No difference in variability of unique hue selections and binary hue selections

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If unique hues have special status in phenomenological experience as perceptually pure, it seems reasonable to assume that they are represented more precisely by the visual system than are other colors. Following the method of Malkoc *et al.* (J. Opt. Soc. Am. A **22**, 2154 [2005]), we gathered unique and binary hue selections from 50 subjects. For these subjects we repeated the measurements in two separate sessions, allowing us to measure test–retest reliabilities ($0.52 \le \rho \le 0.78$; $p \ll 0.01$). We quantified the within-individual variability for selections of each hue. Adjusting for the differences in variability intrinsic to different regions of chromaticity space, we compared the within-individual variability for unique hues to that for binary hues. Surprisingly, we found that selections of unique hues did not show consistently lower variability than selections of binary hues. We repeated hue measurements in a single session for an independent sample of 58 subjects, using a different relative scaling of the cardinal axes of MacLeod–Boynton chromaticity space. Again, we found no consistent difference in adjusted within-individual variability for selections of unique and binary hues. Our finding does not depend on the particular scaling chosen for the Y axis of MacLeod–Boynton chromaticity space.

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1. INTRODUCTION

Unique hues are given special distinction by color scientists as phenomenologically pure [1]. They are thought to be elemental, subjectively containing one color quale but not any other. A unique yellow, for example, is a yellow that is neither reddish nor greenish, and a unique red is a red that is neither bluish nor yellowish. Unique hues are often assumed to form the basis of the perceptual organization of color [2–4], and though they do not map onto the early color mechanisms known to exist in the retina and the lateral geniculate nucleus [2,5,6], higher-level color mechanisms representing the unique hues have been sought [7–10]. Whether unique hues provide the basis for universals in color perception has been much debated [11–16], including the relationship between unique hues and *focal colors* (prototypical colors of different categories) [17,18].

If unique hues really are distinctively perceptually pure [13], it seems reasonable to assume that subjects should be able to identify them more reliably than they are able to identify other colors. It should be easier to identify the particular chromaticity of unique red that contains no other color qualities than to identify the chromaticity of an orange, say, which might be defined as a range of colors subjectively experienced as mixtures of red and yellow.

We aimed to compare the precision with which subjects can identify unique hues and the precision with which they can identify binary hues. Malkoc *et al.* [19] have made similar measurements, and we broadly follow the method that they used. But Malkoc *et al.* were interested in the correlation between selections of different hues across individuals (which turns out to be surprisingly low) rather than variability *per se*. Here we report within-individual as well as between-individual and overall variability for selections of unique and binary hues. It is the comparison across hues of within-individual variability that will allow us to conclude whether unique hues are represented more precisely by the visual system than are binary hues.

When comparing variability of color selections across different parts of color space, it is important to consider the nature of the metric used. We chose the MacLeod–Boynton [20] chromaticity diagram as a metric, but MacLeod–Boynton space, like all color spaces to some degree, is perceptually nonuniform: one just-noticeable difference (JND) is represented by larger distances in some regions of the color space than others. The variability of selections of a particular hue will therefore depend, in part, on the location of the hue in color space and the distance representing one JND at that location. To account for the nonuniformity of MacLeod–Boynton space, we apply a transformation to our data on variability of hue selections. Using a method similar to that of Witzel and Gegenfurtner [21], we fit ellipses to polar plots of the standard deviation of hue settings (r) against mean angle of hue setting (θ). The residuals to the fitted ellipse allow us to estimate whether the variability of selections of a particular hue is greater or less than expected for the hue's position in color space. Further details of this procedure are given in the results section for Experiment 1.

One source of the nonuniformity of MacLeod–Boynton chromaticity space is an arbitrary scaling factor that determines the relative scaling of the two cardinal axes S/(L + M) and L/(L + M). It is possible that different choices of this scaling factor would change the results for particular hues, depending on whether they happen to be located near the S/(L + M) axis or the L/(L + M) axis. We thus conducted our experiment twice, with independent samples of subjects, using different factors for the relative scaling of the cardinal axes. In Experiment 1 we applied a scaling factor of 3.88 to the L/(L + M) axis of MacLeod–Boynton chromaticity space, and in Experiment 2 we applied a scaling factor of 2.8 (see Fig. 3 in Section 4).

2. EXPERIMENT 1: METHODS

A. Stimuli

Stimuli were annuli of colored segments. The segments were isoluminant, with a luminance of 28 $\mathrm{cd\,m^{-2}}$, and isosaturated in the scaled version of the MacLeod–Boynton chromaticity diagram that we used. The locus of chromaticities from which the colors of the segments were taken is shown in Fig. 1(a). We applied a scaling factor of 3.88 to the L/(L + M) axis of the MacLeod–Boynton (1979) chromaticity diagram [while maintaining the L/(L + M) coordinate of D65]. This scaling factor was chosen to equate the salience of variation along the two cardinal axes for the average color-normal observer, measured using a method suggested by Regan and Mollon [22]. To investigate the possible effect of the choice of scaling factor on the relative variability of unique and binary hue selections, we used a different scaling factor in Experiment 2.

The background on which the stimuli were presented was metameric with D65 and had a luminance of 14 $\mathrm{cd\,m^{-2}}$. The chromaticity of D65 is indicated in Fig. 1(a) by the central gray disc.

The stimulus was an annulus of 25 selectable segments containing 25 discrete hues [Fig. 1(b)], with an approximate outer diameter of 30° and an inner diameter of 24.5°. The rotation of the hue circle varied randomly across trials. The chromaticity coordinates of the hue segments presented on each trial also varied somewhat. The range of hues always covered the full hue circle [Fig. 1(a)], and the hue angle separating each neighboring pair of segments was always constant, but the randomized rotation was not quantized, so the hue angles of the colored segments presented on each trial depended on the rotation of the hue circle.

B. Procedure

Each trial consisted of two frames. Presented on the first frame was an annulus of 25 selectable segments with chromaticities ranging over the full hue circle. The color terms (red, orange, yellow, yellow–green, green, blue–green, blue, and purple) and instructions to subjects were the same as those used by Malkoc *et al.* [19]. According to the block, the subject was asked to choose, for example, "a red that is neither too orange nor too purple" or "an orange that is neither too red nor too yellow." On each trial the subject would select the segment he or she thought best matched the instruction by tapping it with a stylus. A small achromatic disc (metameric with D65 and with a luminance of 35 $\mathrm{cd\,m^{-2}}$) would then appear beside the selected segment. The subject was allowed to change the selection by tapping another segment or to confirm it by selecting a check symbol presented in the lower right part of the screen.

On frame 2, following the subject's selection, the circle of hues "zoomed in," so that instead of containing the full range of hues, the colors of the selectable segments spanned only a quarter of the full hue circle. The range of hues included the subject's previous match, but the match was not necessarily at the center of the range. Instead, there was a 30° rotational jitter on the quarter-hue circle, so that the subject's previous selection appeared somewhere between one-third and two-thirds of the way along the quarter-hue circle. The purpose of the rotational jitter was to discourage subjects from adopting a strategy of selecting the hue halfway through the selectable range, which would match the hue of their selection from the first part of the trial. The full hue circle was also presented for reference on this second part of the trial: it formed a second smaller circle of hues, with an outer diameter of approximately 18.5°, unselectable, and presented inside the first [see Fig. 1(b)].

There were 16 blocks, each of five trials. In each block one of the four unique hues (red, green, blue, and yellow) or one of the four binary hues (orange, purple, blue–green, and yellow–green) was measured. In the first eight blocks all eight hues were tested in a random order, and again in the second eight blocks in a different random order. The 50 participants were tested twice, in two sessions between 3 and 10 days apart. Results for each participant and for each hue are therefore based on 20 selections, split over two experimental sessions.

Subjects completed the experiment in a dark room at a viewing distance of approximately 35 cm. They viewed the

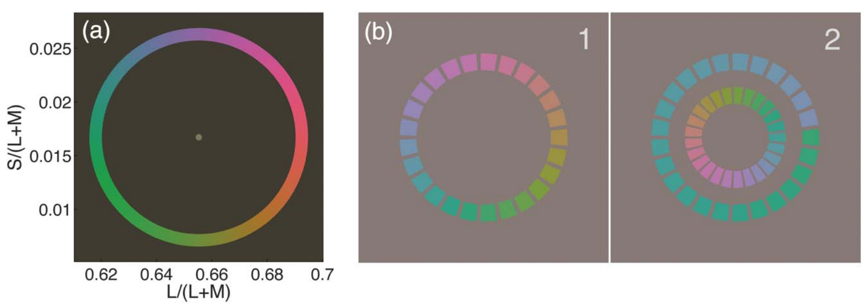

Fig. 1. Stimuli. Panel (a) shows the range of chromaticities, in our scaled version of MacLeod–Boynton chromaticity space, from which the stimuli were drawn. Panel (b) indicates the two frames of a trial. In frame 1, 25 colored segments were presented whose range chromaticities spanned the full hue circle shown in panel (a). In frame 2, the 25 selectable segments had chromaticities from a quarter of the full hue circle, according to the subject's selection on frame 1. For reference, an inner annulus was presented of 25 unselectable segments with chromaticities that ranged over the full hue circle.

stimuli binocularly and were allowed to move to make themselves comfortable; their heads were not in a fixed position.

C. Apparatus

To record subjects' responses, we used a Magic Touch ProE-X touch screen (model no. ET2032C, Keytec, Garland, Texas, USA) attached to the CRT monitor. Stimuli were presented on a GDM F550 monitor (Sony, Tokyo, Japan), calibrated using a CRS ColorCal (Cambridge Research Systems, Rochester, UK) and a PR650 SpectraScan spectroradiometer (PhotoResearch, Chatsworth, California, USA).

D. Subjects

50 subjects took part in the experiments, 40 female and 10 male, aged 16–40. All subjects had normal color vision as assessed by the Ishihara plates presented under natural daylight, though we note that a small number of anomalous trichromats, minimal anomals, pass the Ishihara plates [23,24]. All subjects were naïve to the purposes of the experiment.

3. EXPERIMENT 1: RESULTS

A. Distributions of Hue Selections and Their Means

A median hue selection was calculated for each subject, based on 10 selections gathered in a session. Figure 2(a) shows polar histograms of average hue selections for our sample. Here, each subject's hue selection is the mean of the two median hue selections for session 1 and session 2.

B. Test–Retest Reliabilities

Test–retest reliabilities were calculated as the correlation between median hue selections in session 1 and median hue selections in session 2 [Fig. 2(b)]. Table 1 presents test–retest reliabilities for our eight hues. Reliabilities are highest for red and lowest for blue. There appears to be no difference between unique hues and binary hues in test–retest reliability (mean ρ is 0.62 for unique hues and 0.605 for binary hues).

C. Within-Individual Variability

For each hue, we calculated within-individual variability as the variance of 20 selections made across the two sessions. We give this in Table 2 in comparison to the total variance (across all subjects) of all hue selections in both sessions. Note that total variance includes between-individual variance and within-individual variance.

The variances listed in Table 2 differ quite widely. The variance of selections of a particular hue will depend partly on whether the hue is situated in a position in chromaticity space where discrimination is better or worse than average. To make a fair comparison between the variability of selections of unique hues and the variability of selections of binary hues, we need to know, for each hue, whether variability is greater or smaller than expected for its position in chromaticity space. To do this we adopted a method similar to that used by Witzel and Gegenfurtner [21] for JNDs. We plotted, in polar coordinates, the standard deviation of unique hue selections

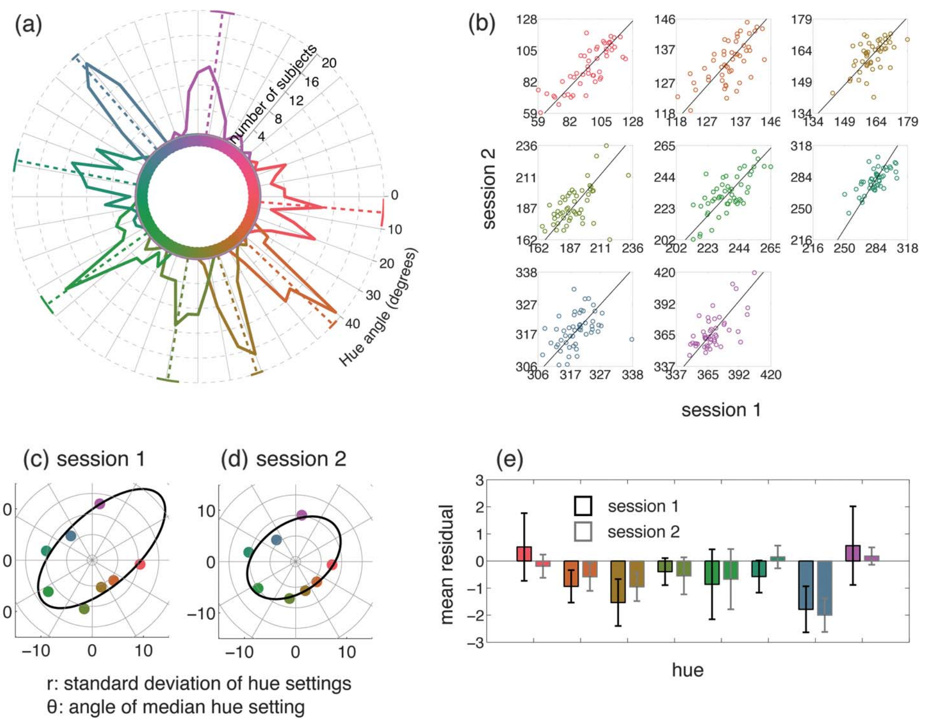

Fig. 2. (a) Histograms of average hue selections. Mean selections are indicated by the dashed lines, and 95% confidence intervals by the solid arcs. Results are colored according to the hue. (b) Test–retest reliabilities. Median hue selections from session 2 are plotted against median selections from session 1. Correlation coefficients are given in Table 1. (c) Polar plot of standard deviation of hue selections (r) as a function of group mean hue selection (θ) for session 1. Group mean selections of each hue are the mean of median hue selections of 50 subjects. The standard deviation is the mean standard deviation of 50 subjects, with 10 selections for each hue. The ellipse is the best-fitting ellipse through the data. (d) Polar plot of standard deviation of hue selections (r) as a function of median hue selections (θ) for session 2. (e) Mean residuals (over 50 subjects) of the positions of each hue from the best fitting ellipse for each subject. If the residual is negative, the standard deviation of hue selections is inside the ellipse and therefore smaller than expected. If the residual is positive, the standard deviation of hue selections is outside the ellipse and therefore greater than expected. Residuals for session 1 are shown by black borders, and residuals for session 2 by gray borders. Bars representing results for the eight hues are colored accordingly. Error bars are 95% confidence intervals on the mean residuals.

Table 1. Test–Retest Reliabilities of Median Selections of Unique and Binary Hues

Color	Spearman's ρ; p
Red	$0.775,\ 2.51 \times 10^{-11}$
Orange	$0.656,\ 1.77 \times 10^{-7}$
Yellow	$0.543,\ 3.87 \times 10^{-5}$
Yellow–green	$0.535,\ 5.18 \times 10^{-5}$
Green	$0.649,\ 2.62 \times 10^{-7}$
Blue–green	$0.661,\ 1.32 \times 10^{-7}$
Blue	$0.524,\ 8.08 \times 10^{-5}$
Purple	$0.568,\ 1.35 \times 10^{-5}$

(r) as a function of the hue angle of the median selections (θ). To this data we fitted an ellipse and then found the residuals of the data points from the best-fitting ellipse. The sign of the residual tells us, for each hue, whether variability is greater or less than expected for its position in chromaticity space. Figures 2(c)–2(e) show this analysis.

Figure 2(c) shows that for the session 1 mean data, orange, blue, green, and yellow lie inside the best-fitting ellipse, while red, yellow–green, purple, and blue–green lie outside the ellipse. We extended this analysis to individual subjects. For each subject, we fit an ellipse to a polar plot of standard deviation of hue selections (r) as a function of average hue selection (θ). We found the residuals for each hue. The mean sizes of the residuals for different hues can be compared in Fig. 2(e). The residuals for blue are most negative, so blue, for most subjects, lies furthest inside the ellipse fit to variability in hue selections. The mean residuals for orange, yellow, green, and yellow–green are also negative. The mean residuals for purple, red, and blue–green are near zero or slightly positive. The residuals do not separate unique from binary hues: For example, orange is selected more consistently than expected from its position in chromaticity space, while red is selected less consistently.

Since there has been interest in comparing the sizes of within-individual variance and between-individual variance for settings of unique hues [25–27], we also list these comparisons in Table 2. Comparing variance within and between observers is tricky, since the latter may be based on data averaged over a larger number of trials, reducing the impact of measurement error. Moreover, it is not possible to isolate between-individual variance from within-individual variance without a perfect measure of individual observers' mean selections (which would require an infinite number of trials).

In Table 2 we provide our best comparison of the magnitudes of the two sources of variance. We list within-individual between-session variance, calculated as the mean variance of the session 1 median selection (based on 10 trials) and the session 2 median selection (based on 10 trials) across observers. For our estimate of between-individual variance we took an average of 10 trials randomly selected from both sessions for each subject and then took the variance across subjects. These values are as fair a comparison between the two sources of variance as it is possible to make: The variances are both of sets of median values based on the same number of trials.

4. EXPERIMENT 2: METHODS

In Experiment 2 we measured unique and binary hues in an independent sample of 58 subjects from a population different from that sampled in Experiment 1 (San Diego, California, versus Cambridge, UK). To address the possibility that our conclusions apply only when using a particular scaling factor for the cardinal axes of MacLeod–Boynton chromaticity space, we used a different scaling factor for the $L/(L+M)$ axis than that used in Experiment 1.

A. Stimulus and Procedure

The stimulus and procedure for Experiment 2 were broadly similar to those for Experiment 1, with the following differences:

1. A scaling factor of 2.8, instead of 3.88, was applied to the $L/(L+M)$ axis of MacLeod–Boynton [20] chromaticity space.
2. Instead of having two frames for each trial, there was only one frame, but there were 90 discrete selectable segments of different hues instead of 25. This greater chromatic resolution eliminated the need to "zoom in" on the subject's selection in a second frame. The outer diameter of the annulus of selectable segments was approximately 30°, and the inner diameter was approximately 18.5°.
3. Three different saturations were tested.
4. There was only one experimental session. Subjects made 10 selections of each hue at each of the three saturations. There were 16 blocks, each of 15 trials. In the first eight blocks the eight unique and binary hues were measured in a random order, and again in a different random order in the second eight blocks. In each block, for the first five trials the saturation was high, for the second five trials it was medium, and for the third five trials it was low.

Table 2. Within-Individual, Overall, and between-Individual Variances of Unique and Binary Hue Selections

Color	Mean within-Individual Variance of All Selections (deg)	Overall Variance of All Selections (deg)	Mean within-Individual between-Session Variance (deg)	Estimated between-Individual Variance (deg)	Estimated Ratio of within:between-Individual Variance
Red	119.1	341.4	56.4	244.5	0.23
Orange	44.6	75.6	12.8	33.0	0.39
Yellow	64.1	110.9	20.4	51.5	0.40
Yellow–green	179.8	309.0	87.1	167.8	0.52
Green	141.2	262.0	52.3	149.9	0.35
Blue–green	144.3	289.5	87.1	146.1	0.60
Blue	53.8	73.8	19.0	21.6	0.88
Purple	166.9	338.0	72.0	183.6	0.39

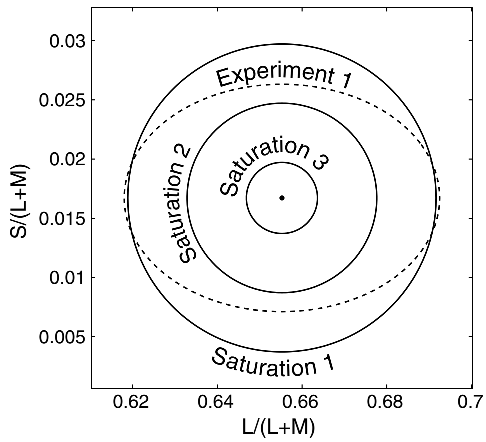

Fig. 3. Chromaticities of selectable segments in Experiment 2 compared to those of Experiment 1. The scaling factor applied to the L/(L + M) axis of MacLeod–Boynton chromaticity space was smaller in Experiment 2 (2.8) than in Experiment 1 (3.88), so the locus of chromaticities presented in Experiment 1 appears as an ellipse in this figure (dashed line). The chromaticities for each of the three saturations are shown separately, and the central black dot indicates the chromaticity of D65, which was the chromaticity of the surround.

Figure 3 shows the range of chromaticities available for subjects' hue selections for each of the three saturations. The range available in Experiment 1 [Fig. 1(a)] is also shown for comparison.

B. Apparatus

Stimuli were presented on a Diamond Pro 2070SB CRT monitor (Mitsubishi, Tokyo, Japan), calibrated using a UDT photometer (United Detector Technology, Hawthorne, CA) and a SpectraScan PR650 spectroradiometer. We used a Keytec Magic ProE-X touch screen to gather subjects' responses.

C. Subjects

Fifty-eight subjects took part in Experiment 2. Fifty-seven subjects were undergraduate students at the University of California, San Diego, who took part in the experiment in exchange for course credit. They were naïve to the purposes of the experiment. One subject was an author (JB). All subjects had normal color vision, assessed using the Ishihara plates, presented under a MacBeth Illuminant C.

5. EXPERIMENT 2: RESULTS

Distributions of hue selections are shown in Fig. 4(a). Both mean hue selections (dashed lines), and the distributions are similar to those measured in Experiment 1. The dominant wavelengths of the mean hue selections can be compared in Table 4.

For Experiment 2 we quantify within-individual variability as the variances of the 10 selections for each hue and saturation. Variances are given in Table 3. The rank order of the eight hues for mean within-individual variance is reproducible: The correlation between the rank order in Experiment 1 and the rank order in Experiment 2 (averaged across the three saturations) is 0.87 ($p = 0.008$). Desaturation has little effect on mean hue selections but tends to increase the variability of hue selections [Fig. 4(a) and Table 3].

As for Experiment 1, we plotted in polar coordinates, for each subject, the standard deviation of hue selections (based on 10 hue selections for each hue of each saturation) (r) as a function of median hue selection (θ). To these data we fit ellipses and took the residuals of the position of each hue from the ellipse. Mean residuals are shown in Fig. 4(c) separately for each saturation. Ellipses fitted to group mean data are shown in Fig. 4(b). The mean residuals for each hue are broadly similar to those of Experiment 1. For all three saturations residuals are most negative for blue, green, orange, and yellow; intermediate for red, yellow–green, and

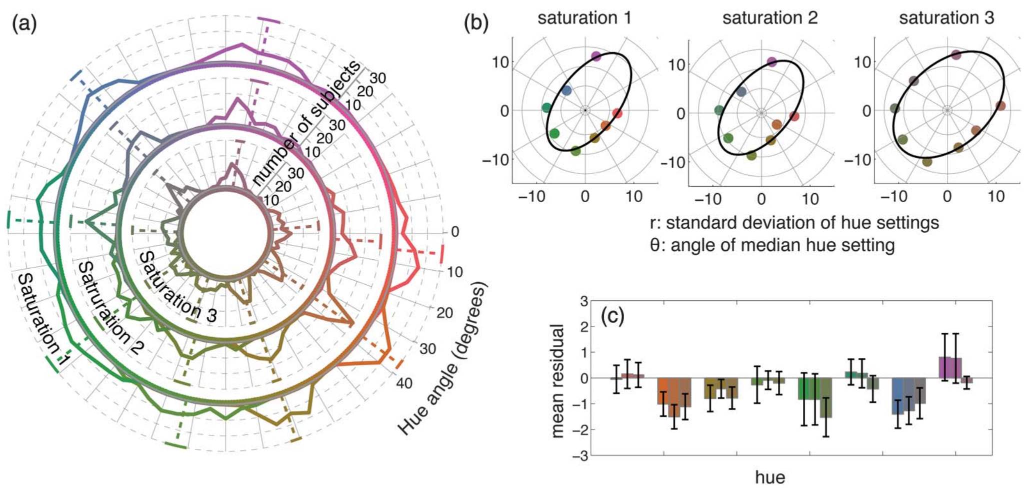

Fig. 4. (a) Distributions of median hue selections measured in Experiment 2 for the three different saturations. Selections for saturation 1 are plotted in the outer annulus, selections for saturation 2 in the middle annulus, and selections for saturation 3 in the inner annulus. Distributions for each hue are colored accordingly, and mean hue selections are indicated by the dashed lines. 95% confidence intervals are indicated by the solid arcs. (b) Best-fitting ellipses through a polar plot of the standard deviation of hue selections (the mean, over 58 subjects, of the standard deviation of the 10 selections for each hue) (r) against the mean hue selection (of median selections of 58 subjects) (θ). (c) Mean residuals. Residuals are the distance of each hue from the best-fitting ellipse [to standard deviation of hue selections (r) as a function of median hue selection (θ)] for each subject. Negative residuals indicate that the standard deviation of selections for that hue is inside the best-fitting ellipse, and so is lower than expected. Positive residuals indicate that the standard deviation of selections for that hue is outside the best-fitting ellipse, and so is greater than expected. Bars are colored according to the hue. For each triplet of bars, results for saturation 1 are left, results for saturation 2 are center, and results for saturation 3 are right. Error bars are 95% confidence intervals on the means.

Table 3. Within-Individual Variance and Overall Variance for Selections of the Eight Hues[a]

	Saturation 1		Saturation 2		Saturation 3	
	Within Individual	Overall	Within Individual	Overall	Within Individual	Overall
Red	52.0	136.1	58.0	160.4	140.9	261.0
Orange	52.1	77.1	18.2	35.2	61.4	94.4
Yellow	46.4	73.2	42.8	81.6	70.3	112.5
Yellow–green	95.1	186.5	104.4	237.2	147.1	295.7
Green	78.9	183.4	92.1	217.9	136.1	243.3
Blue–green	74.5	147.7	90.1	155.7	184.3	272.3
Blue	37.0	91.3	44.3	101.5	101.9	156.5
Purple	159.6	271.3	157.6	299.7	157.2	252.7

[a]Within-individual variance is the variance of the 10 selections for each hue gathered in a single session. Overall variance is the variance of all selections for all subjects.

blue–green; and most positive for purple. These residuals show that the standard deviations of hue selections for orange, blue, green, and yellow are smaller than expected for their position in chromaticity space, while those for purple are greater than expected. The residuals do not separate the unique hues, as a group, from the binary hues. There is no evidence, therefore, that the unique hues are selected more consistently, on average, than would be predicted from their position in chromaticity space.

6. DISCUSSION

A. Positions of the Unique and Binary Hues

Unique hues have been measured using many different methods, most commonly using monochromatic lights but also using CRT monitors and using surfaces, for example Munsell papers. To compare our unique and binary hues with those that have been previously reported, we calculated dominant wavelengths, with D65 as the white point. In Table 4, results from the present two experiments are compared with those from previous studies that have reported mean hues as dominant wavelengths, using 15 or more subjects. For Experiment 1, dominant wavelengths are based on the mean selections (averaged for each subject across the two sessions). For Experiment 2, dominant wavelengths are based on mean hue selections from the single session for stimuli of saturation 1.

The dominant wavelengths of our unique hues are generally comparable to those reported in other studies. There is less existing data for unique red than for other unique hues, largely because unique red lies outside of the spectrum locus for most observers, so it cannot be measured using monochromatic lights. Our results for green and blue are within the range of means previously reported, while we find yellow to be at a dominant wavelength a little shorter than the other five studies listed here.

Differences in method of measurement are likely to produce differences in the mean unique hue selections. One major difference between the studies listed in Table 4 is in the spectral power distributions of the stimuli used. As saturation varies, the paths of the unique hues through chromaticity space are curved [28]. Monochromatic lights are more saturated than the broader-band spectra produced by CRT monitors and those reflected from Munsell surfaces. The chromaticities of unique hues measured using monochromatic lights and using Munsell papers or stimuli presented on a CRT monitor will therefore fall at different positions on the curved loci, so dominant wavelengths will not be equal for the different types of stimuli.

Settings for green show especially large variability across studies, with a range of more than 60 nm, from 498 nm [30] to 549.4 nm [19]. The difference in mean selection between our own Experiments 1 and 2 is much greater for green than for the other seven hues. There also seems to be a difference between studies using different stimuli, with unique green set at longer wavelengths for stimuli presented on a CRT than for monochromatic lights. Kuehni's [30,35] results are against this pattern, however, with unique green at a very short wavelength of 498 nm, despite the fact that the spectra of his Munsell papers are very broadband compared to those of monochromatic lights. Interindividual variation can explain only a small part of the difference between studies, since most of the sample sizes for the measurements listed in Table 4 are

Table 4. Comparison between Mean Unique and Binary Hues Measured in the Present Study and Those That Have Been Previously Reported

	Method	n	Red[a]	Orange	Yellow	Yellow–Green	Green	Blue–Green	Blue	Purple[a]
Experiment 1	CRT	50	495.7	583.9	572.6	562.8	528.6	493.7	482.7	563.5
Experiment 2	CRT	58	494.9	582.5	571.0	562.7	542.0	495.7	480.0	563.2
Jordan and Mollon [29]	Monochromatic lights	97					511			
Kuehni [30]	Munsell surfaces	40			578		498		477	
Malkoc *et al.* [19]	CRT	73	495.5	579.2	572.8	566.1	549.4	489.0	475.3	565.1
Schefrin and Werner [31]	Monochromatic lights	50			577.4		507.7		480.1	
Volbrecht *et al.* [32]	Monochromatic lights	100					514–520.5[b]			
Webster *et al.* [33]	CRT	51			574		545		477	
Wuerger *et al.* [34]	CRT	18			571		542		467	

[a]Dominant wavelengths for red and purple are complementary.
[b]Depending on background.

greater than 50, though we note that there may be population differences in color perception [36], and our own Experiments 1 and 2 were conducted on different populations. Differences in the saturation of stimuli between studies may contribute, but the Abney effect does not seem to be any greater for green than for other hues (it is relatively more pronounced for red and blue) [28]. Luminance differences are another possibility, but studies of the Bezold–Brücke hue shift have produced mixed results. Some show a relatively large effect near the locus of unique green (510–550 nm) compared to the loci of unique blue (475–480 nm) and unique yellow (571–578 nm) [37–41], but others show comparable small shifts for the three colors [42–44].

B. Within-Individual Variability

The variance of hue selections depends on the position of the hue in MacLeod–Boynton chromaticity space: Variance is lowest for colors close to the blue–yellow axis: orange, blue, and yellow. To account for this we fit ellipses to polar plots of standard deviation of hue selections (r) as a function of average hue selection (θ). For a particular hue, the sign of the residual of the fit indicated whether the standard deviation of selections was smaller or larger than expected from the location of the hue in chromaticity space. If subjects are able to select unique hues more reliably than binary hues, we would expect that the residuals would be negative for unique hues and positive for binary hues. However, in both experiments, the standard deviations of selections of orange, blue, yellow, and green were smaller than expected [Figs. 2(e) and 4(b)], while the standard deviations of selections of blue–green, yellow–green, red, and purple were generally as expected or larger than expected. The analysis of residuals does not separate unique hues as a group from binary hues.

In this study we chose hue angle in MacLeod–Boynton chromaticity space as a metric for comparing the variability of hue selections in different parts of color space. Though our analysis of residuals accounts for the fact that chromatic discrimination is nonuniform around the hue circle, it is possible that the results depend on the particular scaling of the orthogonal axes of chromaticity space that are chosen. In Experiments 1 and 2 we applied different scaling factors to the cardinal axes of MacLeod–Boynton space (Fig. 3). However, the results of both experiments are similar (Figs. 2 and 4). The variability of hue selections is not consistently lower for the unique hues than for the binary hues in either experiment. The results of both experiments provide no evidence to support the hypothesis that unique hues are represented more precisely by the visual system than are binary hues.

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