or the Neitz color vision test [21]. All observers selected for the study had normal trichromatic vision. All observers were naive in regard to the purposes of the experiments. Table 1 summarizes each of the experiments regarding the number of observers, the distribution by gender, the number of observations, and the viewing conditions employed.

D. Data Analysis

Similar to other published data pertaining to UH experiments, our data in some cases indicate nonnormal distributions. Hence, in all cases, tests for significance were done using one of two nonparametric tests, Wilcoxon and Mann–Whitney.

3. RESULTS AND DISCUSSION

A. Intra-Observer Variability of UH Stimulus Selections Without the Mask

A total of 102 observers performed the UH stimulus selection test more than once: 69 observers a total of four times (two times under two different conditions), and 33 observers two times under one condition. To determine intra-observer variability, the data from experiments I–III were combined. The first analysis was carried out using only

Table 2. Intra-Observer Variability of UH Stimulus Choices in Munsell 40 Hue Grades between Two Assessments for All Observers without the Mask (Experiments I–III Combined)

Colors	Observer Group	Mean Variability	Standard Deviation	Range
Yellow	Females	0.63	0.59	0–2
	Males	0.60	0.74	0–2
	All observers	0.62	0.66	0–2
Green	Females	0.83	0.88	0–4
	Males	1.27	1.25	0–4
	All observers	1.04	1.09	0–4
Blue	Females	0.72	0.79	0–3
	Males	0.89	0.88	0–4
	All observers	0.80	0.83	0–4
Red	Females	0.93	1.00	0–4
	Males	1.15	1.11	0–4
	All observers	1.03	1.06	0–4
All colors	Females	3.11	1.77	0–7
	Males	3.92	2.07	0–9
	All observers	3.49	1.95	0–9

the data obtained for UH stimulus selections without a mask (i.e., all the Munsell chips were visible throughout the entire experiment, as shown in Fig. 1(a)). The intention was to see whether there is a significant difference in intra-observer variability of UH stimulus selection without a mask according to gender. The number of Munsell grades by which the judgments differed for the selection of the same UH between observations was added by observer and totaled by sex. Summary data of the range and mean variability in the number of grades for each UH stimulus choice and for the combined data are given in Table 2.

Since the selection of UH stimuli does not usually follow a normal distribution, a nonparametric Mann–Whitney statistical test was conducted in order to confirm the statistical significance of results for each UH at the 95% confidence level, as shown in Table 3.

As summarized in Table 3, variations in UH stimulus choices were found to be statistically insignificant at the 95% confidence level between males and females. Under the test conditions used, the average observer repeated her/his UH stimulus choices with a variability of approximately one Munsell 40 hue step per hue. In the total group there were three females and two males with zero variability between UH stimulus choices in separate observations for all four UHs. The results indicate that UH stimulus choices are on average well repeatable.

Table 1. Summary of Observers Used in Each Experiment and Type of Viewing Method

Experiment	Males	Females	Total Observers	Number of Observations	Conditions
I	9	10	19	4	With and without mask
II	13	20	33	2	Without mask
III	26	24	50	4	With and without mask

Table 3. Summary Data of a Mann–Whitney Test for Each UH Stimulus Choice Variation between Females and Males (No Mask)

Color	Mann–Whitney Test Statistics	<i>P</i> -Value
Yellow	2855.5	0.58
Green	2560.5	0.12
Blue	2637.5	0.30
Red	2563.0	0.33
Total	2491.5	0.05

B. Intra-Observer Variability of UH Stimulus Selections with the Mask

To determine the effect of a mask reducing the number of chips that can be viewed at any given time to three [Fig. 1(b)], 35 males and 34 females selected their UH chip choices two times, each in the presence and absence of the mask. The results for males and females are summarized in Table 4, which show that intra-observer variability of females is significantly increased when the mask is used, while the intra-observer variability remains approximately the same for males. Table 4 shows that the range in intra-observer variability for the females in the uG stimulus selection doubled when the mask was used.

Table 5 shows that the difference in selections made by females with and without the mask is due mostly to a significant difference for the uG choice. No statistically significant difference was found for the other UH selections. Table 5 also shows the relevant statistics for males by UH stimuli selected.

There is an interesting difference in repeatability between males and females in respect to the restriction of the visual field by the mask. For as yet unexplained reasons, the ability to see more than three chips at a time appears necessary for females to make highly repeatable choices of uG and uB stimuli. For instance, one female observer had zero changes in her UH stimulus choices without the mask and a total of five step changes with the mask. All but one female observer showed improved repeatability without the mask, while the result was random in the case of males.

Table 5. Summary Data for the Wilcoxon Analysis of Intra-Observer Variability Differences between UH Stimulus Selection with and without the Mask for Females and Males

UH Selections	Females		Males	
	Wilcoxon Statistics	<i>P</i> -Value	Wilcoxon Statistics	<i>P</i> -Value
Yellow	111	0.60	94.0	0.68
Green	53	0.01	242.0	0.86
Blue	62	0.10	236.5	0.68
Red	108	0.60	179.5	0.83
Total	105	0.04	180.0	0.61

The direction of change in UH stimuli selection (without the mask) between repetitions was analyzed for all 102 observers. No general trend was found for the shifts in choice between the first and the repeat test, although the shift ranges for uY and uB were found to be smaller than those for uG and uR, indicating that observers were more consistent in their selection of uY and uB than for uG and uR. The random hue shifts are indicative of the absence of a training effect and that averaging the repeat selections is appropriate for data analysis.

C. Inter-Observer Variability

Figure 3 shows plots of the frequency of mean Munsell chip UH selections (without the mask) for all 102 observers according to gender. Of the 40 chips of the Munsell hue circle used in the experiments, a total of 34 (or 85%) were selected as a UH choice by at least one observer in one experiment. Figure 4 plots the means and ranges for all 102 observers in the Munsell hue diagram based on the average UH angle calculated. The ranges of all individual choices are in good agreement with ranges reported for investigations involving spectral and monitor-based lights [16]. In a full Munsell hue circle, each chip is separated from the next by 9°. The average UH selection by all observers between two repetitions, expressed in angles, was calculated for each hue. Each unique hue

Table 4. Intra-Observer Variability of UH Stimulus Selections for 34 Females and 35 Males

Colors	Observers	Without Mask			With Mask		
		Mean	Standard Deviation	Range	Mean	Standard Deviation	Range
Yellow	Females	0.71	0.58	0–2	0.79	0.69	0–3
	Males	0.66	0.76	0–2	0.74	0.66	0–3
Green	Females	0.71	0.68	0–2	1.29	1.14	0–4
	Males	1.37	1.33	0–4	1.34	1.21	0–5
Blue	Females	0.79	0.81	0–3	1.12	0.88	0–3
	Males	1.00	0.94	0–4	0.91	0.82	0–3
Red	Females	1.00	1.07	0–4	0.94	1.18	0–6
	Males	1.11	1.13	0–4	1.20	1.30	0–5
Total	Females	3.21	1.53	0–6	4.15	1.94	0–9
	Males	4.20	2.06	1–9	4.14	2.08	1–9
	All observers	3.68	1.87	0–9	4.17	2.00	0–9

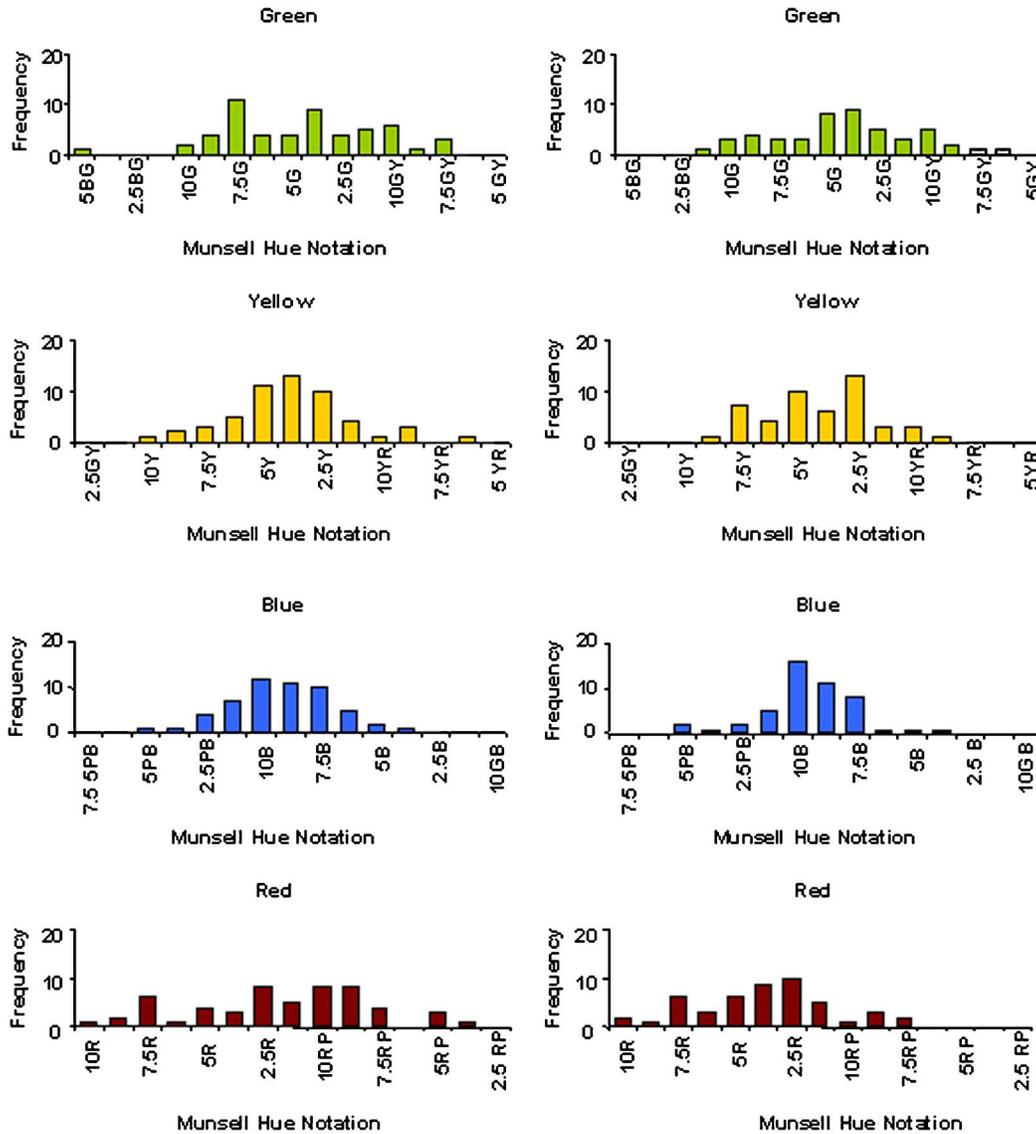


Fig. 3. (Color online) Frequency of mean selection of Munsell chips by 54 females and 48 males without the mask.

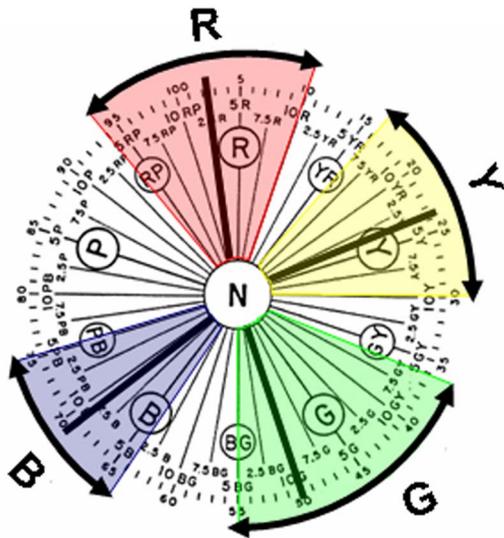


Fig. 4. (Color online) Munsell psychological hue diagram with the mean unique hues of all 102 observers (solid lines) and the corresponding ranges based on mean observer data.

range was then divided by 9 to obtain the total inter-observer variability steps. Total inter-observer variability was uY (5.5 grades), uR (6.5 grades), uB (4.5 grades), and uG (7.5 grades).

D. Intra-Observer Variability as a Percentage of Inter-Observer Variability

In this study the average intra-observer variability for each hue was calculated and the mean values are shown in Table 2. For each hue, the percentage of intra-observer variability relative to inter-observer variability was calculated by dividing the mean steps in variation for all observers, shown in Table 2, by the total inter-observer variation for each hue given in Subsection 3.C. The percentage of intra- to inter-observer variability was 11.27% (uY), 17.78% (uB), 15.85% (uR), and 13.87% (uG), with an average total variability of approximately 15%. Hence, approximately 85% of the inter-observer variability in UH stimuli selection is due to inter-observer differences in choices, demonstrating that variability between observers

is by far the major component of variability in the selection of UH stimuli.

E. UH Stimulus Choice “Signatures”

One might expect inter-observer variability to express itself by comparably rotated choices for the four UHs around the hue circle. However, this is not the case. Varying individual signatures of six observers in a modified cone-opponent diagram have been shown by Webster *et al.* [10] Angles between choices can be expressed in such stimulus-based chromatic diagrams. We believe that angles in the Munsell psychological UH diagram are more relevant in our case. Table 6 shows summary data of the distances in angles between selected UH samples in the Munsell hue diagram for average choices of all 102 observers.

The mean angles between UH choices between males and females are similar. However, females have larger intervals between uG and uB, whereas for males the uR-to-uY and uY-to-uG intervals are the largest.

Three examples of the resulting UH stimulus “signatures” are shown in Figs. 5(a)–5(c). In Fig. 5(a) there are only 5 hue steps between the uB and uG choices, but 12 steps between the uG and uY choices. Figure 5(b) shows a signature with more nearly diagonal lines connecting the opposing UHs and similar intervals. Figure 5(c) has a difference of 14 hue steps between uB and uG but only 5 steps between uG and uY. It is evident that individual (and well-repeatable) signatures of UH choices vary widely in the color normal population. A theory of UH generation must account for this kind of inter-observer variability.

Wuerger *et al.* analyzed UH stimulus choice data in the DKL color stimulus space [22], the axes of which represent physiologically (in macaque monkeys) measured opponent color properties of neurons in the LGN that receive input from the three cone types [16]. Based on average axes for their 18 observers, they propose a compensatory model for cone data input into the UH generation mechanism, with the LGN cells an intermediary way station. Because of the near-diagonal line connecting the mean lines in the chromatic diagram, they concluded that three chromatic mechanisms are required for the generation of the four UHs, uY and uB being generated by the same mechanism. In the case of the perception of uR and uG, separate mechanisms are deemed necessary because in the chromatic plane the mean semiaxes form a sharply obtuse angle of approximately 35°.

When plotting the average UH stimulus selections for our 102 observers in the Webster *et al.* version of the DKL chromatic diagram (a modified version of the McLeod–Boynton diagram) [10], angles for the average uY and uB choices (via green) between the lines from the origin (2° observer, illuminant C) to the position of the Munsell chip in the diagram have a mean of 173.1°, with a standard deviation (SD) of 8.3°. Hence, the mean angle for our data is less than a diagonal with a relatively large range. Malkoc *et al.* reported in the same diagram that we used here an even smaller angle between mean uY and uB stimuli (via green) of 167.6° for 73 observers (163.5° for the “21 subjects who set the hues most consistently”) [12].

In addition, we have calculated, in the general manner of Webster *et al.* [10], the nonparametric Spearman rank correlation between the angles of UH stimulus choices in the Munsell hue diagram. The results are shown in Table 7. Similar to the results of Webster *et al.*, no significant correlation was found between any pairs of UHs, indicating that three mechanisms are insufficient to describe all four UH selection processes for individual observers.

F. Relationship between UH Stimulus Choice and Hue Ordering Ability

We hypothesized that in the case of a causal relationship between hue perception and hue ordering ability, the size of the angles between UH stimulus choices (see Subsection 3.E) would correlate with hue ordering ability. Hue ordering first requires the existence of conscious hue percepts that are ordered according to the progression of dominant and complementary wavelengths. If the hypothesis is correct, the relatively small angle between uY and uG for observer FI10 [Fig. 5(c)], for instance, would likely result in this observer making errors when attempting to order samples with small perceptual differences in hue in the yellow–green region of the space. On the other hand, according to the hypothesis, the large interval for this observer between uB and uG stimuli would result in fewer errors in hue discrimination in the blue–green region. To test the hypothesis, the hue ordering performance of a subset of 33 observers (20 females and 13 males) was determined in a modified FM100 hue test. This test comprises 85 closely spaced samples in a complete hue circle with near-constant lightness and chroma. The FM100 test is routinely used to test an individual’s ability to ordinally order colored chips with small hue differences according to hue [19]. Interestingly, no correlation between hue ordering errors and UH selections was found. That is, hue ordering errors were not concentrated

Table 6. Mean Angles between UH Stimuli Selections, Ranges, and Intervals of the Ranges Expressed in Degrees in the Munsell UH Diagram for Females and Males for Average Results of all 102 Observers, without the Mask

Statistics	uY to uG		uG to uB		uB to uR		uR to uY	
	Females	Males	Females	Males	Females	Males	Females	Males
Mean (deg)	73.9	72.5	89.0	91.3	117.4	123.2	79.6	73.0
Range (deg)	40.5–108	45–117	45–126	63–126	81–148.5	94.5–148.5	54–108	36–108
Interval (deg)	67.5	72.0	81.0	63.0	67.5	54.0	54.0	72.0
Standard deviation	15.16	14.7	15.4	14	16.4	12.6	14.7	15.1

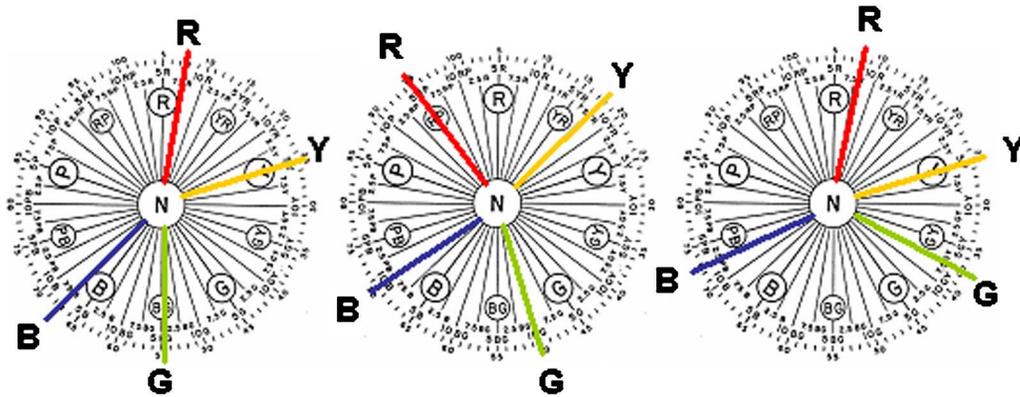


Fig. 5. (Color online) Munsell psychological uniform hue diagram with the unique hue chip choices of (a) observer F20II, (b) observer F2II, and (c) observer F10I.

in the hue region corresponding to the smallest angle between UH selections. Hence, no support for the hypothesis was obtained.

G. Bimodality of uG Stimulus Distribution

In past evaluations of uG stimulus selection, dating back as far as 1939, a bimodal distribution of uG stimuli was found in some experiments [23,24] but not in others [e.g., [25]]. Bimodal distributions were found for mixed-gender observer groups as well as for male groups. A detailed review of this matter is found in Volbrecht *et al.* [26] Our data (Fig. 3) point to a possible bimodal distribution for the female observers for uG stimuli but not for the males, indicating that further work is warranted on gender-specific assessment of bimodality.

4. CONCLUSIONS

We have tested three hypotheses important to the understanding of the perception of the four UHs, as described in the Introduction. While males showed no difference in observer repeatability with and without a mask that restricted the viewing scene to just three Munsell chips, the variability for females, contrary to our hypothesis, was larger when the visual scene was restricted to a small number of stimuli.

The data show that, in the experimental conditions used, observers select UH stimuli with, on average, a high degree of repeatability. Inter-observer ranges of selected stimuli for the 102 observers investigated confirmed the findings of earlier experiments with object color stimuli. The largest range is found for uG with a span of 7.5 Munsell hue notation grades, followed by uR with 6.5 grades, uY with 5.5, and uB with 4.5 Munsell hue notation grades. The distributions generally do not follow a stan-

dard Gaussian distribution. The results from our experiments, where UH choices were made under controlled but relatively natural conditions from a circular series of color chips varying in hue, fall within results obtained from greatly restricted conditions using spectral or monitor lights. No correlation was found between UH stimulus signature and hue ordering ability when a modified FM100 hue test was employed, indicating that the visual mechanisms of perception of UHs and hue ordering may constitute different components of the human visual system. In addition, the following gender-related facts were found:

- (a) In unrestricted viewing conditions, females have intra-observer variability comparable to that of males.
- (b) While the ranges of samples picked as representing UHs are quite similar for females and males, females have broader ranges of the intervals between uG–uB and uB–uR.
- (c) Females have more widely varying individual UH stimulus signatures than males.
- (d) A possible bimodal distribution of the uG stimuli choices was observed for females.

Such gender-related differences may have their basis in known genetic differences in regard to the kind of genes that enable tetrachromacy or even pentachromacy in females [27]. The relationship between stimulus and perceived color, to the extent it can be judged using the paradigm of the four UHs, is tenuous but individually quite strong. UH stimulus signatures can vary widely for reasons that are as yet unknown. From the vantage point of the findings of this paper and similar findings elsewhere, Hering’s insistence on a distinction between psychological color experiences and stimuli appears justified. Judged by the relationship of stimulus and UH experience, human color experiences of objects in relatively natural viewing scenes vary much more than is assumed in applied color science, such as in the development of uniform color spaces and color appearance models.

Table 7. Matrix of Nonparametric Spearman Rank Correlation Coefficients between Hue Angles in the Munsell Hue Diagram of Mean Individual UH Stimulus Choices of 102 Observers

UH	uR	uB	uG
uY	0.09	0.06	0.15
uR		0.00	-0.13
uB			0.07

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References

1. E. Hering, *Grundzüge der Lehre vom Lichtsinn* (Springer, 1905–1911).
2. L. M. Hurvich and D. Jameson, transl., *Outlines of a Theory of the Light Sense* (Harvard U. Press, 1964).
3. E. Hering, *Zur Lehre vom Lichtsinne* (Gerold, 1872–1874).
4. M. D. Fairchild, *Color Appearance Models*, 2nd ed. (Wiley, 2005).
5. M. L. Rubin, "Spectral hue loci of normal and anomalous trichromates," *Am. J. Ophthalmol.* **52**, 166–172 (1961).
6. M. Ayama, T. Nakatsue, and P. E. Kaiser, "Constant hue loci of unique hue binary balanced hues at 10, 100, and 1000 Td," *J. Opt. Soc. Am. A* **4**, 1136–1144 (1987).
7. R. Pridmore, "Unique and binary hues as functions of luminance and illuminant color temperature, and relations with invariant hues," *Vision Res.* **39**, 3892–3908 (1999).
8. B. E. Scheffrin and J. S. Werner, "Loci of spectral unique hues throughout the life span," *J. Opt. Soc. Am. A* **7**, 305–317 (1990).
9. J. Nerger, V. J. Vollbrecht, and C. J. Ayde, "Unique hue judgments as a function of test size in the fovea and at 20-deg temporal eccentricity," *J. Opt. Soc. Am. A* **12**, 1225–1232 (1995).
10. M. A. Webster, E. Miyahara, G. Malkoc, and V. E. Raker, "Variations in normal color vision. II. Unique hues," *J. Opt. Soc. Am. A* **17**, 1545–1555 (2000).
11. M. A. Webster, S. M. Webster, S. Bharadwaj, R. Verma, J. Jaikuma, G. Mada, and E. Vaithilingham, "Variations in normal color vision. III. Unique hues in Indian and United States Observers," *J. Opt. Soc. Am. A* **19**, 1951–1962 (2002).
12. G. Malkoc, P. Kay, and M. A. Webster, "Variations in normal color vision. VI. Binary hues and hue scaling," *J. Opt. Soc. Am. A* **22**, 2154–2168 (2005).
13. I. Abramov and J. Gordon, "Seeing unique hues," *J. Opt. Soc. Am. A* **22**, 2143–2153 (2005).
14. R. G. Kuehni, "Determination of unique hues using Munsell color chips," *Color Res. Appl.* **26**, 61–66 (2001).
15. R. G. Kuehni, "Variability in unique hue selection: a surprising phenomenon," *Color Res. Appl.* **29**, 158–162 (2004).
16. S. M. Wuerger, P. Atkinson, and S. Cropper, "The cone inputs to the unique-hue mechanism," *Vision Res.* **45**, 3210–3223 (2005).
17. A. Raz, J. Fan, and M. I. Posner, "Hypnotic suggestion reduces conflict in the human brain," *Proc. Natl. Acad. Sci. U.S.A.* **102**, 9978–9983 (2005).
18. T. Hansen and K. R. Gegenfurtner, "Higher level chromatic mechanisms for image segmentation," *J. Vision* **6**, 239–59 (2006).
19. D. Farnsworth, "The Farnsworth–Munsell 100 hue dichotomous tests for color vision," *J. Opt. Soc. Am.* **33**, 568–574 (1943).
20. S. Ishihara, *Series of Plates Designed as Tests for Colour-Blindness* (Kanehara, 1917).
21. J. Neitz, *Manual: Neitz Test of Color Vision* (Western Psychological Services, 2001).
22. A. M. Derrington, J. Krauskopf, and P. Lennie, "Chromatic mechanisms in lateral geniculate nucleus of macaque," *J. Physiol. (London)* **357**, 241–265 (1984).
23. G. H. M. Waaler, "The heredity of two types of normal colour vision," in *Avandlinger Utgitt av det Norske Videnskap-Akademi* (Universitetsforlaget, 1967).
24. S. R. Cobb, "The unique green phenomenon and colour vision," *Clin. Genet.* **7**, 274–279 (1975).
25. W. Richards, "Differences among color normals: classes I and II," *J. Opt. Soc. Am.* **57**, 1047–1055 (1967).
26. V. J. Vollbrecht, J. L. Nerger, and C. E. Harlow, "The bimodality of unique green revisited," *Vision Res.* **37**, 407–416 (1997).
27. M. Neitz, T. W. Kraft, and J. Neitz, "Expression of *L* cone pigment gene subtypes in females," *Vision Res.* **38**, 3213–3219 (1998).