How Well Can People Use Different Color Attributes?

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Abstract

Two psychophysical experiments have been conducted to analyze the perception and understanding of different color representations. Experiment I is a matching experiment using method of adjustment. Three different adjustment control methods were used. The results showed that the Lightness, Chroma, Hue (LCH) and Lightness, red/green, blue/yellow (LRGYB) adjustments elicited significantly better performance than the display RGB adjustment in terms of both precision and time, but were not significantly different from each other. Expert observers have significantly better performance than naive observers in terms of precision. Experiment II is a replication and extension of Melgosa, et al.'s judgment experiment. 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. For experts, in the case of large color differences, constant lightness and chroma were more identifiable, while in the case of small color differences, constant hue was more identifiable. There were no significant differences found between male and female.

Introduction

In order to describe color appearance, it is generally agreed that five perceptual dimensions, or attributes are necessary: brightness, lightness, colorfulness, chroma, and hue.[1] 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, which is used for color specification and communication, CIELAB, which is used for formulating color differences, and CIECAM02, 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 physiologically-based color spaces and chromaticity diagrams which specify the color signal as opposed to the appearance attributes. In addition, alternative color order systems, such as the Swedish Natural Color System (NCS) (blackness, chromaticness, and hue) and the Duesches Institute für Normung (DIN) 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, the psychological description of color representation remains elusive. We can describe color description 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 Herring opponency 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 language and cognition. At a still higher level, there is evidence for categorical representation that is tightly associated with language.

Melgosa, et al.[2] asked the question whether we are able to distinguish the color attributes of lightness, hue, and chroma. In their experiments, 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. Montag[3] had observers determine the color that was intermediate between two others 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, Herring-opponent, description to distinguish the differences.

In this paper we explore this issue using two psychophysical experiments. In the first experiment, the speed and accuracy of color matching is measured in a task in which observers use 3 different adjustment controls: lightness, chroma, and hue (LCH); lightness, redness/greenness, yellowness/blueness (LRGYB); and display RGB. In the second experiment, observers were presented with color difference pairs that were specified in either LCH or LRGYB and decided the attribute the colors shared or differed by. If the LCH or LRGYB 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 people's abilities to control and distinguish different color attributes. Experiment I was a matching experiment using the method of adjustment. It compared matching a patch using three different controls: 1) Display RGB, 2) Lightness, Hue, and Chroma (LCH), 3) Lightness, Redness/Greenness, and Yellowness/Blueness (LRGYB). Experiment II was a judgment experiment. It was a replication and extension of Melgosa, et al.'s experiment.[2] In experiment II, observers were asked to judge similarities or differences of color pairs using two sets of color attributes: 1) LCH, 2) LRGYB.

Experiment I

Four colors were carefully selected for Experiment I. Since LRGYB was also used in the experiment, the experimental color patches were chosen to be combinations of the four unique hues. Therefore, the hue angles of the four colors were selected at 45°, 125°, 195°, and 320°. The Lightness, Chroma, and Hue values of the four pairs of color patches in CIECAM02 perceptual attributes are shown in Table 1. The parameters settings of CIECAM02 are shown in Table 2.

Table 1. The CIECAM02 color attributes of the four pairs of color patches and the initial CIEDE00 between the standard patch and the test patch.

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

Table 2. The Parameter Settings of CIECAM02

	L_A	Y_b	C	N_C	F
Self-luminous display in a dark room	20.00	18.00	0.59	0.9	0.9

CIECAM02 hue quadrature was modified to define the four unique hues (red, yellow, green, blue) 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.

Two patches (the target and test) were juxtaposed on the LCD screen with a separation of 0.5 cm subtending a visual angle of 27.1° x 13.7° for an observer at a normal viewing distance of 25 cm. The LCD display was carefully calibrated using the commonly used technique consisting of three 1-D LUTs and a 3 by 4 matrix.[8] The observers' task was to match the color of the test patch to the target using three sliders. Since the time taken to make a match was also measured, observers were asked to try to make the match as quickly as possible. Each match was repeated 4 times for each of the three controls in a random order for a total of 48 trials.

Experiment II

The purpose of Experiment II was to determine how well observers use color attributes to identify differences (task 1) and similarities (task 2) between pairs of color patches. There were 4 parts in this experiment in total. In each part, 36 pairs (part 3 had 35 pairs due to an error) of color patches with two patches of each pair either differing in only one of the color attributes or having only one of the color attributes in common were carefully prepared. For Part 1 (LCHDiff) and Part 2 (LCHSame), the attributes were Lightness, Hue, and Chroma. For Parts 3 (LRGYBDiff) and 4 (LRGYBSame), the attributes were Lightness, redness/greenness, and yellowness/blueness. For Parts 1 and 3, the observer had to identify the attribute that differed between the two color patches. In Parts 2 and 4, the task was to choose the attribute that was in common.

Table 3. The CIECAM02 color attributes, ΔE^*_{ab}, and CIEDE00 of the two patches of each pair for Experiment II – Part 1 (LCHDiff).

Patch1 L/C/h	Patch2 L/C/h	ΔE^*_{ab}	CIEDE00	%Correct
50/20/85	59/20/85	8.88 (99.4%L)	7.96	77
50/35/85	68.5/35/85	18.01 (97.8%L)	15.09	81
50/43/60	77/43/60	25.88 (96.6%L)	20.76	61
50/35/55	50/47/55	14.34 (99.9% C)	4.53	68
60/30/75	60/46/75	20.84 (99.8% C)	6.65	65
70/35/70	70/60/70	33.39 (99.8% C)	8.87	68
60/45/78	60/45/86	6.90 (99.1% H)	4.62	42
70/50/78	70/50/91	12.98 (98.7% H)	8.26	65
80/56/80	80/56/96	18.70 (98.0% H)	11.21	87
50/20/174	58.5/20/174	8.40 (100%L)	7.47	81
50/38/172	68.5/38/172	17.93 (99.8%L)	14.78	68
54/45/159	78/45/159	22.70 (99.2%L)	17.23	77
50/30/152	50/40/152	11.98 (99.8% C)	4.66	81
64/30/158	64/50/158	25.68 (99.8% C)	8.87	71
71/30/165	71/51/165	27.47 (99.8% C)	9.47	71
62/44/165	62/44/177	9.32 (93.2% H)	5.20	55
72/48/159	72/48/179	17.48 (94.2% H)	9.15	90
80/51/162	80/51/185	21.92 (92.5% H)	11.38	94
50/30/265	59/30/265	8.89 (99.5%L)	7.92	74
50/40/265	68 /40/265	17.45 (99.3%L)	14.65	77
50/50/265	75/50/265	23.94 (98.9%L)	19.28	71
50/35/260	50/45/260	11.27 (98.9% C)	3.52	58
60/35/260	60/52/260	19.93 (99.0% C)	5.70	58
70/35/260	70/58/260	27.85 (99.1% C)	7.42	65
60/60/265	273/60/265	8.16 (73.7% H)	4.57	71
70/50/265	280/50/265	12.09 (78.6% H)	7.39	94
80/40/265	283/40/265	11.31 (81.1% H)	7.39	87
50/20/355	59/20/355	8.88 (99.1%L)	8.03	71
50/40/355	68.5/40/355	18.02 (96.8%L)	15.33	74
50/50/355	7750/355	26.01 (95.3%L)	21.01	61
50/40/350	50/57/350	17.26 (99.8% C)	5.33	71
60/40/350	60/63/350	24.34 (99.8% C)	7.00	68
70/40/350	70/71/350	33.93 (99.8% C)	9.01	71
60/60/355	3/60/355	10.27 (97.9% H)	4.45	35
70/60/355	6 /60/355	14.58 (98.7% H)	6.26	74
80/40/355	9 /40/355	12.21 (99.7% H)	6.36	65

The 36 pairs of color 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 differing in the attribute and magnitude of the color difference as shown in Tables 3 and 4. 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˚, the Lightness, R/G, Y/B values are shown in Tables 5 and 6.

For each part, the color pairs were randomly presented on the same screen at the same size as in Experiment I. For each pair, the observers indicated the desired attribute by pressing the appropriate key on the keyboard.

Table 4. The CIECAM02 color attributes, ΔE^*_{ab}, and the CIEDE00 of the two patches of each pair for Experiment II – Part 2 (LCHSame).

Patch1 L/C/h	Patch2 L/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 5. The CIECAM02 color attributes, ΔE^*_{ab}, and the CIEDE00 of the two patches of each pair for Experiment II – Part 3 (LRGYBDiff).

Patch1 L/(r/g) /(y/b)	Patch2 L (r/g) /(y/b)	ΔE^*_{ab}	CIEDE00	%Correct
50/32/30	57/32/30	7.02 (96.0%L)	6.39	61
50/34/30	66/34/30	15.73 (95.9%L)	13.46	65
50/35/30	75 /35/30	24.11 (96.0%L)	19.56	55
50/24/40	50/32/40	7.07 (87.7%a)	3.54	48
60/24/40	60/40/40	14.96 (87.1%a)	6.97	55
70/24/40	70/50/40	25.43 (86.5%a)	10.90	58
50/40/15	50/40/35	21.64 (99.8%b)	10.70	42
60/43/15	60/43/42	30.36 (99.8%b)	13.96	35
70/40/15	70/40/47	37.58 (99.9%b)	16.38	55
50/-15/30.6	70/-15/30.6	19.44 (98.0%L)	16.03	74
50/-20/35.6	64/-20/35.6	13.89 (96.7%L)	11.79	84
50/-28/30	57/-28/30	7.06 (96.8%L)	6.26	81
50/-25.6/38	50/-35.5/38	8.69 (89.5%a)	4.13	42
60/-25.6/40	60/-43.4/40	16.58 (89.4%a)	7.20	52
70/-25.6/36	70/-49/36	23.79 (89.2%a	9.39	52
50/-15/20.3	50/-15/34.7	16.84 (98.8%b)	7.53	58
60/-20/20.3	60/-20/42	26.00 (98.1%b)	10.86	71
70/-22/20.3	70/-22/48.4	34.73 (98.0%b)	13.55	68
50/-18/-20	77 /-18/-20	25.66 (99.9%L)	20.30	81
50/-22/-26	67/-22/-26	16.50 (99.8%L)	13.77	81
50/-25/-25 (Dropped)	57/-25/-25	6.95 (99.8%L)	6.19	74
60/-22/-23	60/-36/-23	16.25 (93.3%a)	7.93	45
70/-22/-20	70/-42/-20	24.30 (93.5%a)	10.84	42
50/-25/-20	50/-25/-30	7.61 (77.1%b)	4.358	52
60/-25/-20	60/-25/-38	14.52 (77.9%b)	7.68	61
70/-25/-20	70/-25/-45	21.12 (78.8%b)	10.42	61
50/28/-25	77 /28/-25	25.74 (98.2%L)	20.81	81
50/31/-29	67 /31/-29	16.56 (97.9%L)	14.22	87
50/40/-35	57/40/-35	7.02 (96.6%L)	6.46	84
50/40/-40	50/50/40	10.20 (91.24%a)	3.80	32
60/40/-45	60/55/45	16.25 (92.8%a)	5.69	48
70/40/-50	70/60/-50	22.83 (94.0%a)	7.56	35
50/50/-40	50/50/-50	16.70 (83.77%b)	4.81	35
60/55/-40	60/55/-55	25.86 (84.4%b)	6.99	48
70/50/-30	70/50/-50	32.63 (89.0%b)	10.05	42

Table 6. The CIECAM02 color attributes, ΔE^*_{ab}, and the CIEDE00 of the two patches of each pair for Experiment II – Part 4 (LRGYBSame).

Patch1 L /(r/g) /(y/b)	Patch2 L /(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

Results and Discussion

Experiment I

24 observers with normal color vision participated in Experiment 1, of which 17 were considered expert and 7 naïve based on self-report (in general, faculty, students, and technical staff of the lab were considered as experts due to their experience with psychophysics and working with color). The color difference between the target and test and the time taken to make a match was measured. Analyses of Variance (ANOVA) were performed on both the color difference and the time using the factors: control type (RGB, LCH, LRGYB), expertise (expert or naive), and patch color (4 colors).

Table 7. ANOVA of Color Difference.

SOURCE	DF	P-VALUE
X1 (Control)	2	0
X2 (Expertise)	1	0
X3 (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	

The color difference results (Table 7) showed that there were significant differences between the three control methods, and between expert and naive observers, and between the four colors. There were also significant 2-way interactions between all pairs of the three factors.

In order to determine which control types, observer levels, and patch colors were significantly different, multiple comparisons were performed with the error rate controlled conservatively by Tukey's honestly significant difference (hsd) criterion.[5]

Figure 1 shows that the LCH (with an average CIEDE00 of 1.97) and LRGYB (with an average CIEDE00 of 2.23) controls were significantly better than RGB (with an average CIEDE00 of 2.95), but were not significantly different from each other.

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 2. This indicates that training may improve the observers' performance.

A multiple comparison of a 2-way ANOVA between adjustment method and observer expertise was performed. The experts' performance with the LCH controls was significantly better than with RGB while there were no significant differences between RGB and LRGYB and between LCH and LRGYB. For the naïve observers, both LCH and LRGYB were significantly better than RGB while there was no significant difference between them.

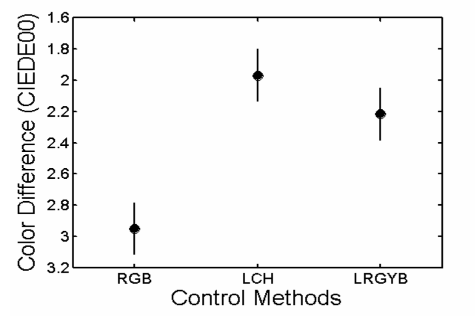

Figure 1. Average CIEDE00 for the three control methods.

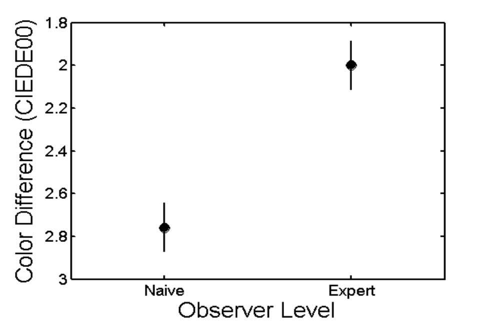

Figure 2. Average CIEDE00 for expert and naive.

These results were consistent with the observers' comments that the RGB was the hardest one 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 naive while for LRGYB there was no significant difference between expert and naive 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, such as, knowing that the green channel is controlling the overall lightness to some degree, and they have some basic knowledge about the principles of additive color mixing of the three primaries, etc. But for LRGYB, both expert and naive observers seemed unfamiliar with the task. Therefore, there was no significant difference between them.

It was also found that the color with a lower lightness was harder to match than that with a higher lightness. This indicates that observers are more sensitive at higher lightness levels.

Table 8 is the ANOVA of the time taken to make a match using the same three factors as for color difference, above.

Figure 3 shows that the average time (66s) for RGB control was significantly longer than those for LCH (52s) and LRGYB control (57s). Again, it reflects that RGB was the hardest control and LCH was the easiest one.

The average time (64s) for the experts was significantly longer than that for the naive observers (52s) as shown in Figure 4.

Table 8. ANOVA of Time

SOURCE	DF	P-VALUE
X1 (Control)	2	0
X2 (Expertise)	1	0
X3 (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	

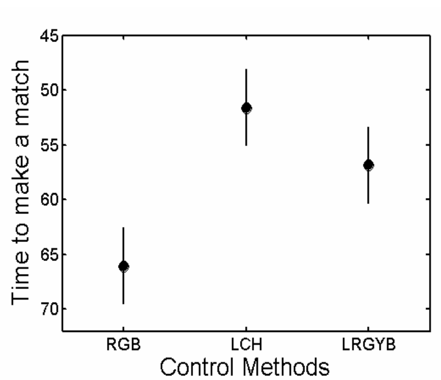

Figure 3. The average time for the three controls.

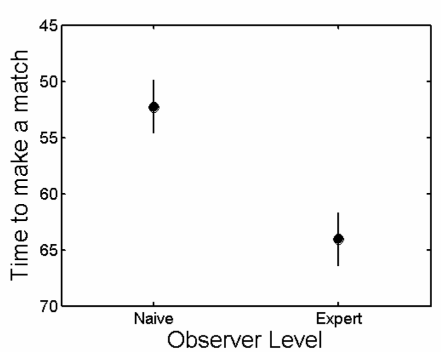

Figure 4. The average time for expert and naive.

A multiple comparison of the 2-way ANOVA between control method and observer level was performed. For experts, the RGB control took significantly longer time than LCH and LRGYB while there was no significant difference between LCH and LRGYB. This indicates that with some previous knowledge of color attributes, observers can achieve higher matching precision 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 precisions for the RGB control.

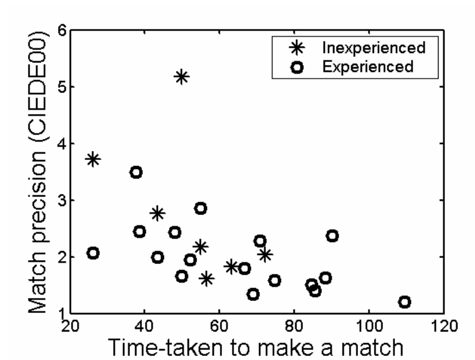

Figure 5. The average CIEDE00 vs. the average time for expert and naive.

The relationship between match precision and match time is shown in Figure 5. One might expect an inverse relationship between them however the results are observer dependent, with a correlation of only 0.29 (r^2). In general, the longer it took to make a match, the more accurate it was.

Experiment II

Each of the 4 parts of Experiment II was conducted with 31 observers having normal color vision, of which 18 were considered experienced (14 males and 4 females) and 13 naive (7 males and 6 females). For the naive observers, the experimenter first illustrated the basic concepts of color attributes with the help of the COLORVURVE Student Education Set[7] before conducting the experiment.

ANOVA analyses (Table 9) were performed on the correct percentage using attributes (L1, C, H, L2, r/g, y/b), expertise (expert/naive), color difference level (small /medium/large), and judgment criteria (different/same) as the main factors.

Each of the factors showed significant main effects. There were also interactions between attributes and judgment criteria, between expertise and judge criteria, and a 3-way interaction between attributes, color difference levels, and judge criteria. Multiple comparison analyses were performed to determine significant differences. The main results are shown in Figure 6 - Figure10.

Table 9. ANOVA of Correct Percentage for Expert/Naive for All Four Parts

SOURCE	DF	P-VALUE
X1 (ATTRIBUTES)	5	0
X2 (EXPERTISE)	1	0
X3 (COLOR DIFF. LEVEL)	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	

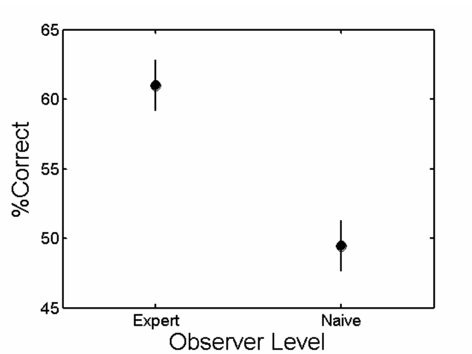

Figure 6. Average % correct answers by each group for all the 4 parts.

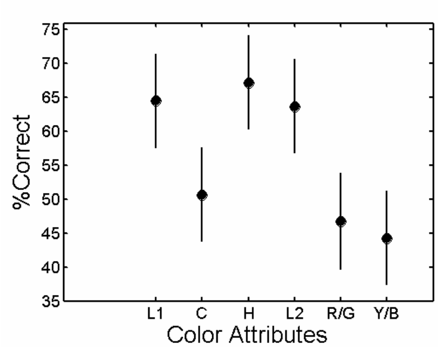

Figure 7. Average % correct answers by all observers for each attribute.

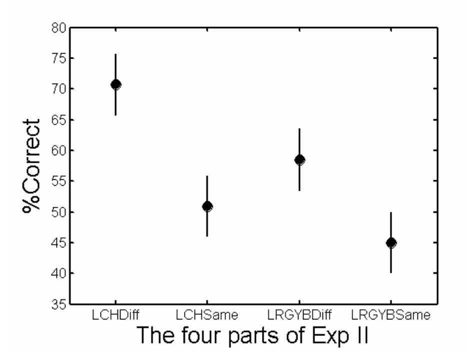

Figure 8. Average % correct answers by all observers for each part.

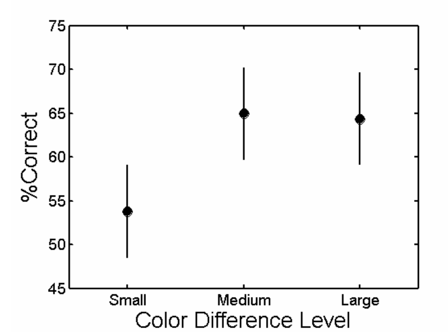

Figure 9. Average % correct answers by expert for each color difference size.

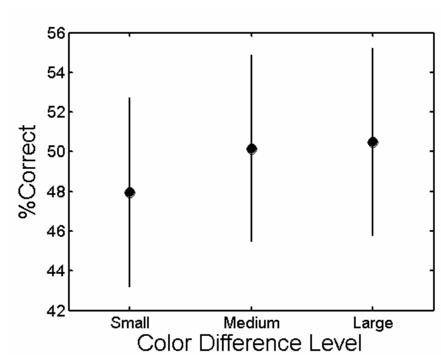

Figure 10. Average %correct answers by naïve for each color difference size.

It was found that for all observers: 1) Part 1 (LCHDiff) was significantly easier than the other 3 parts, and part 3 (LRGYBDiff) was significantly easier than part 4 (LRGYBSame), but there were no significant differences between Part 2 (LCHSame) and part 3 (LRGYBDiff) nor between part 2 and part 4; 2) Hue, and lightness were significantly easier to identify than Chroma, r/g, and y/b; 3) Identification of the different attribute was significantly easier than identification of the common attribute.; 4) For all 4 parts, experts have significantly better performance than the naïve observers; and 5) For the experts, performance with the medium range of color differences was better than for the small ones but the large color differences did not improve performance much. For the naïve observers, there are no significant differences between the three color-difference levels.

It was also found that in both tasks, there were no significant differences in identifying Hue (more identifiable in both cases) and R/G (less identifiable in both cases) though there does exist significant differences in identifying Lightness (in both LCH and LRGYB), Chroma, and Y/B. The first observation indicates that people are more sensitive to Hue while not as sensitive to R/G while the second observation just indicates that identifying difference or similarity are tasks with different difficulty levels. For experts, to identify difference is significantly easier than to identify similarity while for naïve observers, both tasks exhibit the same difficulty.

Multiple comparisons were also performed on each part for all observers and each group. In part 1 (LCHDiff), hue difference was the most difficult to identify among the three attributes when the entire color difference was small while it was the most identifiable when the entire color difference was large. In Part 2 (LCHSame), there was no significant difference between the expert and naïve observers (that is, the difficulty for both expert and naïve observers was the same), and hue and lightness were significantly more identifiable than Chroma. In Part 3 (LRGYBDiff), experts were significantly better than the naïve observers, and lightness was significantly more identifiable than R/G and Y/B. In part 4 (LRGYBSame), the results were similar to that in Part 2; there were no significant difference between expert and naïve observers, and lightness was significantly more identifiable than Y/B. Also, in part 4 (LRGYBSame), a constant lightness was more identifiable for the experts when the entire color difference was small, while there was not much difference for naïve observers. For the experts, part 1 (LCHDiff) was significantly easier than Parts 2, 3, and 4, and part 3 (LRGYBDiff) was significantly easier than Parts 2 and 4, but there was no significant difference between parts 2 and 4. For naïve observers, there was only a significant difference between part 1 (LCHDiff) and part 4 (LRGYBSame), but there were no significant differences between parts 1 and 3 or between parts 2 and 4. There were no significant differences found between males and females.

Table 10 summarizes the results of Part 1 (LCHDiff) and Part 2 (LCHSame), and Table 11 summarizes the results of Part 3 (LRGYBDiff) and Part 4 (LRGYBSame), for all the observers and each group: expert/naive, males/females. These two tables list the percentages of correct and each type of incorrect answers. With a similar specification to Melgosa, et al.'s, 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 responses was referred by dividing the times of each type of confusion by the total number of trials.

Table 10. Summary of the percentage of correct and incorrect responses in Part 1 and Part 2 for each group and for all the observers.

	Experiment II		Part 1/Part 2		
	Expert	Naive	Male	Female	Total
%Correct	79.5/53.2	58.8/48.1	71.3/49.7	69.7/53.9	70.8/5
LC	4.0/ 4.2	9.0/7.7	5.6/5.7	7.2/5.6	6.1/5.6
LH	1.7/9.9	4.5/7.3	2.6/10.1	3.3/6.1	2.9/8.8
CH	2.5/17.6	8.3/12.8	4.5/15.5	5.8/15.8	4.9/15.
CL	5.1/ 4.6	6.8/ 9.2	6.0/ 6.6	5.6/6.4	5.8/ 6.
HL	0.9/4.6	3.4/6.0	1.7/ 5.3	2.5/5.0	2.0/5.2
HC	6.3/5.9	9.2/9.0	8.3/7.1	5.8/7.2	7.5/7.2

Table 11. Summary of the percentage of correct and incorrect responses in Part 3 and Part 4 for each group and for all the observers.

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

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 Melgosa, et al.'s. 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 attribute was Chroma. For LRGYB, the most identifiable attribute was lightness and the least identifiable attributes was Y/B. That the percentage of correct responses in Part 1 (LCHDiff) was greater than in part 2 (LCHSame), and part 3 (LRGYBDiff) was greater than part 4 (LRGYBSame), 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 Melgosa, et al.'s conclusion 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.

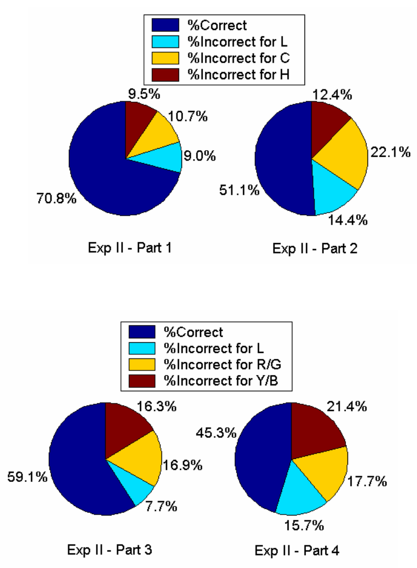

Figure 11. Distribution of correct/incorrect responses given by all the observers for Exp II – part 1, part 2, part 3, and part 4.

Conclusion

Experiment I demonstrated that the performance with the LCH and LRGYB adjustment controls were significantly better than the display RGB control both in terms of matching precision and time, but there was no significant difference between LCH and LRGYB. Experiment II 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.[2] In both experiments, LCH was better than LRGYB. This consistent result was reasonable since the observers' ability to distinguish color attributes in experiment II may influence their performance in experiment I to some degree.

This was contrary to our expectation that the lower level, red/green, yellow/blue, representation of color attributes would allow better matching and color attribute determination. 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.

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Biographies

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