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How well can people use different color attributes?

Hongqin Zhang and Ethan D. Montag

Munsell Color Science Laboratory
Chester F. Carlson Center for Imaging Science
Rochester Institute of Technology, Rochester, NY

Abstract

Two psychophysical experiments were conducted to analyze the role of color attributes in simple tasks involving color matching and discrimination. In Experiment I observers made color matches using three different adjustment control methods. The results showed that the Lightness, Chroma, Hue (LCH) and the Lightness, redness/greenness, blueness/yellowness ($\{L, r/g, y/b\}$) adjustment controls elicited significantly better performance than the display RGB controls in terms of both accuracy and time, but were not significantly different from each other. Expert observers performed significantly better than naive observers in terms of accuracy. Experiment II was a replication and extension of Melgosa, et al.'s experiment in which observers judged differences and similarities for color attributes in pairs of colored patches. At a 95% confidence level, the results from judging difference were significantly better than those from judging similarity. Hue and Lightness were significantly more identifiable than Chroma, r/g , and y/b . For all observers, lightness differences were more easily detected for less chromatic pairs than for higher chromatic ones. With respect to the size of the color differences, it was found that larger hue differences were more easily identifiable than smaller ones. Experts could more readily identify constant lightness and chroma for large color differences while constant hue was more

Correspondence to: Dr. Ethan D. Montag, Munsell Color Science Laboratory, Chester F. Carlson Center for Imaging Science, Rochester Institute of Technology, 54 Lomb Memorial Drive, Rochester, NY 14623 (email: montag@cis.rit.edu)

identifiable for small color differences. There were no significant differences found between males and females. These results indicate that people do not have ready access to the lower level color descriptors such as the common attributes used to define color spaces and that higher level psychological processing involving cognition and language may be necessary for even apparently simple tasks involving color matching and describing color differences.

Key words: color attributes, color appearance, color matching, color difference

Introduction

The perception of color is a complex process in the human visual system. Being a blend of physics, neurophysiology and phenomenology, it encompasses a wide range of specification from neural transduction to linguistic classifications and conscious percepts. Theories of the internal coding of color – both within an elementary and an ecological perspective – are often only very indirectly linked to appearances of color, however, observations about color appearances usually provide a starting point and motivation for investigations of color coding.^{1,2}

In order to describe appearances of color, it is generally agreed that five perceptual dimensions, or attributes are necessary: brightness, lightness, colorfulness, chroma, and hue.¹⁻⁴ For color reproduction, hue and the relative color attributes, chroma and lightness are typically used for color specification. Many color spaces, such as the Munsell Book of Colors,⁵ which is used for color specification and communication, CIELAB,⁶ which is used for formulating color differences, and CIECAM02,⁷ which is used for the specification of color appearance, use the lightness, hue, and chroma attributes to specify color attributes. However, there are alternative methods to specify color, including chromaticity diagrams^{3,4} which specify the color signal as opposed to the appearance attributes and physiologically-based color spaces⁸⁻¹⁰ which specify cone excitation or the response of subsequent visual mechanisms.¹¹ In addition, alternative color order systems,¹ such as the Swedish Natural Color System (NCS)¹² (blackness, chromaticness, and hue) and the Duetsches Institut für Normung (DIN)¹³ System (hue, saturation, and darkness) use other perceptual attributes to organize the space.

It is interesting to consider how color is represented psychologically in order to define color spaces that more intuitively match our internal representation of color. However, despite the trichromatic nature of color, the psychological description of color representation remains

elusive. We can describe color representation in a hierarchy. At the lowest levels of processing, the color signal can be described using three numbers indicating cone excitations or physiological opponent channels. This does not take into account color appearance. At the next higher level, color can be described in terms of Hering opponency¹⁴ where red/green, blue/yellow and lightness describe color appearance. The color attributes used for color appearance, difference, and specification seem to be located at still a higher level of representation approaching a cognitive and linguistic level of representation. At a still higher level, there is evidence for categorical representation that is tightly associated with culture and language.¹⁵⁻¹⁷ Claims have been made^{18,19} for a physiological basis for categorical color perception, which if true, could influence the hierarchical framework described here.

Melgosa, et al.²⁰ asked the question whether we are able to distinguish the color attributes of lightness, hue, and chroma. In their experiment, observers had to judge which attribute, Value, Chroma, or Hue (in Munsell specification) two colors either differed by or shared. They found that the level of performance was below what would be expected if these attributes were the best perceptual or cognitive classification system. Montag²¹ had observers determine a color that was intermediate between two colors that shared the same lightness and chroma but differed in hue. The observers chose an intermediate color that was located geometrically between the two at a lower chroma as opposed to sharing the same chroma attribute. Both these experiments point to a different representation of color than lightness, chroma, and hue. Perhaps when confronted with a color difference pair, observers rely on a lower level, Hering-opponent, (L, r/g, y/b) description to distinguish the differences.

In this paper we explore this issue using two psychophysical tasks. In the first experiment, the speed and accuracy of color matching was measured in a task in which observers

used three different adjustment controls: lightness, chroma, and hue (LCH); lightness, redness/greenness, yellowness/blueness ($\{L, r/g, y/b\}$); and display RGB. In the second experiment, observers were presented with color difference pairs that were specified in either LCH or $\{L, r/g, y/b\}$ and had to decide the attribute the colors shared or differed by. If the LCH or $\{L, r/g, y/b\}$ specification of color is a better match to the internal psychological representation of color, we would expect to see better performance.

Experimental

Two psychophysical experiments were conducted to explore observers' abilities to control and distinguish different color attributes. Experiment I was a matching experiment using the method of adjustment. It compared performance in matching patches using three different controls: 1) Display RGB, 2) Lightness, Hue, and Chroma (LCH), 3) Lightness, Redness/Greenness, and Yellowness/Blueness ($\{L, r/g, y/b\}$). Experiment II was a judgment experiment. It was a replication and extension of Melgosa, et al.²⁰ In experiment II, observers were asked to judge similarities or differences of color pairs using two sets of color attributes: LCH and $\{L, r/g, y/b\}$.

Color Space Selection

In both experiments, in order to more accurately control the perceptual attributes, the internationally agreed upon color appearance model CIECAM02^{7,22-24} was used. This model was developed by CIE Technical Committee 8-01 by refining and simplifying the CIECAM97s²⁵ color appearance model with considerable improvement in the hue uniformity, especially for the blue hues, and an improvement in the chroma relative to the results for CIECAM97s. It provides mathematical formula to transform physical measurements of stimuli into perceptual attributes of color under different viewing conditions and can be used as a device and viewing condition independent color space.

Monitor Setup

A 23-inch (diagonal) Apple Cinema HD LCD Display, controlled by a Macintosh PowerPC in 24-bit color mode, was used in these experiments. The LCD display was carefully characterized using a technique consisting of three 1-D LUTs and a 3 x 4 matrix.²⁶ Measurements of the characterization color patches were taken using an LMT C-1200 colorimeter. Based on these measurements, the display was set up for the Matching and Judgment experiments as described below.

Viewing Conditions

The experiments were conducted in a darkened room and the color patches were presented on the characterized LCD display with a 20% gray background. The viewing condition parameters used in CIECAM02 are shown in Table I. These parameters were chosen for the experimental conditions in which a self-luminous display is viewed in a darkened room.

Insert Table I about here

Matching Experiment

Design

Four pairs of color patches were carefully selected for the Matching Experiment. Since the {L, r/g, y/b} adjustment controls were used in this experiment, the experimental color patches were chosen to be combinations of and intermediate to the four unique hues instead of unique hues themselves. In CIECAM02, the hue angles of the four unique hues are:

Red: $h_1 = 20.14^\circ$, Yellow: $h_2 = 90.00^\circ$, Green: $h_3 = 164.25^\circ$, and Blue: $h_4 = 237.53^\circ$.

Therefore, the hue angles of the four colors were selected at 45°, 125°, 195°, and 320°, respectively, as illustrated in Figure 1.

Insert Figure 1 about here

The Lightness, Chroma, and Hue values of the four pairs of color patches in CIECAM02 perceptual attributes and the initial color differences between the standard patches and the test patches in CIEDE00²⁷ units were shown in Table II.

Insert Table II about here

Because the four unique hues are not orthogonal to each other in CIECAM02, it is impossible to calculate the compositions of each unique hue for a given color by projection. In CIECAM02, Hue quadrature, H , is calculated from the unique hue data via linear interpolation, however, H for the unique hues, red, green, yellow and blue, are defined as 0 (or 400), 100, 200, and 300, respectively. They are also not orthogonal to each other. In order to control the proportion of each unique hue, another hue quadrature, H' , was calculated in the same way as calculating H , but the H' for the four unique hues were defined as 0 (or 360), 90, 180, and 270, respectively. In this way, the r/g and y/b components for a given color were then calculated by direct projection onto each unique hue axis.

Procedure

The two patches of each pair were positioned in the center of the screen with a separation of 0.5 cm subtending a visual angle of $27.1^\circ \times 13.7^\circ$ for an observer at a normal viewing distance of 25 cm configured as shown in Figure 2.

Insert Figure 2 about here

The observers' task was to adjust the color of the test patch on the right using three sliders so that the two patches matched each other as well as possible. Since the time taken to make a match was also recorded, observers were asked to try to make the match as quickly as possible. Matching each of the four pairs of color patches was repeated four times for each of the three controls in a random order for a total of 48 trials.

The observers were asked to fill out a survey at the end of the task in which they rated which matching procedure they found to be the easiest and the hardest to perform. In addition, they were encouraged to comment on the procedures.

Judgment Experiment

Design

The purpose of the Judgment Experiment was to determine how well observers can use color attributes to identify differences (task 1) and similarities (task 2) between pairs of colored patches. There were 4 parts in this experiment. In each part, 36 pairs (except for Part 3, in which 35 pairs were used due to an error) of colored patches were carefully prepared so that each pair differed in only one of the color attributes or had only one of the color attributes in common. For

Part 1 (LCH Diff) and Part 2 (LCH Same), the attributes were Lightness, Hue, and Chroma. In Part 1, the pairs differed in either Lightness, Chroma, or Hue while in Part 2 the pairs had only Lightness, Chroma, or Hue in common. Part 3 (L, r/g, y/b Diff) and Part 4 (L, r/g, y/b Same) were similar to Part 1 and Part 2 except that the attributes were Lightness, redness/greenness (r/g), and yellowness/blueness (y/b) instead of Lightness, Hue, and Chroma.

The 36 pairs of colored patches of Part 1 and Part 2 were distributed into 4 groups around the hue angles 85°, 170°, 265°, and 355°, with 9 pairs per group. In part 1, in each group, 3 pairs differed only in Lightness, 3 pairs differed only in Chroma, 3 pairs differed only in Hue, and the magnitude of color differences varied within each series. In part 2, in each group, 3 pairs had the same Lightness, 3 pairs had the same Chroma, 3 pairs had the same Hue, and the magnitude of color differences also varied within each series. Part 3 and Part 4 followed a similar design, having also 4 groups of 9 sample pairs with the 4 groups distributing around the Hues 55°, 105°, 200°, and 330°. In part 3, in each group, 3 pairs differed only in Lightness, 3 pairs differed only in r/g (2 pairs for the third group), 3 pairs differed only in y/b with varied magnitude of color differences within each series. In part 4, in each group, 3 pairs had the same Lightness, 3 pairs had the same r/g, and 3 pairs had the same y/b again with varying magnitudes of color differences within each series. The CIECAM02 color attributes and the CIEDE00 of the two patches of each pair for the 4 parts are shown in Tables III - VI. Also shown are the total color differences between the members of each pair in units of ΔE^*_{ab} and the percentage of the difference accounted for along the CIE L*, a*, and b* dimension most closely related to the differing (Parts 1 and 3) and constant (Parts 2 and 4) dimensions of the task.

Procedure

For each part, each of the 36 pairs of color patches from the 4 groups were randomly presented on the same characterized LCD screen at the same size as in the Matching Experiment. Each part of the experiment was run in a separate block with the order of presentation randomized within each block.

For each pair, the observers' task was to judge which attribute that the two patches differed by (in Parts 1 and 3) or which attribute that the two patches had in common (in Parts 2 and 4) by pressing the appropriate key on the keyboard.

Insert Table III about here

Insert Table IV about here

Insert Table V about here

Insert Table VI about here

Results and Discussion

Matching Experiment

The Matching Experiment was conducted with 24 observers having normal color vision, of which 17 were considered expert and 7 naïve (the terms “expert” and “naïve” are used here to indicate the level of experience and expertise of the observers as opposed to their knowledge of the purpose of the experiment) based on self-report (in general, faculty, students, and technical staff of the laboratory were considered as experts due to their experience doing psychophysics and working with color). The performance was measured by the color difference between the standard patch and the test patch, and also the time taken to make a match was measured. Analyses of Variance^{28,29} (ANOVA) were performed on both the color difference and the time using control type (RGB; LCH; {L, r/g, y/b}), expertise (expert or naïve), and patch color (4 colors) as the three factors.

The color difference results (Table VII) showed that there were significant differences among the three control methods, between expert and naïve observers, and among the four colors. There were also significant 2-way interactions between all pairs of the three factors.

Insert Table VII about here

In order to determine whether the effects between controls, observer expertise, patch colors and their interactions were significant, multiple comparisons between conditions were performed with error rates controlled conservatively using Tukey's test.^{28,29} The results are shown in Figure 3.

Insert Figure 3 about here

Figure 3A shows that the matches made with the LCH (with an average CIEDE00 of 1.97) and $\{L, r/g, y/b\}$ (with an average CIEDE00 of 2.23) controls were significantly better than those made with the RGB controls (with an average CIEDE00 of 2.95), but there is no significant difference between LCH and $\{L, r/g, y/b\}$.

As expected, the performance of the experts (with an average CIEDE00 of 2.01) was significantly better than that of the naïve observers (with an average CIEDE00 of 2.76), as shown in Figure 3B. This indicates that experience and training may improve the observers' performance.

Figure 3C shows that the reddish-yellow (hue angle of 45°) was the hardest color to make a match, while the greenish-blue (hue angle of 195°) was the easiest with significantly better performance than the reddish-yellow and the yellowish-green (hue angle of 125°). There was no significant difference between the greenish-blue and the bluish-red (hue angle of 320°) or between the yellowish-green and the bluish-red. There is a trend (see Figure 3C and Table II) that accuracy in color matching increases with increasing lightness. It is interesting to consider the relationship between match accuracy and location of the color in color space. In particular, as with the MacAdam ellipses,³⁰ the variance in color matching can be considered as a metric for absolute sensitivity to color change. It is recognized that as the magnitude of color difference increases from threshold to suprathreshold, the contours that describe equally perceived color difference change shape.³¹⁻³⁴ However, there is not enough data in this experiment to draw any

firm conclusions about the differences in sensitivity to color difference based on the location of the color.

A multiple comparison of 2-way ANOVA analysis between adjustment methods and observer expertise was performed (Figure 4).

Insert Figure 4 about here

As shown in Figure 4, for the experts, at a 95% confidence level, the LCH control was significantly better than RGB while there were no significant differences between RGB and {L, r/g, y/b} and between LCH and {L, r/g, y/b}. For the naïve observers, both LCH and {L, r/g, y/b} was significantly better than RGB while there was also no significant difference between them.

These results are consistent with the observers' comments that RGB was the hardest control method to use and that having a Lightness control facilitates matching. For both RGB and LCH, the performance of the experts was significantly better than that of naïve while for {L, r/g, y/b} there was no significant difference between expert and naïve observers.

This may be explained as follows: for LCH, the previous knowledge and experience of the expert observers did help. For RGB, the expert observers may also have some tricks learned from experience, such as, knowing that the green channel contributes more to overall lightness. In addition, we expect that these observers have some basic knowledge about the principles of additive color mixing of the three primaries. However, for {L, r/g, y/b}, both expert and naïve observers seemed unfamiliar with the task. Therefore, there was no significant difference

between them. It is possible, however, that further experience with the $\{L, r/g, y/b\}$ controls would lead to improvement

In addition to the accuracy of matching, we also measured matching time as another metric to compare the three control methods. Table VIII shows the ANOVA of the time taken to make the matches using the same three factors as for the color difference analysis above.

Insert Table VIII about here

The small P-values in the first three rows indicated that there were significant differences among the three control methods, between expert and naive, and among the four colors. As done for the color difference data above, multiple comparisons between conditions were performed while controlling error rate. The results are shown in Figure 5.

Insert Figure 5 about here

Figure 5A shows that the average time (66 s) for RGB control is significantly longer than those for LCH (52 s) and $\{L, r/g, y/b\}$ control (57 s). Again, it reflects that RGB was the hardest control and LCH was the easiest one.

Contrary to what we may expect, it is interesting to see that the average time (64 s) for experts was significantly longer than that for naive (52s) as shown in Figure 5B. This might be due to the criteria difference for matching between expert and naive and the naïve observers' lack of patience.

As shown in Figure 5C the time taken to match each of the four colors follows the same trends as the matching accuracy (Figure 3C), but the differences among them are not significant.

Also, a multiple comparison of 2-way ANOVA analysis between control method and observer level was performed. As shown in Figure 6, for experts, the RGB control needed significantly longer time than LCH and {L, r/g, y/b} while there was no significant difference between LCH and {L, r/g, y/b}. This indicates that with some previous knowledge of color attributes, observers can achieve higher matching accuracy with shorter time, while RGB, a control based on the principles of additive color mixing, is the hardest one. For naïve observers, there were no significant differences among the three controls. This means that the three controls have the same difficulty level for them. For the RGB control, experts spent significantly longer time than the naïve observers. This may be one of the reasons that experts achieved significantly higher accuracy for the RGB control.

Insert Figure 6 about here

Insert Figure 7 about here

Of interest is the relationship between match accuracy and match time (Figure 7). One might expect an inverse relationship between them; however, Figure 7 shows that the results are quite observer dependent, with a coefficient of determination (r^2) of only 0.29. In general, however,

the longer it took to make a match, the more accurate it was (notice that the most accurate observer took the longest time).

Judgment Experiment

Each of the 4 parts of the Judgment Experiment was conducted with 31 observers having normal color vision, of which 18 were considered experienced (14 males and 4 females) and 13 naïve (7 males and 6 females). The expert observers either had been working on different research field of color or had extensive knowledge of the fundamentals of colorimetry. For the naïve observers, the experimenter first illustrated the basic concepts of color attributes with the help of the Colorcurve Student Education Set³⁵ before conducting the experiment.

Analysis of variance (Table IX) was performed on the percentage of correct responses using attributes (L_1 , C, h, L_2 , r/g, y/b), expertise (expert/naïve), color difference level (small/medium/large), and judgment criteria (different/same) as the main factors. Lightness was common to both sets of attributes, however its use in each set (L_1 for the LCH set and L_2 for the (L, r/g, y/b) set were analyzed separately. The results showed considerable agreement between Lightness in both sets of experiments (see Figs 8B and 9).

Insert Table IX about here

The results showed that the observers' performances are significantly different for judging different attributes, different color difference levels, and for identifying difference or similarity. There are significant differences between the expert and naïve observers. There were also interactions between attributes and judgment criteria, between expertise and judge criteria, and a

three-way interaction between attributes, color difference levels, and judge criteria. Multiple comparison analyses were performed to determine which factors are statistically significant. The results are shown in Figure 8.

Insert Figure 8 about here

Overall, the performance of the observers was rather poor with a high of only 70.8% correct in Part 1 and a low of 45.3% correct in Part 4. The results in Figure 8 are summarized as follows:

1) Hue, and lightness were significantly easier to identify than Chroma, r/g, and y/b (Figure 8A). This corresponds to the main effect of color attribute in Table IX. There is no improvement using the (L, r/g, y/b) set over the LCH. In fact, performance with Hue is better than r/g and y/b but Chroma judgments are not significantly better than these opponent attributes. 2) Overall, the main effect of expertise shows, unsurprisingly, that experts have significantly better performance than the naïve observers (Figure 8B). 3) There was a significant main effect for the magnitude of the color difference in which an overall improvement was seen in correctly choosing the color attribute as the color difference increased (from approximately 51% correct for the small color difference to approximately 57% correct for the medium and large color difference), however the interaction between level of expertise and color difference magnitude did not quite reach the level of statistical significance (Figure 8C). As seen in Figure 8C, the main effect of expertise (Figure 8B) is due to the differences between experts and naïve observers for the medium and large color difference magnitudes. 4) Identifying the different attribute led to better performance than the common attribute for both sets of attributes (the main effect of judgment criterion). However, this effect was larger for the LCH set corresponding to

the significant interaction between attribute and judgment criterion. Part 1 (LCH Diff) was significantly easier than the other 3 parts, and Part 3 (L, r/g, y/b Diff) was significantly easier than Part 4 (L, r/g, y/b Same), but there were neither significant differences between Parts 2 (LCH Same) and 3 (L, r/g, y/b Diff) nor between Parts 2 (LCH Same) and 4 (L, r/g, y/b Same), as shown in Figure 8D. 5) For experts, to identify difference was significantly easier than to identify similarity while for naïve observers, both tasks exhibited the same difficulty. This interaction between expertise and judgment criterion is shown in Figure 8E.

The only significant three-way interaction was for attributes, color difference magnitude, and judgment criterion. The pattern of average correct response changes significantly for the different magnitudes of color difference when judging different criterion and attributes. There is general improvement as the magnitude of color difference increases, but this improvement varies for the different attributes in each part of the experiment. Although statistically significant, we could find no interpretable trends in this three-way interaction.

Expanding on the results shown in Figure 8D, a multiple comparison of 2-way ANOVA between attributes and judgment criteria was performed as shown in Figure 9. It was found that in both tasks, there were no significant differences in identifying whether Hue or r/g was the common or different attribute though there does exist significant differences in identifying Lightness, Chroma, and y/b. In general, the judgment of the different attribute was easier than choosing the common attribute but this effect was mainly due to Lightness and Chroma judgment differences.

Insert Figure 9 about here

Insert Figure 10 about here

Figure 10 shows the differences in performance between the expert and naïve observers in each part of the experiment. The expert observers were significantly better than the naïve observers in identifying the different attribute in Parts 1 and 3. However, there were no significant differences when judging which attribute was shared in Parts 2 and 4. Additional analysis (not shown) determined that there were no significant differences found between males and females.

Table X summarizes the results of Part 1 (LCH Diff) and Part 2 (LCH Same), and Table XI summarizes the results of Part 3 (L, r/g, y/b Diff) and Part 4 (L, r/g, y/b Same), for all the observers and each group: expert/naïve, males/females. These two tables list the percentages of correct and each type of incorrect answers. With a similar specification to Melgosa, et al., the 6 possible confusions are designated as LC, LH, CH, CL, HL, and HC where the first letter represents the correct attribute (different/same in Part 1 and Part 2, respectively) and the second letter the wrong attribute selected by the observers. The percentage of each type of incorrect response was calculated by dividing the number of each type of confusion by the total number of trials.

Insert Table X about here

Insert Table XI about here

Insert Figure 11 about here

The total percentage of correct and incorrect answers given by all the observers is also shown in the Figure 11. Generally, the results were comparable with those in Melgosa, et al. On average, the observers' ability to distinguish color attributes was somewhat low with an overall average of 56.6% correct.

For LCH, the most identifiable attributes were hue and the least identifiable attributes were Chroma. For L, r/g, y/b, the most identifiable attributes were lightness and the least identifiable attributes were y/b. That the percentage of correct responses in Part 1 (LCH Diff) was greater than in Part 2(LCH Same), and Part 3 (L, r/g, y/b Diff) was greater than Part 4(L, r/g, y/b Same), should be attributable to the greater complexity of parts 2 and 4 since two attributes differed simultaneously which made those pairs perceived as more different than those with only one attribute different, though the total color differences were of similar size. This might confirm the conclusion of Melgosa, et al. that our visual system is somewhat better at identifying a differing attribute, which is basically a perceptive process than a shared attribute, which is a process where cognitive or intellectual component can also play a large role in addition to perception.

In our experiments, the CIECAM02 space was used because it is state-of-the-art for specifying color appearance and contains specification for the unique hues and hue quadrature

that allowed specification of red/green and yellow/blue dimensions of color variation. Our stimuli were adequately rendered to the extent that CIECAM02 captures the desired perceptual attributes. In addition to possible artifacts in CIECAM02 (such as non-uniform change in the contribution of the unique hues between their corresponding hue angles and non-uniform lines of constant hue) there are color appearance phenomena^{1,3} such as the Helmholtz- Kohlrausch effect (Lightness changes with hue or saturation), the Bezold-Brücke (hue changes with lightness) and the Abney effect (hue changes with colorimetric purity) that may have had a negative impact on our results.

Conclusion

The Matching Experiment demonstrated that the performance with the LCH and L, r/g, y/b adjustment controls were significantly better than the display RGB control both in terms of matching accuracy and time, but there was no significant difference between LCH and L, r/g, y/b. The Judgment Experiment demonstrated that it is quite difficult to discern different color attributes in color sample pairs. This indicates that the human vision system does not possess adequate analytical faculties to distinguish such attributes when confronted with only one sample pair.¹⁶ In both experiments, LCH was better than L, r/g, y/b. This consistent result was reasonable since the observers' ability to distinguish color attributes in the Judgment Experiment may influence their performance in the Matching Experiment to some degree.

This was contrary to our expectation that the lower level, redness/greenness, yellowness/blueness, representation of color attributes would allow better matching and color attribute determination. The use of the Hue and Lightness attributes seemed to lead to better performance than Chroma or the opponent r/g and y/b dimensions, however the use of Chroma

was not significantly better than r/g and y/b. This indicates that our ability to describe similarities and differences between colors that vary in a dimension of colorfulness is hampered because we do not have sufficient access to descriptors for these differences.

In both experiments, experts have significantly better performance than the naïve observers. This indicates that appropriate training and knowledge can improve the distinction of color attributes and better control of them. These results may indicate that higher level psychological processing involving cognition and language may be necessary for even apparently simple tasks involving color matching and describing color differences.

The fundamental nature of the red/green, yellow/blue dichotomy described by Hering¹⁴ suggested that these dimensions perhaps would allow for an increased ability to make matches or judge color attributes. This turns out not to be the case. Their fundamental nature suggests that they represent real dimensions with a physiological underpinning as opposed to arbitrary directions in color space. Yet these perceptual dimensions do not find utility (with the exception of the NCS¹² system) in the development of color-order systems and color appearance spaces and are not fundamental to physiologically based color spaces and chromaticity diagrams.

One of our motivations for this work was to determine whether there was a set of color attributes that more naturally expressed our ability to perceive color differences. For the design of color scales for information display, we would like to devise scales that vary uniformly along easily interpretable dimensions of color change. These results do not help us determine whether there are dimensions in color space that satisfy such design requirements although we see better performance for Lightness and Hue judgments. Unfortunately, the Hue dimension is a qualitative (a metathetic dimension as defined by Stevens^{36,37}) perceptual dimension that does not lend itself well to expressing changes in magnitude (Stevens' prothetic dimensions) as we might expect

from scales of colorfulness or lightness. It may be the case that arbitrary paths in color space may work just as well as paths defined by any of the canonical directions or dimensions used in the myriad of color spaces in use today. An argument against this can be made based on the previous finding²¹ that when selecting a color intermediate between two others that differ only in hue, observers tend to choose a color located between the two that is closer to the Cartesian mean rather than the color with the intermediate hue and identical chroma.

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Table captions:

Table I. The parameter settings for CIECAM02.

Table II. The CIECAM02 color coordinates of the four pairs of color patches and the initial color difference (CIEDE00) between the standard patch and the test patch.

Table III. The CIECAM02 color coordinates, ΔE^*_{ab} , CIEDE00, and percentage correct responses for the two patches of each pair for Experiment II – Part 1 (LCH Diff).

Table IV. The CIECAM02 color coordinates, ΔE^*_{ab} , CIEDE00, and percentage correct responses for the two patches of each pair for Experiment II – Part 2 (LCH Same).

Table V. The CIECAM02 color coordinates, ΔE^*_{ab} , CIEDE00, and percentage correct responses for the two patches of each pair for Experiment II – Part 3 (L, r/g, y/b Diff).

Table VI. The CIECAM02 color coordinates, ΔE^*_{ab} , CIEDE00, and percentage of correct responses for the two patches of each pair for Experiment II – Part 4 (L, r/g, y/b Same).

Table VII. Analysis of Variance (ANOVA) of the color differences (CIEDE2000) between matched pairs in Experiment I.

Table VIII. Analysis of Variance (ANOVA) of the the time (s) taken to make the matches in Experiment I.

Table IX. Analysis of Variance (ANOVA) of the percentage of correct responses for Experiment II.

Table X. Summary of the percentage of correct and incorrect responses in Part 1 and Part 2 for each group and for all the observers.

Table XI. Summary of the percentage of correct and incorrect responses in Part 3 and Part 4 for each group and for all the observers.

Table I.

	L_A	Y_b	C	N_c	F
Viewing self-luminous display in a darkened room	20.00	18.00	0.59	0.9	0.9

Table II.

	Pair 1	Pair 2	Pair 3	Pair 4
	J/C/h	J/C/h	J/C/h	J/C/h
Patch1 (Standard)	40/50/45	50/30/125	75/40/195	60/60/320
Patch2 (Test)	53/40/55	60/40/115	70/45/210	52/50/310
CIEDE00	14.76	10.99	8.05	8.05

Table III.

Experiment II – Part 1 (LCH Diff)				
Patch 1 J/C/h	Patch 2 change	ΔE^*_{ab}	CIEDE00	% Correct
50/20/85	59 J	8.88 (99.4%L)	7.96	77
50/35/85	68.5 J	18.01 (97.8%L)	15.09	81
50/43/60	77 J	25.88 (96.6%L)	20.76	61
50/35/55	47 C	14.34 (99.9% C)	4.53	68
60/30/75	46 C	20.84 (99.8% C)	6.65	65
70/35/70	60 C	33.39 (99.8% C)	8.87	68
60/45/78	86 h	6.90 (99.1% h)	4.62	42
70/50/78	91 h	12.98 (98.7% h)	8.26	65
80/56/80	96 h	18.70 (98.0% h)	11.21	87
50/20/174	58.5 J	8.40 (100%L)	7.47	81
50/38/172	68.5 J	17.93 (99.8%L)	14.78	68
54/45/159	78 J	22.70 (99.2%L)	17.23	77
50/30/152	40 C	11.98 (99.8% C)	4.66	81
64/30/158	50 C	25.68 (99.8% C)	8.87	71
71/30/165	51 C	27.47 (99.8% C)	9.47	71
62/44/165	177 h	9.32 (93.2% h)	5.20	55
72/48/159	179 h	17.48 (94.2% h)	9.15	90
80/51/162	185 h	21.92 (92.5% h)	11.38	94
50/30/265	59 J	8.89 (99.5%L)	7.92	74
50/40/265	68 J	17.45 (99.3%L)	1	77
50/50/265	75 J	23.94 (98.9%L)	19.28	71
50/35/260	45 C	11.27 (98.9% C)	3.52	58
60/35/260	52 C	19.93 (99.0% C)	5.70	58
70/35/260	58 C	27.85 (99.1% C)	7.42	65
60/60/265	273 h	8.16 (73.7% h)	4.57	71
70/50/265	280 h	12.09 (78.6% h)	7.39	94
80/40/265	283 h	11.31 (81.1% h)	7.39	87
50/20/355	59 J	8.88 (99.1%L)	8.03	71
50/40/355	68.5 J	18.02 (96.8%L)	15.33	74
50/50/355	77 J	26.01 (95.3%L)	21.01	61
50/40/350	57 C	17.26 (99.8% C)	5.33	71
60/40/350	63 C	24.34 (99.8% C)	7.00	68
70/40/350	71 C	33.93 (99.8% C)	9.01	71
60/60/355	3 h	10.27 (97.9% h)	4.45	35
70/60/355	6 h	14.58 (98.7% h)	6.26	74
80/40/355	9 h	12.21 (99.7% h)	6.36	65

Table IV.

Experiment II – Part 2 (LCH Same)				
Patch 1 J/C/h	Patch 2 J/C/h	ΔE^*_{ab}	CIEDE00	% Correct
60/30/85	60/49/80	25.35 (0.02%L)	8.53	45
70/30/85	70/46/75	23.46 (0.06%L)	9.07	48
80/30/85	80/53/70	34.85 (0.07%L)	13.02	52
50/20/85	59/20/90	9.16 (0.27%C)	8.25	13
50/37/83	67/37/92	18.22 (1.04%C)	15.11	23
50/40/75	75/40/86	26.01 (1.83%C)	20.69	26
62/50/84	68/40.5/84	14.55 (0.29%h)	5.76	48
62/50/85	78/35.5/85	26.21 (0.13%h)	12.57	48
62/50/84	85/30/84	36.62 (0.09%h)	17.45	29
60/20/173	60/28/170	9.35 (0.13%L)	5.43	29
70/20/173	70/35/168	18.42 (0.13%L)	9.16	52
80/20/176	80/43/164	30.78 (0.11%L)	13.40	48
51/33/167	57/33/174	7.09 (1.57%C)	5.82	6
52/35/165	62/35/177	12.08 (1.83%C)	9.43	23
53/37/161	67/37/185	20.33 (3.55%C)	14.54	39
50/38/172	58/43/172	10.61 (0.00%h)	7.59	77
52/34/172	66/47/172	22.38 (0.00%h)	13.22	61
55/30/176	75/50/176	32.85 (0.00%h)	17.97	35
60/20/265	60/29.5/260	8.78 (0.03%L)	5.44	48
70/20/265	70/38.5/255	17.52 (0.05%L)	10.76	77
80/20/265	80/49/248	27.73 (0.09%L)	17.02	81
40/30/265	48.5/30/270	9.09 (3.02%C)	8.82	35
40/40/265	57.5/40/275	18.56 (4.91%C)	17.36	42
40/50/265	69.5/50/280	30.57 (6.11%C)	26.15	61
50/40/260	55/50/260	12.58 (2.10%h)	5.29	81
50/40/275	65/55/275	24.83 (1.48%h)	13.57	81
50/32/285	72/50/285	31.27 (0.34%h)	18.96	77
60/25/358	60/36/350	12.88 (0.13%L)	5.53	61
70/25/355	70/40/350	17.09 (0.17%L)	6.60	61
80/25/355	80/48/348	27.22 (0.16%L)	9.54	71
45/30/355	50/30/0	5.80 (0.79%C)	5.33	13
45/40/355	57/40/5	14.38 (1.25%C)	12.33	58
45/50/355	60/50/10	21.46 (1.19%C)	16.07	65
50/50/340	58/42/340	11.21 (0.11%h)	7.98	74
50/50/350	64/35/350	19.45 (0.03%h)	13.41	71
50/50/359	74/30/359	28.75 (0.01%h)	20.57	71

Table V.

Experiment II – Part 3 (L, r/g, y/b Diff)				
Patch 1 J/(r/g)/(y/b)	Patch 2 Change	ΔE^*_{ab}	CIEDE00	% Correct
50/32/30	57 J	7.02 (96.0%L)	6.39	61
50/34/30	66 J	15.73 (95.9%L)	13.46	65
50/35/30	75 J	24.11 (96.0%L)	19.56	55
50/24/40	32 r/g	7.07 (87.7%a)	3.54	48
60/24/40	40 r/g	14.96 (87.1%a)	6.97	55
70/24/40	50 r/g	25.43 (86.5%a)	10.90	58
50/40/15	35 y/b	21.64 (99.8%b)	10.70	42
60/43/15	42 y/b	30.36 (99.8%b)	13.96	35
70/40/15	47 y/b	37.58 (99.9%b)	16.38	55
50/-15/30.6	70 J	19.44 (98.0%L)	16.03	74
50/-20/35.6	64 J	13.89 (96.7%L)	11.79	84
50/-28/30	57 J	7.06 (96.8%L)	6.26	81
50/-25.6/38	-35.5 r/g	8.69 (89.5%a)	4.13	42
60/-25.6/40	-43.4 r/g	16.58 (89.4%a)	7.20	52
70/-25.6/36	-49 r/g	23.79 (89.2%a)	9.39	52
50/-15/20.3	34.7 y/b	16.84 (98.8%b)	7.53	58
60/-20/20.3	42 y/b	26.00 (98.1%b)	10.86	71
70/-22/20.3	48.4 y/b	34.73 (98.0%b)	13.55	68
50/-18/-20	77 J	25.66 (99.9%L)	20.30	81
50/-22/-26	67 J	16.50 (99.8%L)	13.77	81
50/-25/-25	57 J	6.95 (99.8%L)	6.19	74
(Dropped)				
60/-22/-23	-36 r/g	16.25 (93.3%a)	7.93	45
70/-22/-20	-42 r/g	24.30 (93.5%a)	10.84	42
50/-25/-20	-30 y/b	7.61 (77.1%b)	4.358	52
60/-25/-20	-38 y/b	14.52 (77.9%b)	7.68	61
70/-25/-20	-45 y/b	21.12 (78.8%b)	10.42	61
50/28/-25	77 J	25.74 (98.2%L)	20.81	81
50/31/-29	67 J	16.56 (97.9%L)	14.22	87
50/40/-35	57 J	7.02 (96.6%L)	6.46	84
50/40/-40	50 r/g	10.20 (91.24%a)	3.80	32
60/40/-45	55 r/g	16.25 (92.8%a)	5.69	48
70/40/-50	60 r/g	22.83 (94.0%a)	7.56	35
50/50/-40	-50 y/b	16.70 (83.77%b)	4.81	35
60/55/-40	-55 y/b	25.86 (84.4%b)	6.99	48
70/50/-30	-50 y/b	32.63 (89.0%b)	10.05	42

Table VI.

Experiment II – Part 4 (L, r/g, y/b Same)				
Patch 1 J/(r/g)/(y/b)	Patch 2 J/(r/g)/(y/b)	ΔE^*_{ab}	CIEDE00	% Correct
50/24/40	50/32/30	10.61 (0.08% L)	6.50	61
60/24/40	60/44/20	23.99 (0.12% L)	15.49	71
70/24/40	70/50/15	2.12 (0.13% L)	20.29	84
50/32/34	55/32/40	9.23 (0.87% a)	5.40	32
50/40/34	62/40/44	18.15 (1.28% a)	11.44	58
50/50/34	67/50/45	23.10 (2.02% a)	15.13	48
60/27/40	63/37/40	10.22 (14.99% b)	4.88	35
60/27/47	70/47/47	22.20 (16.169% b)	10.68	39
60/27/45	75/50/45	27.87 (15.99% b)	13.86	39
50/-5/30.3	50/-15/35.6	9.83 (0.07% L)	4.78	61
60/-5/30.3	60/-20/40.6	17.77 (0.05% L)	7.24	55
70/-5/29.9	70/-28/42	25.77 (0.07% L)	10.53	48
50/-15/30.3	55/-15/40.7	14.07 (1.16% a)	6.71	35
50/-20/30.4	60/-20/45	21.30 (1.07% a)	11.07	39
50/-22/30.3	65/-22/47.4	27.01 (0.80% a)	14.82	65
60/-5.6/43	63/-15.5/43	7.39 (0.39% b)	4.94	19
60/-5.6/45	70/-20.4/45	13.58 (0.00% b)	9.50	35
60/-5.6/41	75/-23/41	18.23 (0.02% b)	12.85	35
50/-14.6/-29.5	50/-18.3/-39.5	9.54 (0.21% L)	4.27	48
60/-14.6/-29.5	60/-22.3/-42.1	14.31 (0.22% L)	6.14	26
70/-14.6/-25.5	70/-28/-43	22.61(0.21% L)	9.48	23
50/-20/-30	55/-20/-34	5.73 (5.57% a)	4.65	32
50/-18/-30	60/-18/-37	11.01 (4.27% a)	8.79	42
50/-15/-30	65/-15/-40	16.25 (3.56% a)	12.61	35
60/-22/-30	63/-32/-30	11.89 (6.29% b)	6.36	29
60/-22/-33	70/-34/-33	17.25 (3.96% b)	10.23	39
60/-22/-29	75/-37/-29	23.15 (3.28% b)	13.84	39
50/18.6/-17.5	50/28.6/-24.5	14.16 (0.14% L)	5.62	55
60/18.6/-17.5	60/31.1/-29.9	21.91 (0.09% L)	7.92	45
70/18.6/-17.5	70/40.7/-35.4	36.19 (0.12% L)	11.54	45
40/50/-32.4	45/50/-36.8	9.39 (16.56% a)	5.47	58
40/55/-32.4	50/55/-40.8	18.59 (18.00% a)	10.93	65
40/60/-32.4	55/60/-45.2	28.64 (19.48% a)	16.49	55
50/36/-30.5	53/48.3/-30.5	12.56 (11.68% b)	5.85	19
50/36/-33.1	60/54.7/-33.1	20.60 (11.75% b)	11.97	45
50/36/-36.6	65/60.9/-36.6	28.11 (11.66% b)	16.53	58

Table VII.

SOURCE	DF	P-VALUE
X1 (Control)	2	0
X2 (Expertise)	1	0
X3 (Patch Color)	3	0
X1*X2	2	0.0044
X1*X3	6	0.0022
X2*X3	3	0.0007
X1*X2*X3	6	0.0773
Error	1128	
Total	1151	

Table VIII.

SOURCE	DF	P-VALUE
X1 (Control)	2	0
X2 (Expertise)	1	0
X3 (Patch Color)	3	0.0459
X1*X2	2	0.3411
X1*X3	6	0.1839
X2*X3	3	0.9617
X1*X2*X3	6	0.9182
Error	1128	
Total	1151	

Table IX.

SOURCE	DF	P-VALUE
X1 (attributes)	5	0
X2 (expertise)	1	0
X3 (color difference size)	2	0.0035
X4 (judge criteria)	1	0
X1*X2	5	0.9213
X1*X3	10	0.4811
X1*X4	5	0
X2*X3	2	0.1097
X2*X4	1	0.0008
X3*X4	2	0.7134
X1*X2*X3	10	0.5321
X1*X2*X4	5	0.5918
X1*X3*X4	10	0.0003
X2*X3*X4	2	0.4715
X1*X2*X3*X4	10	0.877
Error	214	
Total	285	

Table X.

	Experiment II Part 1/Part 2						
	% Correct	% Incorrect					
		LC	LH	CH	CL	HL	HC
Expert	79.5/53.2	4.0/ 4.2	1.7/9.9	2.5/17.6	5.1/4.6	0.9/4.6	6.3/5.9
Naive	58.8/48.1	9.0/7.7	4.5/7.3	8.3/12.8	6.8/9.2	3.4/6.0	9.2/9.0
Male	71.3/49.7	5.6/5.7	2.6/10.1	4.5/15.5	6.0/6.6	1.7/ 5.3	8.3/7.1
Female	69.7/53.9	7.2/5.6	3.3/6.1	5.8/15.8	5.6/6.4	2.5/5.0	5.8/7.2
Total	70.8/51.1	6.1/5.6	2.9/8.8	4.9/15.6	5.8/ 6.5	2.0/5.2	7.5/7.2

Table XI.

	Experiment II Part 3/Part 4						
	% Correct	% Incorrect					
		L-r/g	L-y/b	r/g-y/b	r/g-L	y/b-L	y/b-r/g
Expert	65.7/47.4	2.1/6.8	3.7/7.7	8.6/ 9.7	5.9/7.1	3.5/10.2	10.6/11.1
Naive	49.9/42.5	5.7/7.7	4.8/9.6	10.5/12.0	9.7/6.8	6.2/10.5	13.2/10.9
Male	58.1/48.1	3.8/6.2	4.9/ 8.3	8.8/9.4	7.3/ 7.4	4.6/10.6	12.4/9.9
Female	61.1/39.4	3.1/9.2	2.6/8.9	10.6/13.3	7.7/6.1	4.6/9.7	10.3/13.3
Total	59.1/45.3	3.6/7.2	4.1/8.5	9.4/10.7	7.5/7.0	4.6/10.3	11.7/11.0

Figure Legends:

Figure 1. The four colors used in the Matching Experiment were chosen at hue angles of 45° , 125° , 195° , and 320° in the CIECAM02 space at Lightness, $J = 70$. These colors were chosen to be intermediate to the unique hues indicated (for illustrative purpose only).

Figure 2. Illustration of the Matching Experiment setup. The observers set matches using three different sets of slider controls: RGB, LCH, and $\{L, r/g, y/b\}$.

Figure 3. Average color difference (CIEDE00) and 95% confidence intervals for the main effect for the Matching Experiment: (A) Control method, (B) Observer expertise, and (C) Patch Color (hue angle).

Figure 4. The average color difference (CIEDE00) for each of the three control methods by both expert and naïve observers.

Figure 5. The average time (s) taken for making a match showing the main effects of (A) Control method, (B) Observer expertise, and (C) Patch Color (hue angle).

Figure 6. The average time (s) taken for making a match by expert and naïve observers for the three different control methods.

Figure 7. The average color difference (CIEDE00) versus the average time for each of the expert and naïve observers.

Figure 8. The average percent correct answers for (A) The main effect of color attribute, (B) Main effect of observer expertise, (C) Magnitude of color difference for expert and naïve observers, (D) Attribute set and judgment criterion (Parts 1 through 4) and (E) Observer expertise and judgment criterion.

Figure 9. The average percent correct answers by all observers for each color attribute and judgment criteria. The squares represent identification of the common attribute when the two other attributes differ and the circles represent the identification of the different attribute when the patches have the other two attributes in common.

Figure 10. The average percent correct answers for each experimental part separated by observer expertise. The Expert observer performance is indicated by the circles and solid lines. Naïve observer performance is indicated by the squares and dashed lines.

Figure 11. The distribution of correct and incorrect responses for all observers for each part of Experiment II.

Fig. 1

Fig. 2

Fig. 3

Fig. 4

Fig. 5

Fig. 6

Fig. 7

Fig. 8

Fig. 9

Fig. 10

Fig. 11