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Developing Color Tolerance Criteria for White LEDs

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Summary

At the present time, most phosphor-based, unbinned, white LEDs show significant color variations. Luminaire manufacturers who participated in the ASSIST-sponsored roundtable meeting that took place on the 4th of August, 2002, in Salt Lake City, Utah, pointed to this fact as the main reason why they would not consider white LEDs for general illumination fixtures. Therefore, for white LEDs to be accepted broadly for illumination applications, the color variation between similar products must become much smaller. Color binning is one option for creating arrays with unnoticeable color variations. Then the question is, how much color variation can there be between similar white LEDs? The American National Standards Institute (ANSI) specifies a four-step MacAdam ellipse as the color tolerance criterion for certain types of fluorescent lamps. MacAdam conducted his first study in 1942 that developed these tolerance contours. Since then several other studies have shown that there are many factors that could impact the size of the color tolerance region. Based on past studies it was hypothesized that the color tolerance area for light sources with multiple-peak spectrums would be different compared to light sources with continuous spectrums. To verify this hypothesis and develop color tolerance criteria for white LEDs, a laboratory human factors experiment was conducted. The study also investigated the impact of light level, visual complexity of the illuminated scene, light source spectrum, and correlated color temperature (CCT) on color tolerance range. From the results of this study, it was concluded that the spectral power distribution of the light source and light level (in the photopic range) had very little influence on the size of the color tolerance area. However, the background of the illuminated scenes affected the size of the color tolerance area very much.

Criteria for binning white LEDs: Based on the results, the following two criteria are proposed for binning white LEDs. The following color binning criteria are based on the assumption that the LEDs have already been binned for light output.

- 2-step MacAdam ellipse – For applications where the white LEDs (or white LED fixtures) are placed side-by-side and are directly visible, or when these fixtures are used to illuminate an achromatic (white) scene. Accent lighting a white wall and lighting a white cove are some examples.
- 4-step MacAdam ellipse – For applications where the white LEDs (or white LED fixtures) are not directly visible, or when these fixtures are used to illuminate a visually complex, multicolored scene. Lighting a display case and accent lighting multicolored objects or paintings are some examples.

Note: *The chromaticity values of presently available T8F32 linear fluorescent lamps operated on electronic ballasts fall within 2-step MacAdam ellipses.*

I. Introduction

Presently, high-power light-emitting diodes (LEDs) are being developed for general illumination purposes, and white LED light sources are beginning to find uses in niche applications. The variety of lamp types and lamp colors in the marketplace today greatly helps lighting designers create visually appealing environments. On the other hand, lamps of similar type with noticeably different colors can cause problems. As an example, if the colors between the lamps used in wall washing applications are not close, observers perceive that difference on the wall and the visual appeal is reduced. Of the many traditional light sources, metal halide lamps are known for their color differences. Alternately, linear fluorescent lamps have very little color difference, which is not noticeable at all. This is one main reason why metal halide technology has had limited acceptance for interior lighting applications.

Similar to the metal halide light source technology, at the present time most phosphor-based white LEDs (unbinned) show significant color variations. Data from a recent LRC study (Figure 1) show that the color variation between several randomly selected white LEDs is about a 12-step MacAdam ellipse [Narendran *et al.* 2003]. This variation is too much for most interior lighting applications. Luminaire manufacturers who participated in the ASSIST roundtable meeting that took place on the 4th of August, 2002, in Salt Lake City, Utah, provided the same input. These leading luminaire manufacturers mentioned that they would not consider white LED fixtures for general illumination until the color differences became unnoticeable.

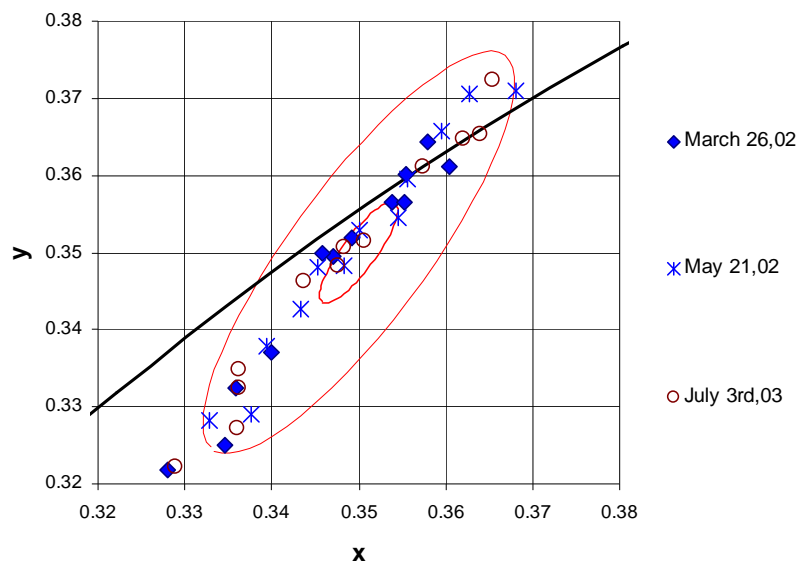


Figure 1: CIE x,y values of high-power white LEDs, shown with 3-step and 12-step MacAdam ellipses.

For white LEDs to be accepted broadly for illumination applications, the color variation between similar products must become much smaller. Color binning is one option for creating arrays with unnoticeable color variation, provided that the color does not shift during the operational life of the product. In the same LRC study mentioned earlier, it was found that the color shift over time was very small (Figure 1) [Narendran *et al.* 2003].

This raises the question of how much color variation there can be between similar white LEDs. In other words, at what point do observers see a just-noticeable color difference between two similar LEDs when they are viewed side-by-side?

II. Background

In 1942 D.L. MacAdam conducted the first systematic experiment that investigated color matching precision [Wyszecki and Stiles 1982]. In this study he used a monocular setup with a 2° test field that was split in half. One side remained as the constant reference stimulus and the other side was the test stimulus. Both sides of the test field were always kept at a constant luminance (48 cd/m²) [Wyszecki and Stiles 1982]. MacAdam used a single observer who varied the color in one half of the test field and matched it to the color of the fixed comparison field [Wyszecki and Stiles 1982]. The observer made repeated color matches, and the standard deviation of the distance between the two stimuli in CIE chromaticity space was determined. The standard deviations of matching a fixed comparison color coordinate along different directions in the CIE 1931 chromaticity diagram produced the 1942 MacAdam ellipse. In a different study, MacAdam found that the just-noticeable color difference was about three times as large as the corresponding color matching standard deviation (3-step MacAdam ellipses) [Wyszecki and Stiles 1982].

The American National Standards Institute (ANSI) specifies a 4-step MacAdam ellipse as the tolerance criterion for certain types of fluorescent lamps (ANSI 1996). However, light source color discrimination depends very much on the application. As an example, if the lamps are close to each other and are directly visible to the observer, a small color variation would be noticeable. On the other hand, if the same lamps are placed far apart and are not directly seen, the color variation may not be noticeable.

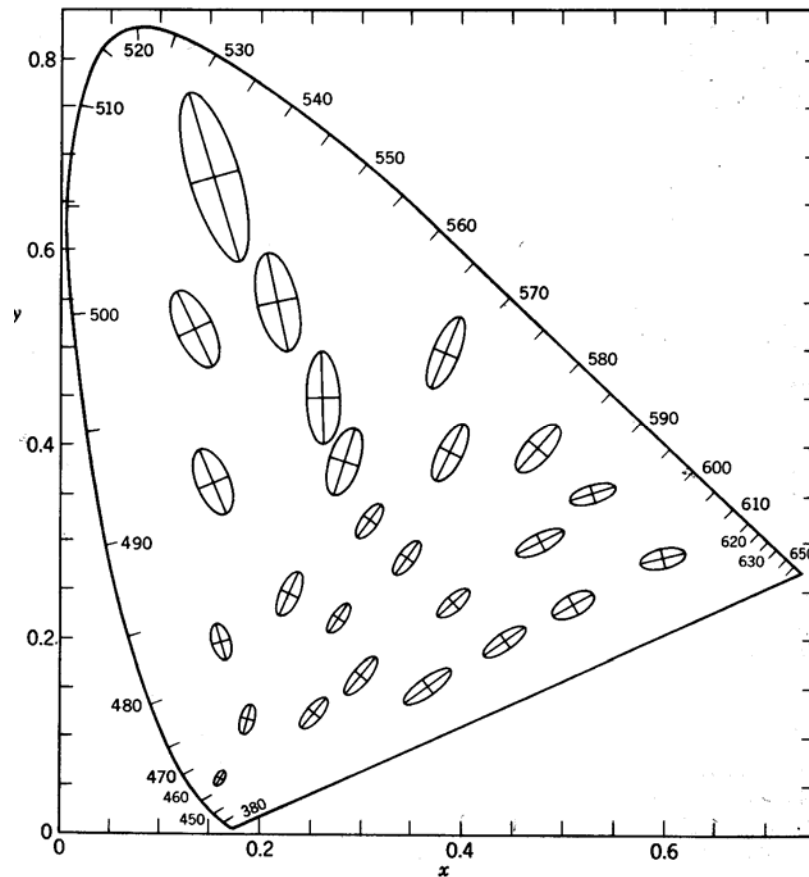


Figure 2: MacAdam ellipses plotted in the CIE 1931 chromaticity diagram.

The axes of the plotted ellipses are 10 times their actual lengths [Wyszecki and Stiles 1982].

A number of studies already exist in the area of color discrimination. These studies show that there are many factors that could impact the size of the color tolerance region. For example, MacAdam's (1942) and Brown's (1957) studies showed that the size of the MacAdam ellipses were different at different locations of the CIE 1931 chromatic diagram (Figure 2). This implies that for white light sources, correlated color temperature (CCT) may impact the tolerance range. In 2000, Vasconez showed that a general color tolerance criterion, such as the 4-step MacAdam ellipse, is too generous for accent light applications where the scene contains a white background and has little visual complexity. On the other hand, for multicolored displays with more visual complexity, the 4-step MacAdam ellipse seems adequate (Narendran *et al.* 2000). Yebra (2001) measured the chromatic-discrimination ellipses with different luminances for 66 stimuli distributed throughout the CIE 1931 chromatic diagram and found a clear influence of the luminance level. Rizzo *et al.* (2002) pointed out in their study that color matching is a

three-dimensional issue, meaning that two light sources with similar CIE x, y values but differences in luminance may result in a noticeable color difference.

Most of the studies mentioned here were conducted using monotonically increasing continuous spectrum light sources, like the incandescent lamp. To the best of our knowledge, there are no studies investigating the color tolerance ranges for multiple-peak spectrum light sources, such as mixed-color white LEDs. Based on past studies, it was hypothesized that the color tolerance area for light sources with multiple-peak spectrums would be different compared to light sources with continuous spectrums. Therefore, a laboratory human factors experiment was conducted to verify the hypothesis and to develop criteria for color tolerance for white LEDs.

III. Experiment

The goal of the experiment was to identify points at which human subjects observed a just-perceivable color difference (JPCD) and a noticeable color difference (NCD) between two similar white light LEDs. The study also investigated the impact of light level, visual complexity of the scene, light source spectrum, and CCT on color tolerance range. In total, nine experiments were conducted. Table 1 illustrates the relationship between these nine experiments.

Table 1: Experiments.

Experiment Condition	SPD	Light Level	CCT	Background
1	LED	90 fc	6500K	White
2	LED	30 fc	6500K	White
3	LED	90 fc	3000K	White
4	LED	30 fc	3000K	White
5	LED	30 fc	3000K	Multicolored painting
6	Halogen	30 fc	3000K	White
7	Halogen	30 fc	3000K	Multicolored painting
8	Halogen mixed with fluorescent	30 fc	3000K	White
9	Halogen mixed with fluorescent	30 fc	3000K	Multicolored food packages

These experiments were conducted to test the following hypotheses:

Hypothesis 1: Impact of light source SPD on color discrimination tolerances

If color discrimination tolerances are obtained for continuous spectrum and multiple-peak spectrum white light sources, then the tolerance ranges for the multiple-peak spectrum light source will be smaller than those for the continuous spectrum light source.

Experiments 4, 6, and 8, and experiments 5 and 7 test hypothesis 1.

Hypothesis 2: Impact of visual background on color discrimination tolerances

If color discrimination tolerances are obtained for white light sources (continuous spectrum and multiple-peak spectrum), then the tolerances obtained with a white background will be smaller than those with multicolored backgrounds.

Experiments 4 and 5, experiments 6 and 7, and experiments 8 and 9 test hypothesis 2.

Hypothesis 3: Impact of light source CCT on color discrimination tolerances

If color discrimination tolerances are obtained at different CCTs on the blackbody locus, then the areas at higher CCTs will be smaller than those at lower CCTs.

Experiments 1 and 3, and experiments 2 and 4 test hypothesis 3.

Hypothesis 4: Impact of light levels on color discrimination tolerances

If color discrimination tolerances are obtained at different light levels, then the tolerances under higher light levels will be smaller than those under lower light levels.

Experiments 1 and 2, and experiments 3 and 4 test hypothesis 4.

Experiment Variables

The dependent and independent variables of the experiment are detailed below.

Independent variables

There are altogether four independent variables in this study, namely:

- 1) Spectral power distribution – monotonically increasing continuous SPD (filtered halogen), and multiple-peak SPD (LEDs) (Figure 6).
- 2) Light level – average vertical illuminance inside the cabinets: 30 fc and 90 fc.
- 3) Correlated color temperatures (CCT) of the light in the cabinets: 3000 K and 6500 K.

- 4) Background color/pattern – Three different backgrounds: a) white, b) multicolored painting, and c) multicolored food packages.

Dependent variables

The dependent variable is the subjective response of the color difference between the two lighted compartments. Four criteria were used for the subjects to judge the extent of color difference:

- Color match (i.e., no difference)
- Just-perceivable color difference (JPCD)
- Noticeable color difference (NCD)
- Obvious color difference (OCD)

IV. Methods

Overview

The objective of this study was to develop color tolerance criteria for white LEDs. These criteria define points at which human subjects observe a just-perceivable color difference between white LED light sources. The methodology used here to verify the specific hypotheses and to develop the color tolerance criteria is based on an earlier LRC study [Vasconez 2000]. As illustrated in Figure 3, a display cabinet with two side-by-side compartments was built in a laboratory environment. Each compartment was outfitted with a red-green-blue (RGB) mixed white light system. The systems used either halogen light sources (continuous spectrum), or RGB LED light sources (multiple-peak spectrum). Each white light system could be tuned to obtain any chromaticity coordinates within the color gamut of the RGB light sources (i.e., filtered halogen or LEDs).

One of the compartments acted as the reference and held a constant white light color at a specific chromaticity value (x, y). This same value was used as the starting point for the other compartment, which acted as the test light source at the beginning of each test. The color of the light source in the test compartment was changed systematically, and at each step observers were asked whether they saw a color match. Color tolerance ranges were then determined based on the subjective responses.

Experimental Setup

The experimental setup consisted of a display cabinet; two MR16 halogen white light systems composed of MR16 lamps, RGB filters, a diffuser panel and six direct current (d.c.) power supplies; two RGB LED

white light systems composed of two rectangular light guides with RGB LEDs; and a computer for presenting the stimuli and recording the subjects' answers.

Display cabinet and lighting systems

As shown in Figure 3, the display cabinet featured two side-by-side compartments, with each compartment measuring 18 inches in length, 24 inches in height, and 18 inches in depth. The cabinet was built of wood laminate painted white (matte finish) inside. The cabinet was topped with an aluminum dome, also painted white inside. The dome-shaped ceiling was chosen because it provided better color mixing of the RGB halogen light sources.

Each cabinet compartment housed its own lighting system. The setup was constructed such that the lighting systems could be added and removed as needed, depending on which type of light source was required for a given experiment (MR16 halogen or LED). The lighting system in the left-side compartment was held constant and provided the reference stimulus, while the right-side compartment contained the lighting system that changed colors systematically during the tests.

The halogen lighting systems were mounted at the top of each compartment, underneath the dome. These lighting systems projected red, green, and blue light upwards, which then mixed in the dome and reflected down into the compartments to create a uniform white light. The halogen lighting system in each compartment consisted of three MR16 lamps, each fitted with a red, green, or blue dichroic filter. An additional diffuser was added above each compartment to better mix the light reflecting down into the compartment. Fans mounted in the dome for each compartment kept the interior ambient temperature constant and maintained color stability during the experiment. Six direct current power supplies, one for each halogen lamp in the cabinet, controlled the lamps' light output to create the different mixed-color variations.

The LED panel in each compartment housed a mixture of red, green, and blue LEDs. These panels were built and supplied by Lumileds Lighting. A feedback control circuit built into the panel controlled the LEDs to ensure that the panel maintained a constant light output and color.



Figure 3: Subject looking at the experimental display cabinet (left); MR16 RGB mixed light system and diffuser (top right); RGB LED panel (bottom right).

Characteristics of the lighting systems

Figure 4 shows the transmittance characteristics for the six dichroic filters used with the MR16 halogen lamps to create different colors. The solid lines represent the filters used for the right-side compartment, and the dashed lines are the filters used for the left-side (reference) compartment.

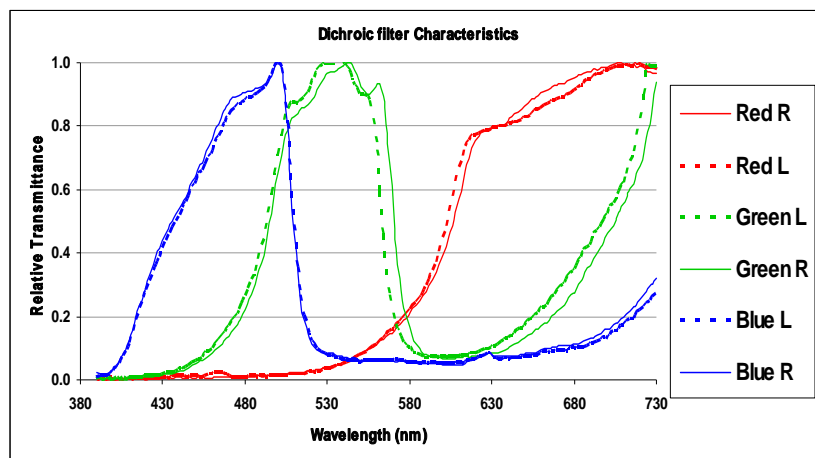


Figure 4: RGB dichroic filter transmission characteristics.

Figure 5 shows the color coordinates and the gamut area for both the MR16 halogen and the LED white light sources. The circle markers in Figure 5 illustrate the chromaticity coordinates of the six filtered MR16 halogen lamps. Open circles represent those in the right compartment, while solid circles represent those in the left compartment. The square markers illustrate the chromaticity coordinates of the RGB LEDs. Open squares represent those in the right compartment, while solid squares represent those in the left compartment. The MR16 color gamut is represented by the dashed-line triangle. The LED color gamut is represented by the solid-line triangle. Mixing the light from the RGB light sources would result in a color whose chromaticity coordinates fall within these triangular spaces. The color variations created in this study were within the overlapped regions.

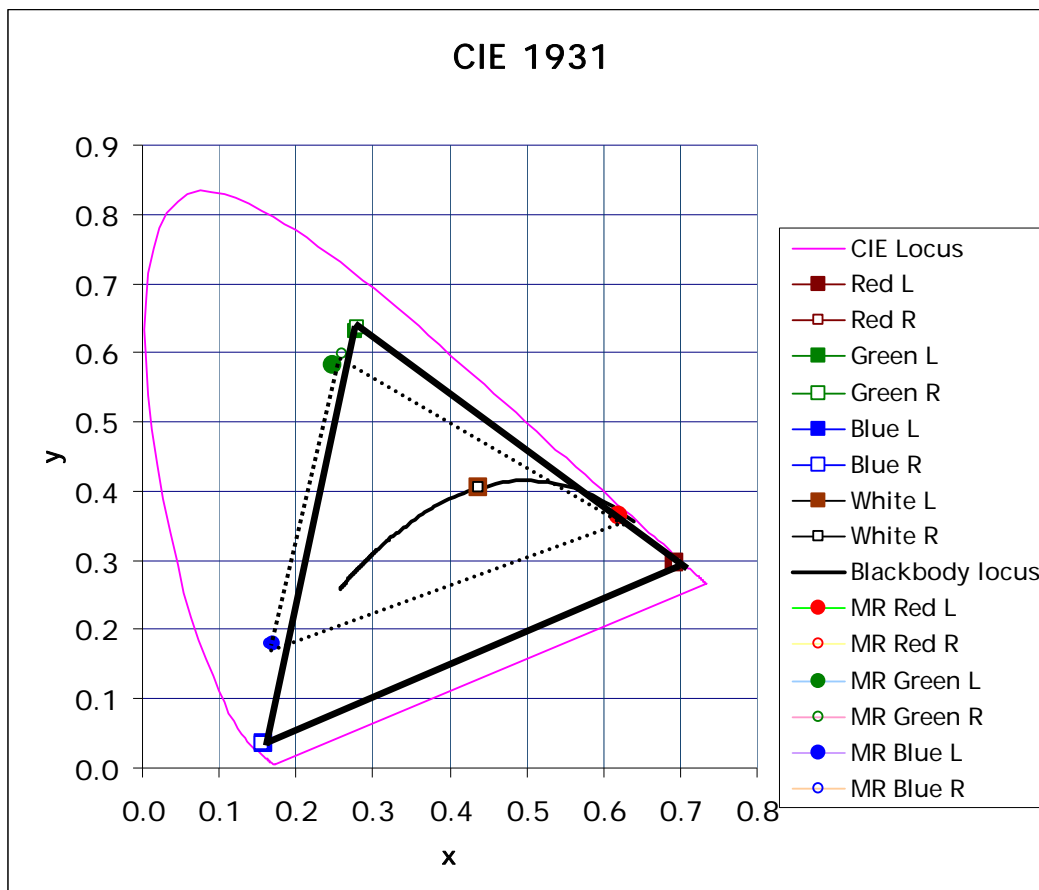


Figure 5: Gamut area of the filtered halogen and LED systems.

Figure 6 illustrates the spectral power distributions (SPDs) of the white light emitted from the filtered halogen and the LED lighting systems. The filtered halogen lamps created a near-continuous spectrum, whereas the LED lamps created spikes at the red, green, and blue LED peak wavelengths. Figure 6 also shows the SPD of the halogen system mixed with the room's ambient fluorescent lighting. During some of the experimental conditions, the fluorescent room lights were left on (see next section for description).

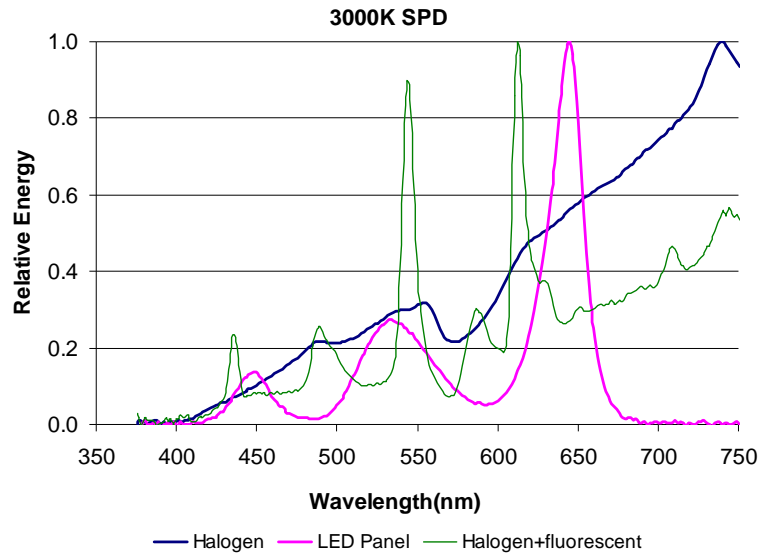


Figure 6: Halogen, LED panel, and halogen plus ambient fluorescent light RGB-mixed white light SPD.

Because the light output of most LED systems needs a relatively long time to stabilize, the LED panels were tested for light output stabilization time prior to starting the experiments. Figure 7 shows the light output stabilization characteristics for the LED panels. Figure 7 indicates that it takes approximately 90 minutes for the LED light output to stabilize. Therefore, the LED panels were turned on for 90 minutes prior to each experimental session to ensure stable light output.

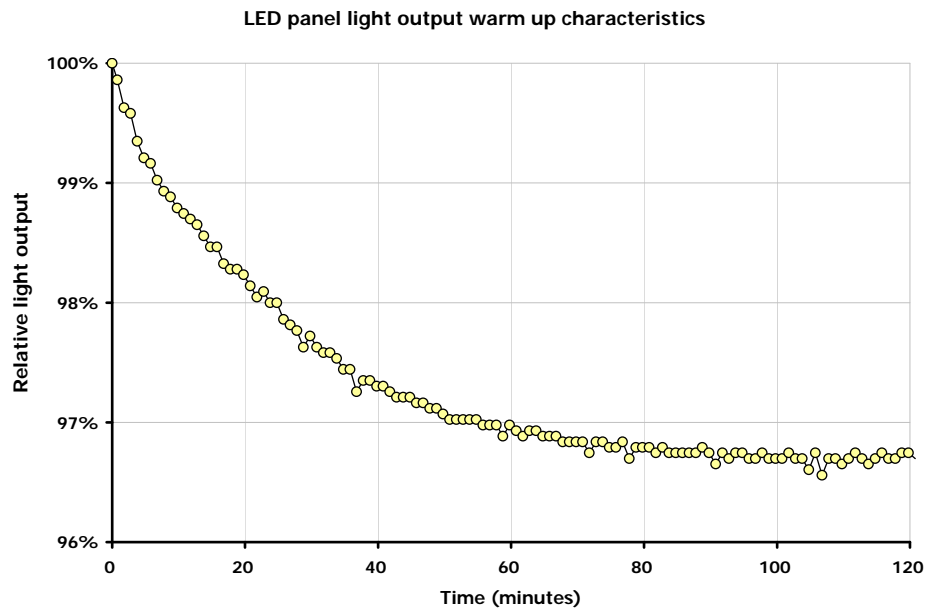


Figure 7: LED panel light output stabilization characteristics.

Because the experiments involved the systematic variation and presentation of colors, it is important to know how long it takes for the color stimuli to stabilize after they change. Figure 8 indicates that it takes approximately three seconds for the color to stabilize within a one-step MacAdam ellipse.

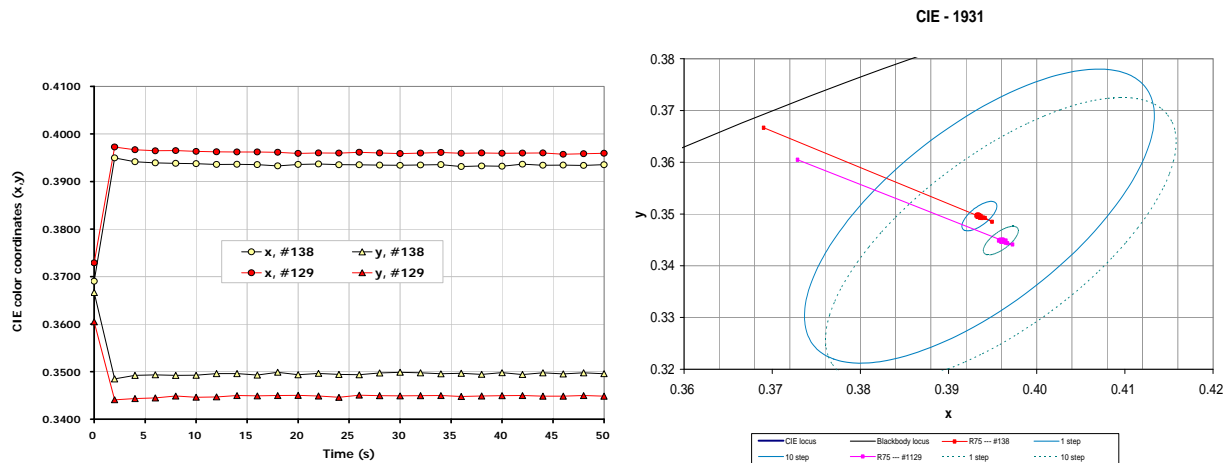


Figure 8: LED panel color stabilization characteristics. The stabilization time between each color change is approximately 3 seconds (left). LED colors stabilize to within a one-step MacAdam ellipse in this timeframe (right). The solid line represents the panel in the left compartment; the dashed line represents the panel in the right compartment.

Display objects

Three different background displays were used in the experiments (Figure 9). The first was a plain white, matte finish background (the back wall of each compartment). The second was a replica of a Picasso painting. The third display used cardboard food packages and mimicked a refrigerator case in a grocery store. The backgrounds for the paintings and the food packages contained a variety of red, green, blue, and yellow colors.



Figure 9: Three background displays shown to subjects during experiments: a plain white, matte finish background (left); replica of a Picasso painting (center); food packages arranged as if in a grocery store refrigerator case (right).

Computer system that presented the stimuli

The communications protocols were developed using LABVIEW™ software that provided accurate and repeatable presentations for the different experimental conditions (Figure 10). The questions to the experiment subjects were broadcasted by the speakers in the computer. Using a modified keyboard, subjects keyed in their answers to the questions by pressing and releasing the appropriate function keys on the keyboard. The computer accepted the subject's response and generated the desired command to control the mix of the RGB light sources. For the halogen light source, the commands contained power supply current information that was sent to the d.c. power supplies. The power supplies then adjusted the current of the RGB filtered halogen lamps to achieve the desired color stimuli inside the display compartments. For the LED panels, the commands contained the chromaticity information, which were sent to the panel control program. The panel control program then generated the desired color stimuli inside the display compartments.

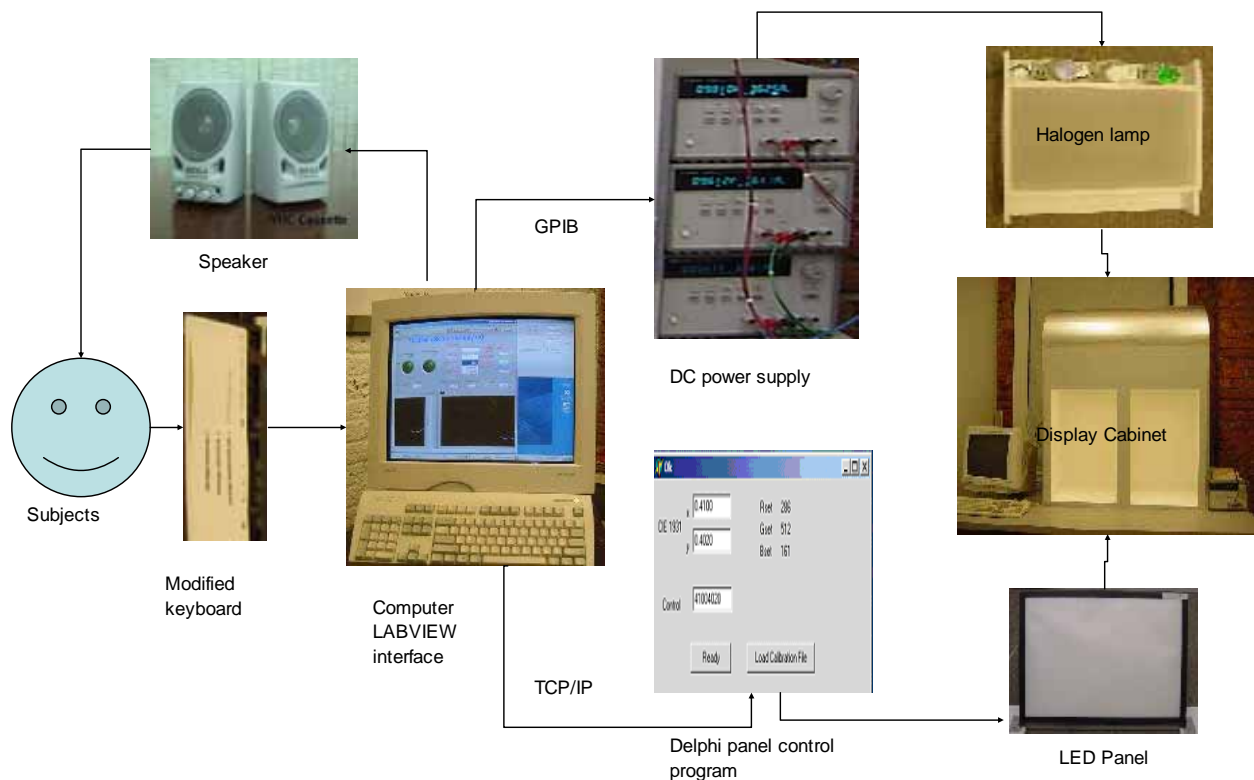


Figure 10: Schematic of experimental computer system and communications protocol.

Human Subjects

The subjects participating in the experiment were employees and graduate students of Rensselaer Polytechnic Institute. Twelve subjects (6 males and 6 females) were involved in experiment 1 through experiment 8, and 7 subjects were involved in experiment 9. Their ages ranged from 23 to 58 years old. In

terms of ethnicity, six subjects were Caucasian, four were Asian Chinese, and another two were Asian Indians.

Experimental Procedure

Prior to starting the experiment, approval from the Institute Review Board (IRB) was obtained. All subjects were screened for color vision deficiencies; only participants with normal color vision participated in the experiments. The subjects were seated in a small office in front of the side-by-side cabinet compartments. The distance between the subjects and the cabinet was six feet. This distance ensured that the aperture of the compartments subtended a 10° field of view at the subject's eyes. No daylight was present in the room during the experimental sessions. At the beginning of the test, the lighting in the two compartments was set to a particular CIE x,y value on the blackbody locus corresponding to a CCT by adjusting the controls of the RGB lighting system. The CCT and the CIE x,y values of the light inside the compartments were measured using a Photo Research PR705 spectrometer. The light levels were measured using an illuminance meter at the center of the back wall of the compartment. The illuminance values on the back wall were kept within 5% to ensure uniform lighting. At this point the light levels and color of the two compartments appeared the same, and the subjects were advised that this represented a perfect match condition.

The color in the left compartment was held constant and served as the reference. The chromaticity of the light in the right compartment was shifted along the line joining the color center and the apex on the triangle corresponding to that color by adding or subtracting a single color from this particular color center. As an example, starting at the 3000 K color center and adding some blue would move the chromaticity value toward the blue apex along the line joining the color center and the blue apex. Likewise, subtracting blue would move it away from the color center, as shown in Figure 11.

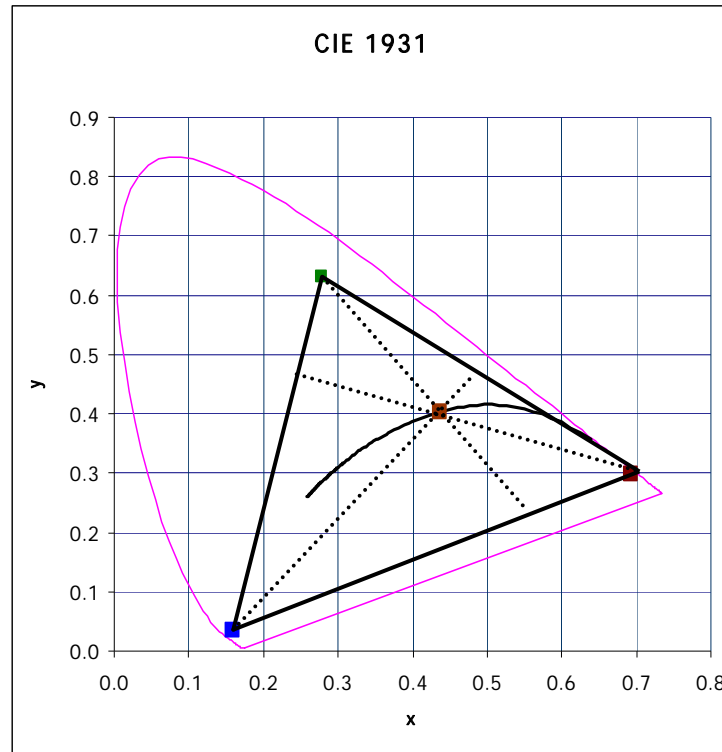


Figure 11: Color axis for the three primary colors used in the study.

As the color of the light in the right compartment changed, the subjects were asked to compare it to the left reference compartment and determine whether the colors were matched. The subjects were instructed to compare the overall color differences between the compartments and not to compare a local region, especially when colored backgrounds were used. Subjects were also asked to ignore reflections, shadows, and brightness differences. At each color change, the computer system asked the subjects, “Do you see a color match?” Subjects had two seconds to answer “Yes” or “No.” The two-second visual exposure was selected as a compromise between chromatic adaptation caused by a long exposure time and interference caused by spatial and temporal integration due to a short exposure time [Vasconez 2000]. If the subjects exceeded the two-second limit, the computer announced a “Time out.” If the subject’s answer was “Yes” for the color match, then the test continued to the next color value. If the answer was “No,” then the computer queried for the amount of difference. There were three choices for this question: just perceptibly different, noticeably different, or obviously different. The subject pressed the corresponding button on the modified keyboard to enter a choice. Then the test continued to the next color value. Between each color value change, subjects were asked to look down at the computer keyboard.

When the colors of the two compartments were sufficiently close in appearance, the subjects usually found it difficult to make a judgment (i.e., they would say yes on some trials and no on others for the

identical condition). To overcome this issue, a well-established psychophysical measurement technique known as the “random double staircase method” was used to present the stimuli [Gescheider 1985]. The staircase started from an obvious color difference condition and moved toward a no-difference condition by adding or subtracting one color. Anytime the subject saw a color match, the staircase was reversed. For example, the green staircase started with the test compartment obviously greenish while the reference compartment was white. By subtracting the green light magnitude step by step, the test compartment approached the same color as the reference. When the subjects said they saw a color match, instead of continuing to subtract the green color, the program added one step of green color. The addition of green was reversed once they saw a color difference again. This process was repeated until the staircase reversed six times. The average of third, fourth, fifth, and sixth reversals represent the boundary for the color match condition. To lessen the possibility that the subject may identify the staircase pattern and fool the staircase, two series of staircase stimuli were run concurrently. One would start at the maximum of a given color in the positive direction, and the other would start at the minimum of a given color in the negative direction. On any given trial, the choice as to which staircase would be represented was made randomly. Figure 12 illustrates one example of the random double staircase.

A practice round was included at the beginning of each session to familiarize the subjects with the procedure and to minimize any learning effects. Each session was divided into three sections, one for each color of red, green, and blue. It took approximately 45 minutes for the subjects to finish one session. Once the necessary data were gathered, a spectrometer was used to measure the CIE x, y values at the center of the back wall of each compartment for each presentation.

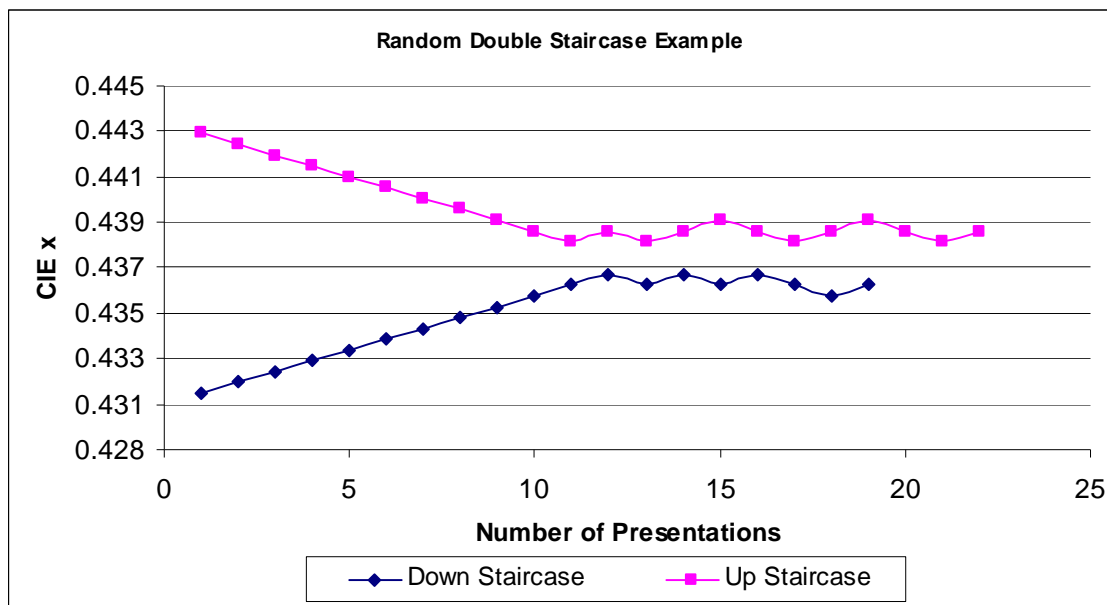


Figure 12: Random double staircase.

V. Results and Data Analysis

Six averaged CIE x, y values (the average between the third, fourth, fifth and sixth reversals) were obtained for each subject. Each value was an added or subtracted RGB color. From the responses of 12 subjects, the median values for the six boundary points were determined. Because the space within the CIE 1931 x, y chromaticity diagram is not uniform, to simplify analysis the CIE x, y values were converted to CIE U', V' values, which are on a more uniform space. Because the circle is a much simpler geometric shape, circular best-fits of these six CIE U', V' values were created using the least-squares fit method. Appendix 1 illustrates the CIE U', V' values and the fitted circles. Since the CIE 1931 x, y chromaticity diagram is a more familiar diagram, the fitted circles and the CIE U', V' values were then converted back to 1931 CIE x, y values. These results are shown in Appendix 2. Once transformed to 1931 CIE x, y chromaticity space, the contours become elliptical. These ellipses are referred to as the “color discrimination contours” in the graphs shown in Figures 13 through 16. Table 2 summarizes the radii of the fitted circles. These radii were used to make comparisons of the color discrimination ranges between the different experimental conditions.

Table 2: Summary of the color tolerance ranges under difference experimental conditions.

Experiment No.	Experiment Description	Match Contour Radius	Just perceivable color difference contour radius	Noticeable color difference contour radius
		*10 ⁻⁴	*10 ⁻⁴	*10 ⁻⁴
1	LED, 6500K, 90 fc, white background	23.5	33.9	73.1
2	LED, 6500K, 30 fc, white background	30	39.5	85.6
3	LED, 3000K, 90 fc, white background	20	27.4	46.4
4	LED, 3000K, 30 fc, white background	32.7	38.1	61.5
5	LED, 3000K, 30 fc, Multicolored painting background	68.9	82.9	118.2
6	Halogen, 3000K, 30 fc, white background	27.6	43.5	68.2
7	Halogen, 3000 K, 30 fc, Multicolored painting background	66.5	76.3	109.6
8	Halogen+fluorescent, 3000 K, 30 fc, white background	23.4	34.5	47.5
9	Halogen+fluorescent, 3000 K, 30 fc, multicolored food packages background	52.9	60	80.9

Table 3: Statistical analysis of the impact of factors on color discrimination tolerances.

(S: statistically significant, NS: not statistically significant)

	Comparisons	Experiment No.		Degree of freedom	Mean area difference	t value	p value	S/NS
Impact of SPD	Halogen vs. LED, multicolored background	7	5	9	-0.22	1.62	0.07	
	Halogen vs. LED, white background	6	4	7	-0.03	1.70	0.07	
	Halogen vs. halogen+fluorescent	6	8	6	0.02	1.17	0.14	
	Halogen+fluorescent vs. LED	8	4	4	-0.03	1.52	0.10	
Impact of Background	Multicolored painting vs. white	5	4	5	0.22	2.19	0.05	S
	Multicolored painting vs. white	7	6	5	0.13	2.22	0.04	S
	Multicolored food packages vs. white	9	8	4	0.15	3.08	0.02	S
Impact of CCT	3000K vs. 6500K	3	1	6	-0.01	0.81	0.22	
	3000K vs. 6500K	4	2	5	0.02	0.54	0.30	
Impact of light level	30 fc vs. 90 fc	2	1	7	-0.01	1.27	0.12	
	31 fc vs. 90 fc	4	3	5	0.02	0.88	0.21	

Hypotheses verification

Hypothesis 1: Impact of light source SPD on color discrimination tolerances

If color discrimination tolerances are obtained for continuous spectrum and multiple-peak spectrum white light sources, then the tolerance ranges for the multiple-peak spectrum light source will be smaller than those for the continuous spectrum light source.

Experiments 4, 6, and 8, and experiments 5 and 7 tested hypothesis 1. Figure 13 illustrates the impact of light source SPD on color tolerance range. **It can be seen that light source SPD has a negligible impact on color tolerance range.** The color discrimination values summarized in Table 3 also verify this.

Statistical analysis performed on the data, paired T-test with confidence level $p=0.05$, also indicates that there is no statistically significant difference between values obtained in experiments 4, 6 and 8, and between experiments 5 and 7 (Table 3).

Based on the results, hypothesis 1 is rejected.

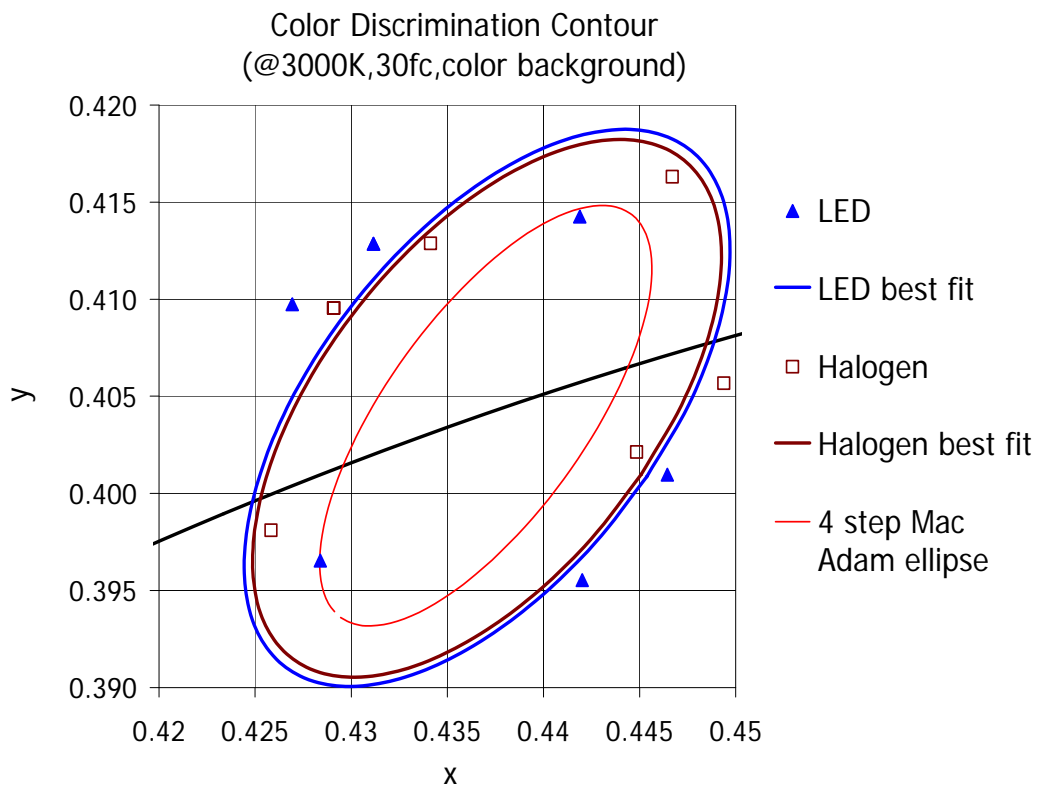
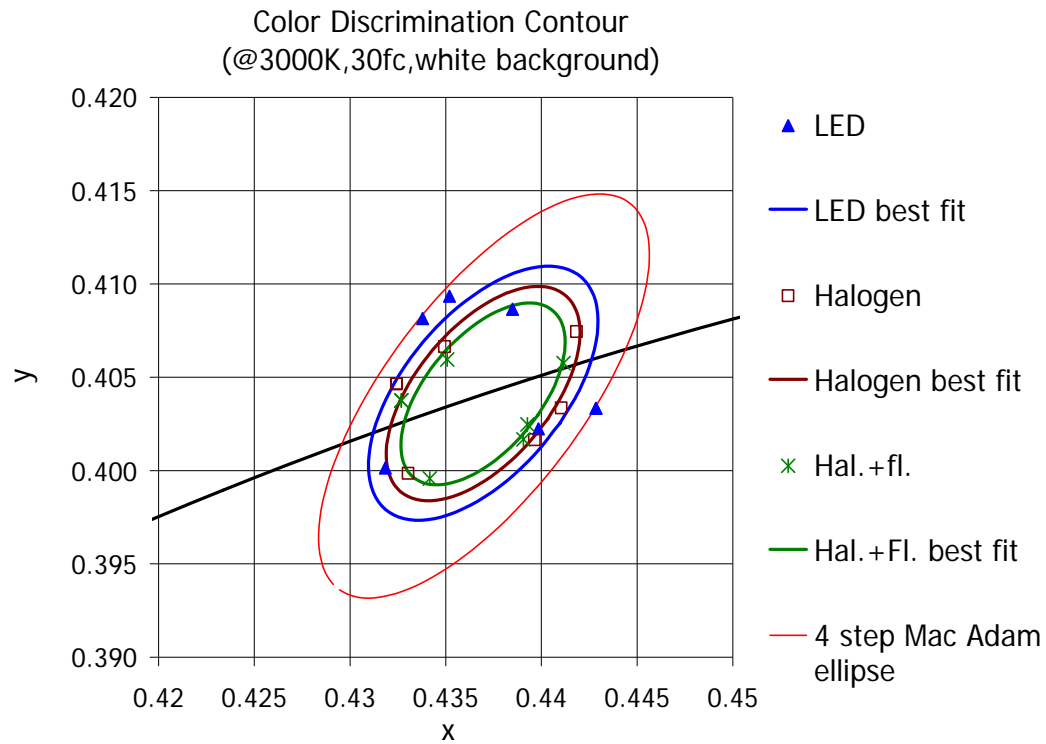


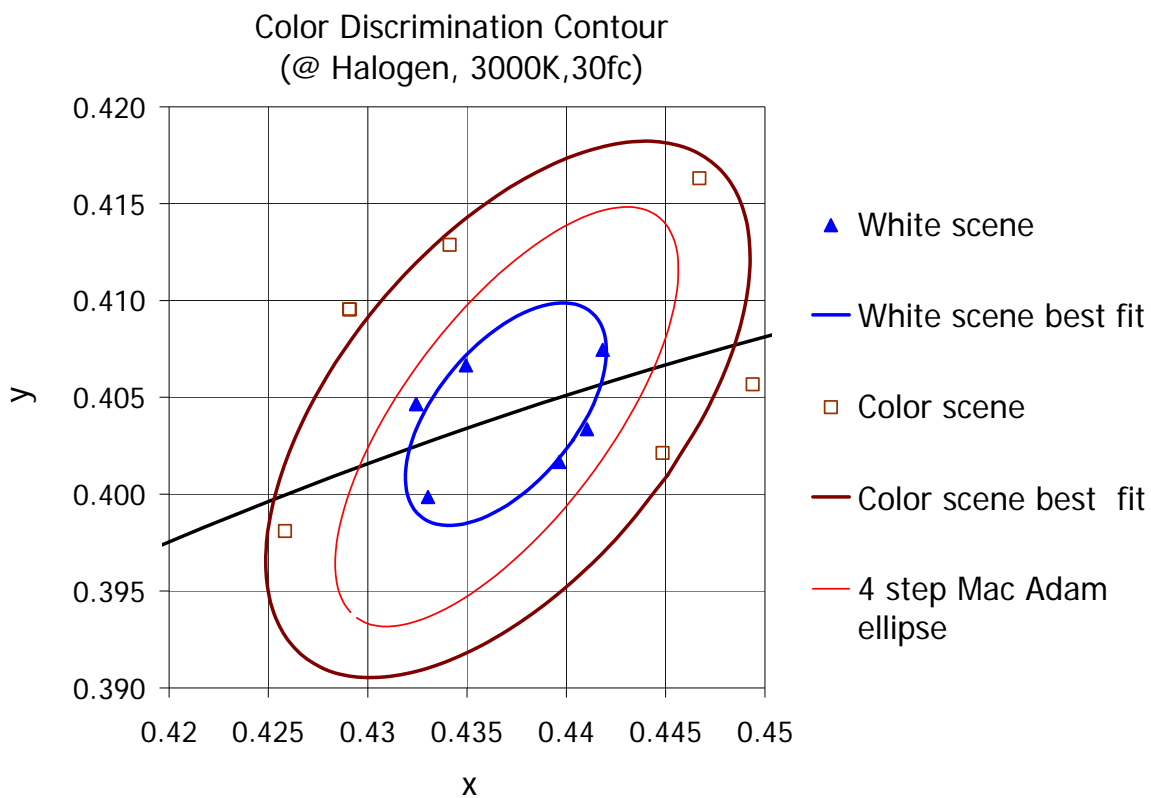
Figure 13: Impact of light source SPD on color tolerance.

Hypothesis 2: Impact of visual background on color discrimination tolerances

If color discrimination tolerances are obtained for white light sources (continuous spectrum and multiple-peak spectrum), then the tolerances obtained with a white background will be smaller than those with multicolored backgrounds.

Experiments 4 and 5, experiments 6 and 7, and experiments 8 and 9 tested hypothesis 2. Figure 14 illustrates the impact of visual background on color tolerance range. It is clear that the background has a large impact on color tolerance range. The color discrimination values summarized in Table 3 also support this conclusion. Statistical analysis performed on the data, paired T-test with confidence level $p=0.05$, also indicates that there is a statistically significant difference between the results obtained from experiments 4 and 5, experiments 6 and 7, and experiments 8 and 9.

Based on the results, hypothesis 2 is accepted.



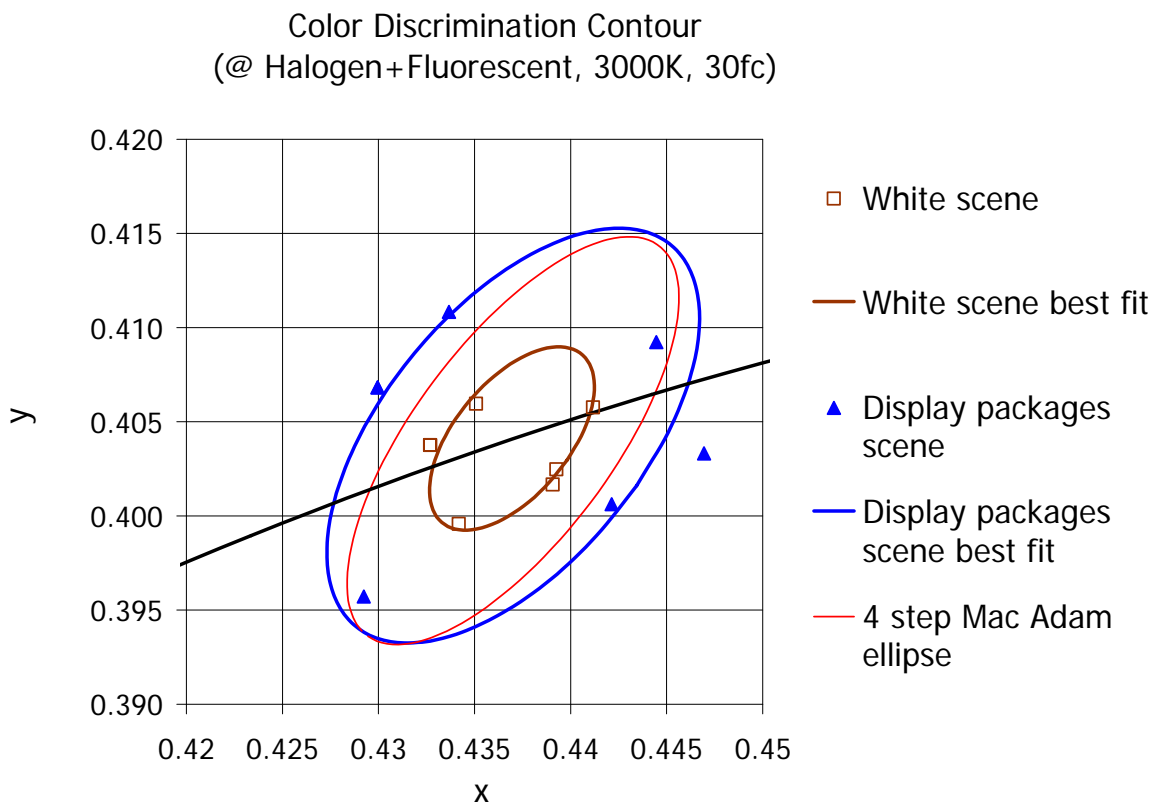
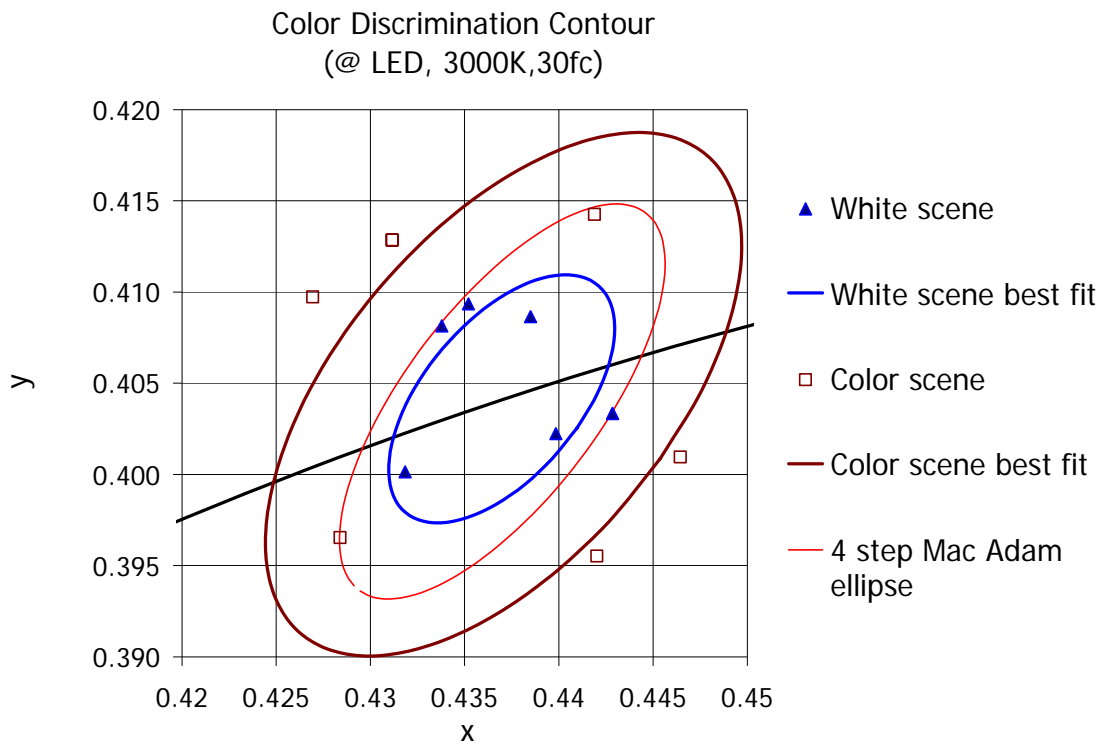


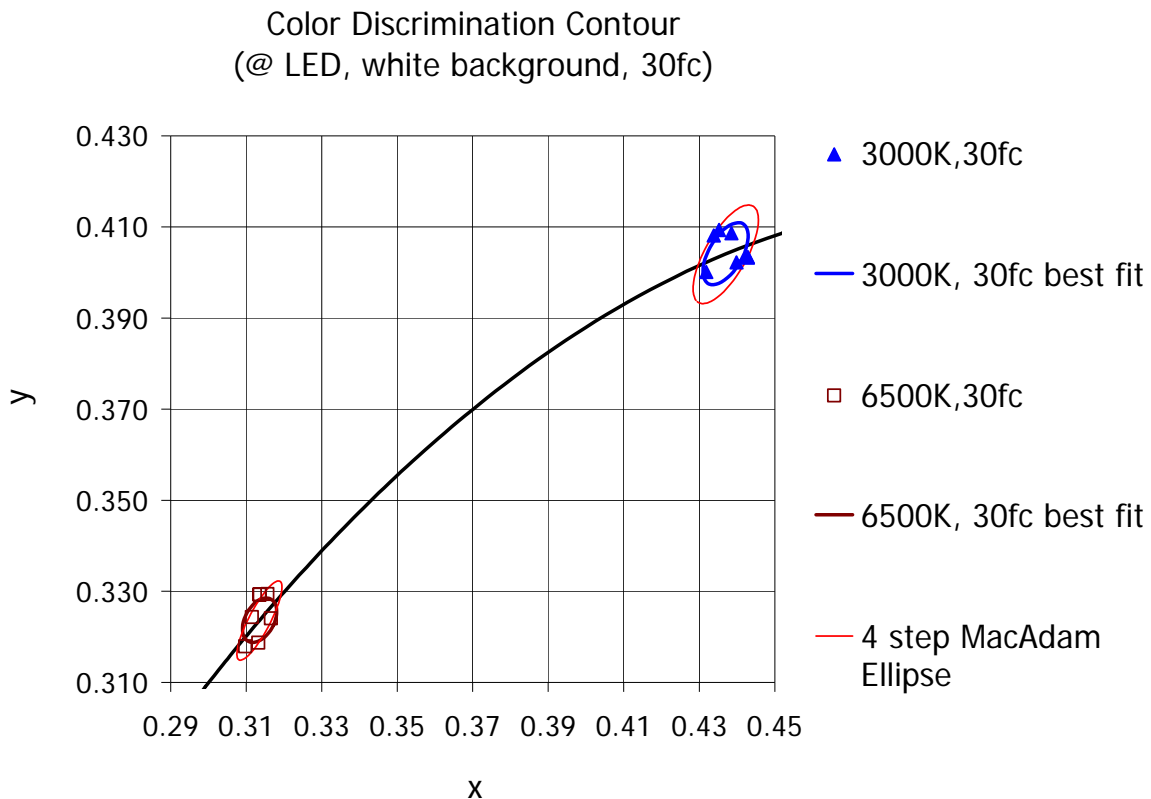
Figure 14: Impact of visual background on color tolerance.

Hypothesis 3: Impact of light source CCT on color discrimination tolerances

If color discrimination tolerances are obtained at different CCTs on the blackbody locus, then the area at higher CCTs will be smaller than those at lower CCTs.

Experiments 1 and 3, and experiments 2 and 4 tested hypothesis 3. Figure 15 illustrates the impact of light source CCT on color tolerance range at two different light levels. It can be seen that light source CCT has a very small impact on color tolerance range. The color tolerance range values summarized in Table 3 also support this. Statistical analysis performed on the data, paired T-test with confidence level $p=0.05$, also indicates that there is no statistically significant difference between experiments 1 and 3, and between experiments 2 and 4.

Based on the results, hypothesis 3 is rejected.



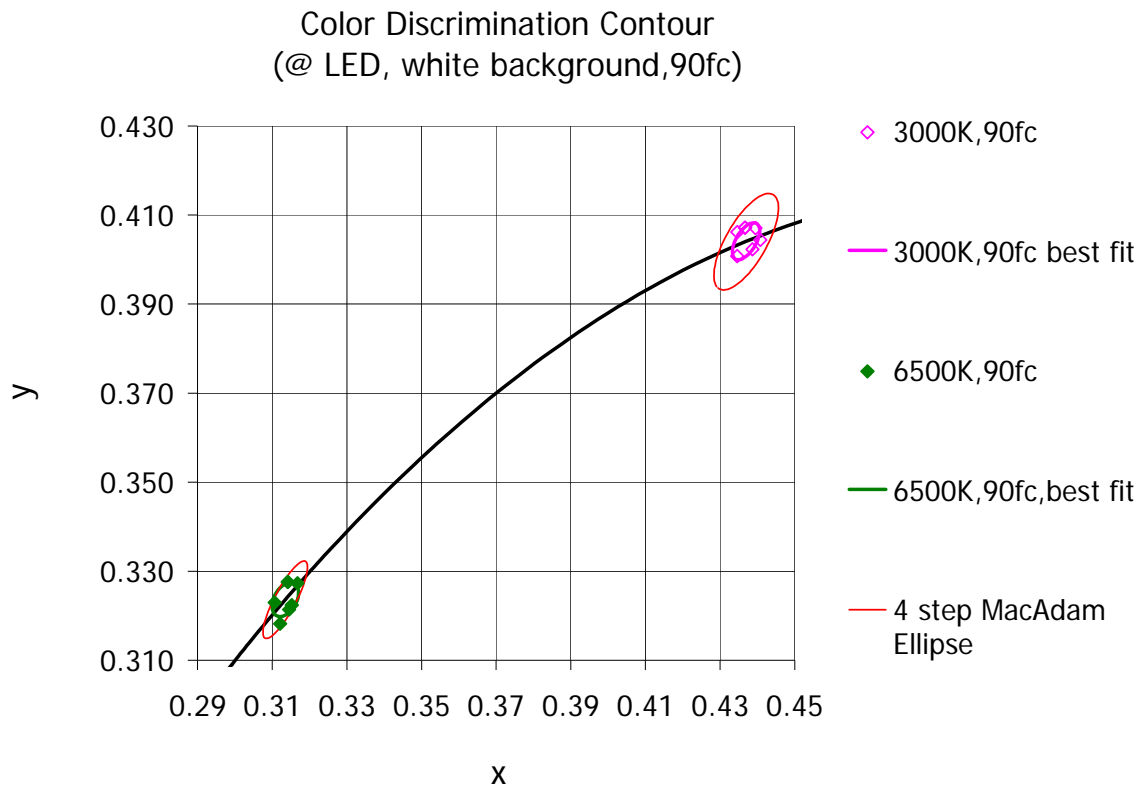


Figure 15: Impact of light source CCT on color tolerance

Hypothesis 4: Impact of light levels on color discrimination tolerances

If color tolerance ranges are obtained at different light levels, then the tolerances under higher light levels will be smaller than those under lower light levels.

Experiments 1 and 2, and experiments 3 and 4 tested hypothesis 4. Figure 16 illustrates the impact of light levels on color tolerance range. It can be seen that light level has a very small impact on color tolerance range. Color tolerance ranges under 90 fc were slightly but consistently smaller than those under 30 fc. The color discrimination metrics summarized in Table 3 also support this. However, statistical analysis performed on the data, paired T-test with confidence level $p=0.05$, indicated that this difference is not statistically significant.

Based on the results, hypothesis 4 is rejected.

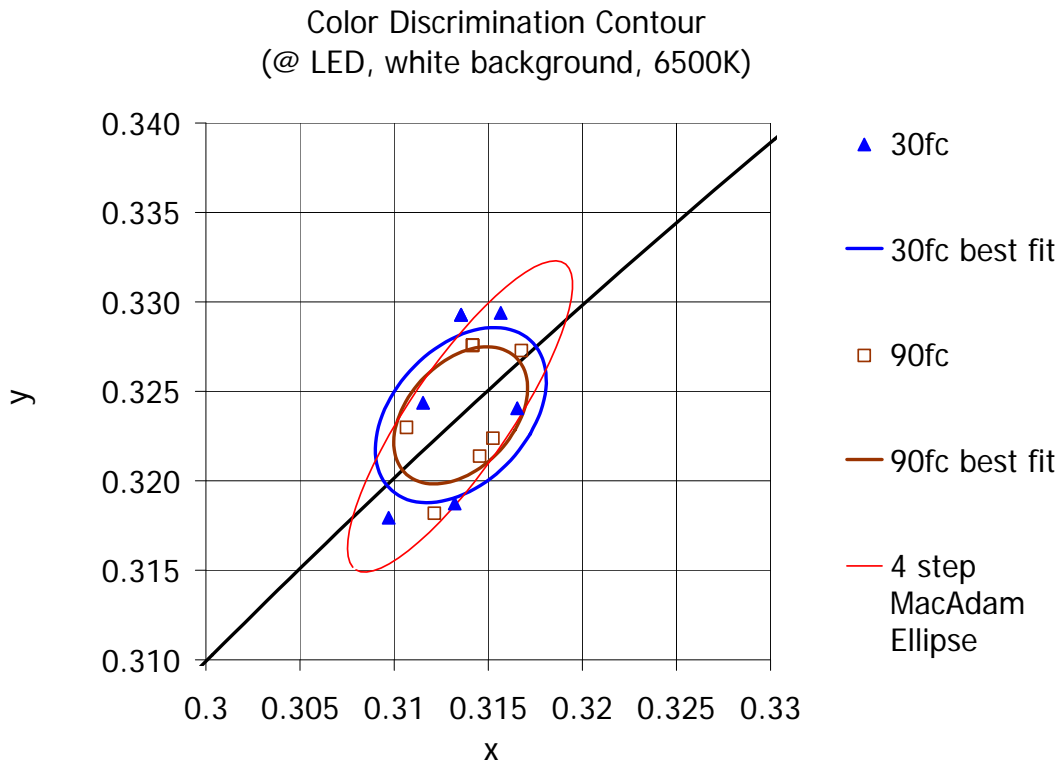
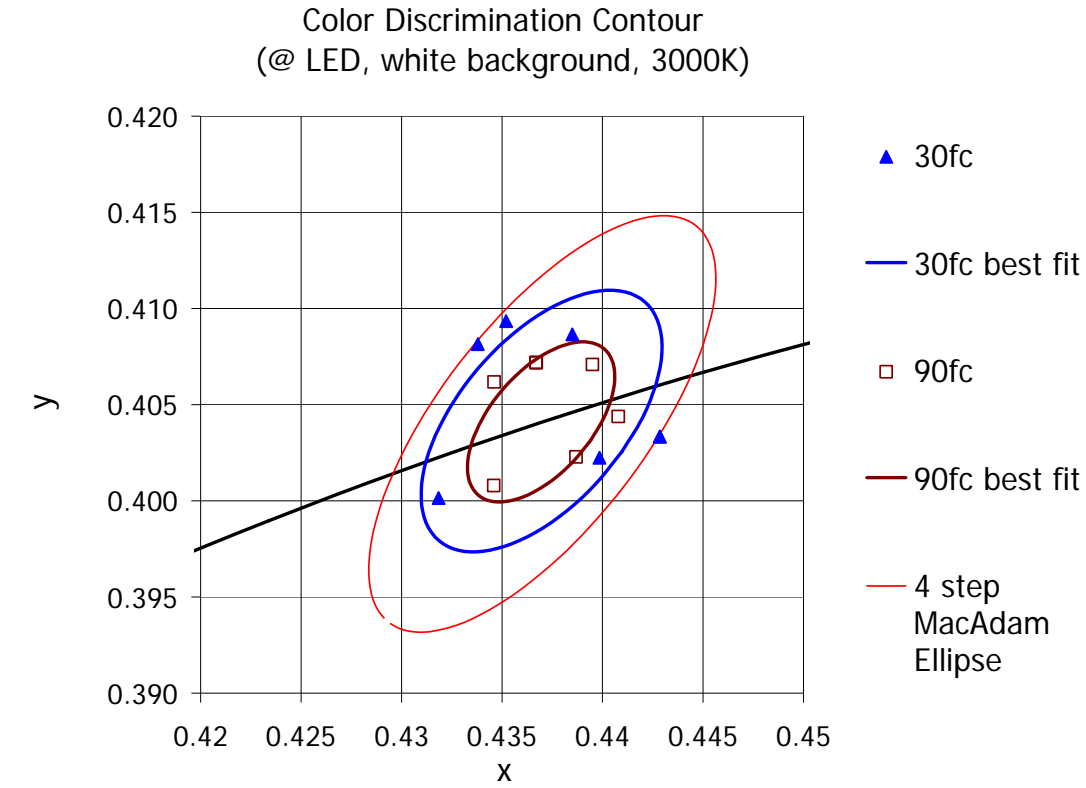


Figure 16: Impact of light levels on color tolerance.

VI. Color Tolerance Criteria Development

The next step was to determine the relevant criteria for binning white LEDs. To verify the hypotheses, the median values of the color match condition (the tolerance range) were selected. However, to set the binning criteria, the just-perceivable color difference (JPCD) and the noticeable color difference (NCD) conditions were analyzed. Appendix 3 shows the 50% JPCD, 10% and 50% NCD, and a reference 4-step or 8-step MacAdam ellipse for the 3000 K, 30 fc condition. The appendix shows the MacAdam ellipses centered over a reference point. When using the MacAdam ellipse criteria, normally, chromaticity coordinates within the elliptical area are compared with the reference center point. Although comparison with the center point does not show a perceived color difference, chromaticity coordinates falling on the farthest opposite boundary points of the ellipse contour, when compared with each other, would show a significant color difference. A color binning criteria must take into consideration all the points within the ellipse, not just a comparison with the center coordinates. Therefore, to develop a binning criteria for selecting LEDs that have unnoticeable color differences, the coordinates of all LEDs must be compared within an elliptical area that is half the size of the resulting MacAdam ellipse.

The assumption is that when more than 10% of the people say that the color difference is noticeable, then it becomes not acceptable. Based on this, the binning criteria for white LEDs (assuming equal light output) are:

- 2-step MacAdam ellipse – For applications where the white LEDs (or white LED fixtures) are placed side-by-side and are directly visible, or when these fixtures are used to illuminate an achromatic (white) scene. Accent lighting a white wall and lighting a white cove are some examples.
- 4-step MacAdam ellipse – For applications where the white LEDs (or white LED fixtures) are not directly visible, or when these fixtures are used to illuminate a visually complex, multicolored scene. Lighting a display case and accent lighting multicolored objects or paintings are some examples.

VII. Conclusions

The following conclusions were reached based on the results.

1. The color tolerance range is affected minimally by the spectrum of the light source. The halogen light source and the RGB white light LED source had similar color tolerance ranges in the CIE chromaticity diagram for the white and colored backgrounds.
2. The color tolerance range is affected very much by the background. For both the halogen light source and the RGB white light LED source, the color tolerance range in the CIE diagram was larger for the complex colored background compared with the white background.
3. The color tolerance area is affected minimally by the CCT of the light source. The halogen light source and the RGB white light LED source had similar color tolerance areas in the CIE chromaticity diagram for the white and colored backgrounds.
4. The color tolerance area is affected minimally by the light level under photopic conditions. Experimental results gathered at 30 fc and 90 fc showed very little difference for the LED RGB white light source.

Using the assumption that color differences noticed by more than 10% of people are unacceptable, the binning criteria for white LEDs (assuming equal light output) are.

- 2-step MacAdam ellipse – For applications where the white LEDs (or white LED fixtures) are placed side-by-side and are directly visible, or when these fixtures are used to illuminate an achromatic (white) scene. Accent lighting a white wall and lighting a white cove are some examples.
- 4-step MacAdam ellipse – For applications where the white LEDs (or white LED fixtures) are not directly visible, or when these fixtures are used to illuminate a visually complex, multicolored scene. Lighting a display case and accent lighting multicolored objects or paintings are some examples.

Note: *The chromaticity values of presently available T8F32 linear fluorescent lamps operated on electronic ballast fall within 2-step MacAdam ellipses.*

VIII. Acknowledgements

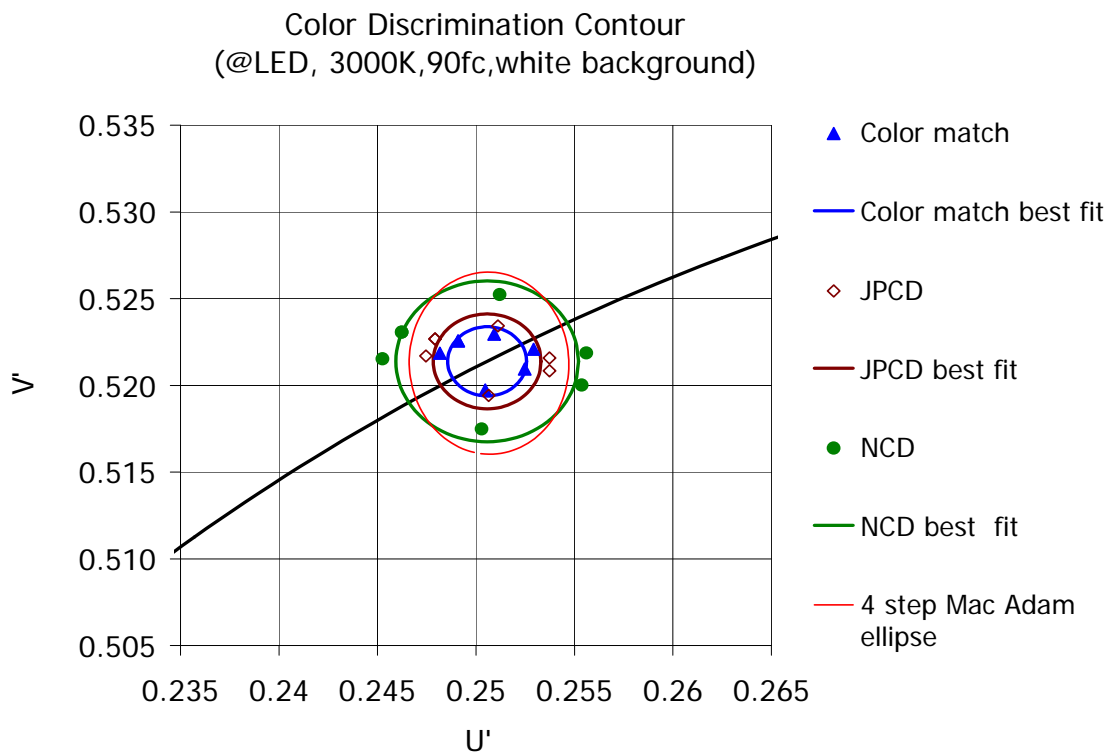
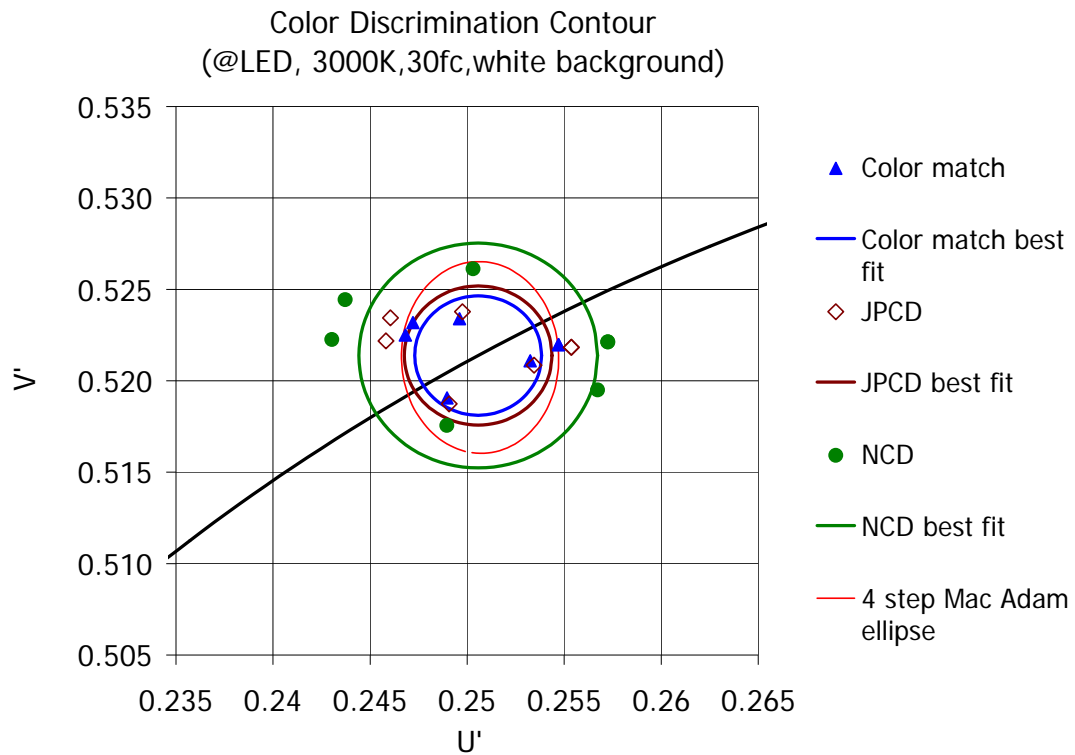
The Lighting Research Center gratefully acknowledges the ASSIST sponsors (Boeing, GELcore, Lumileds Lighting, New York State Energy Research and Development Authority, NICHIA America Corporation, OSRAM SYLVANIA / Osram Opto Semiconductors, and California Energy Commission) for providing the financial support for this project. In addition, Sjeff de Krijger and Willem Sillevius-Smitt from Lumileds Lighting are thanked for their technical support in developing the program to control the RGB LED panels. David Cyr is thanked for building the display cabinet for this study. Dr. Peter Boyce of the LRC is thanked for his valuable discussion and review of the human factors experimental protocols.

IX. References

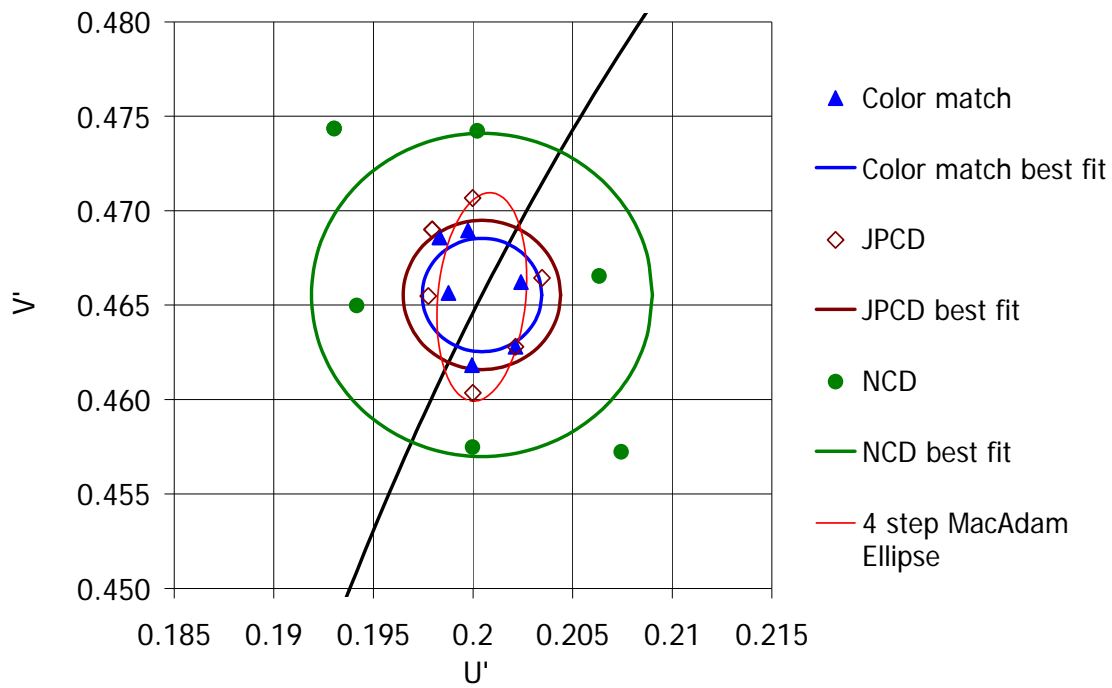
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Appendix 1

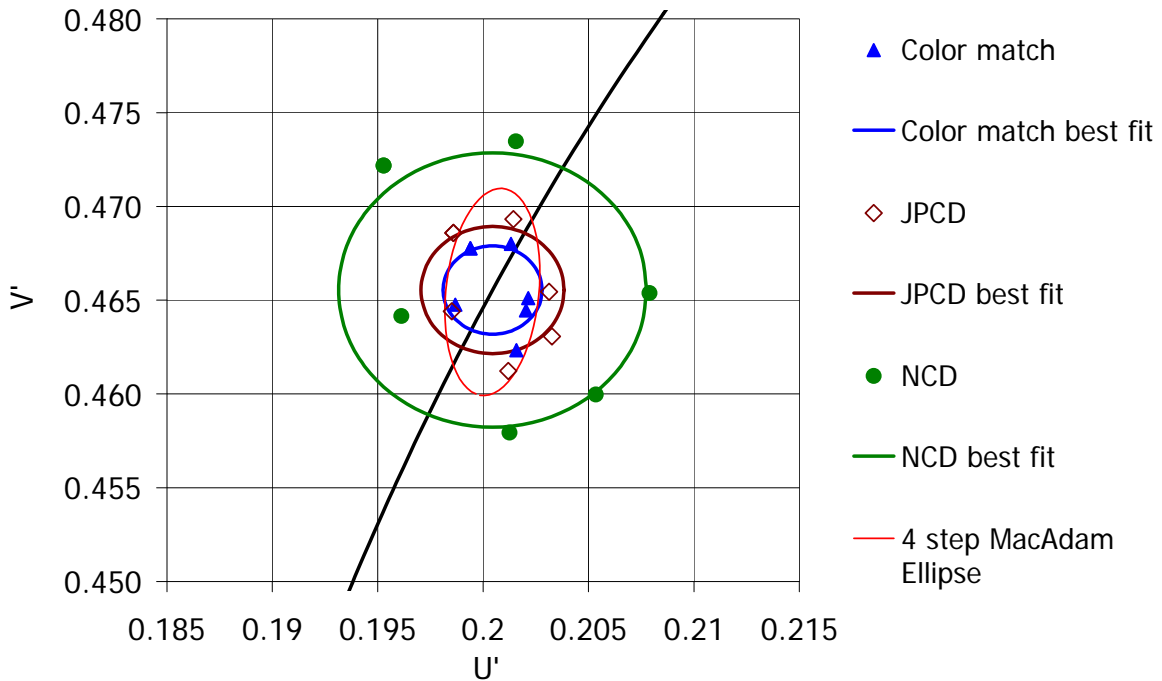
Results are shown on a U' , V' chromaticity diagram. Data points indicate the mean values of the subject ratings for match, just-perceivable color difference (JPCD), and noticeable color difference (NCD) conditions. Best-fit circles for each data group and a reference 4-step MacAdam ellipse are also illustrated in each graph.

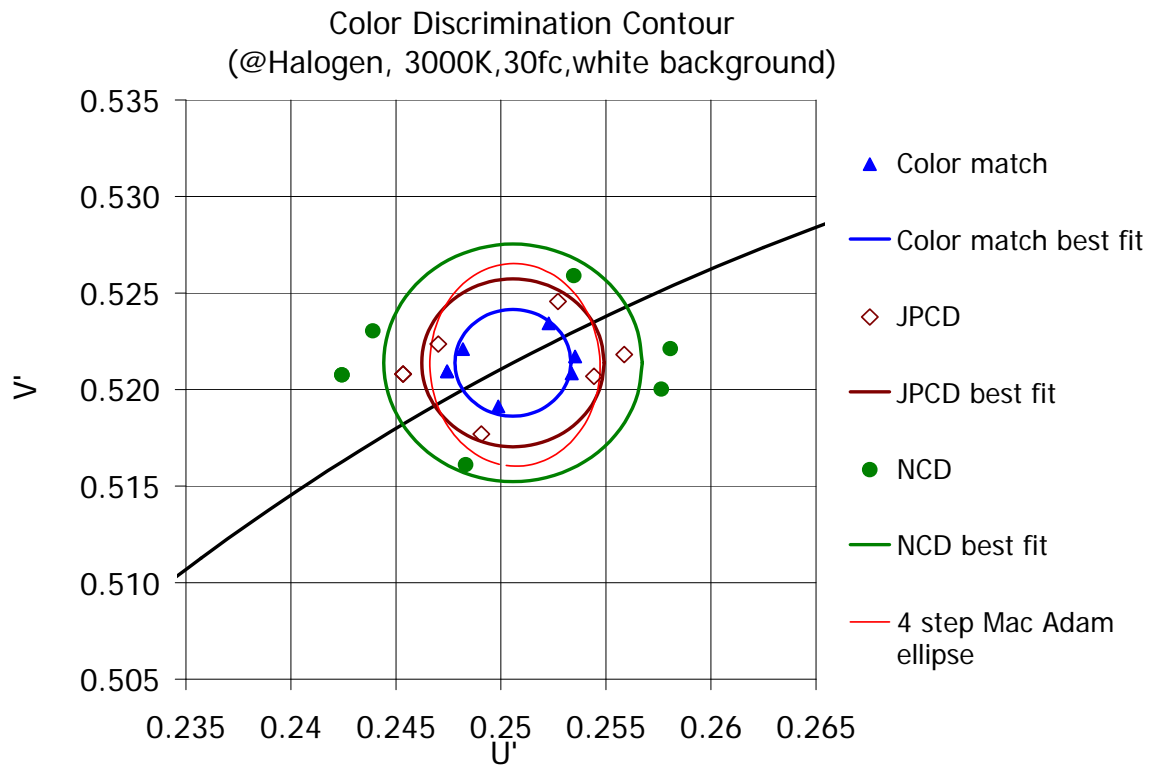
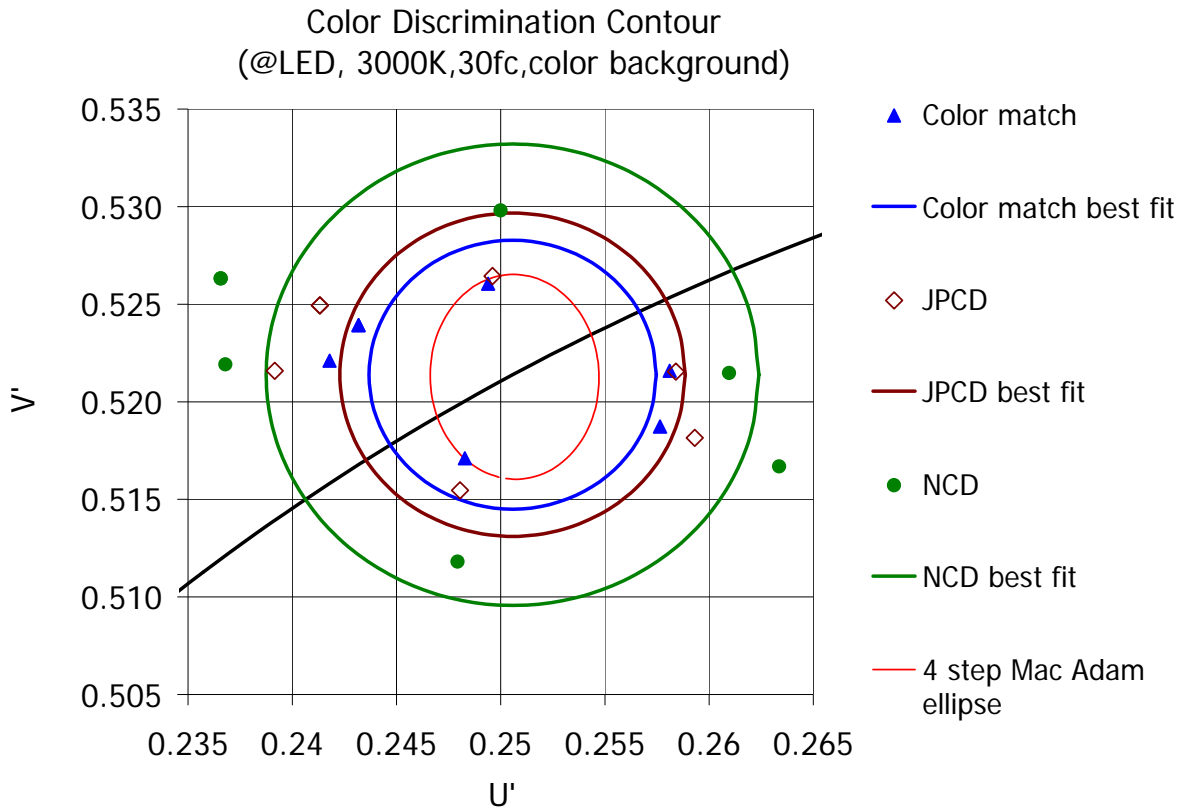


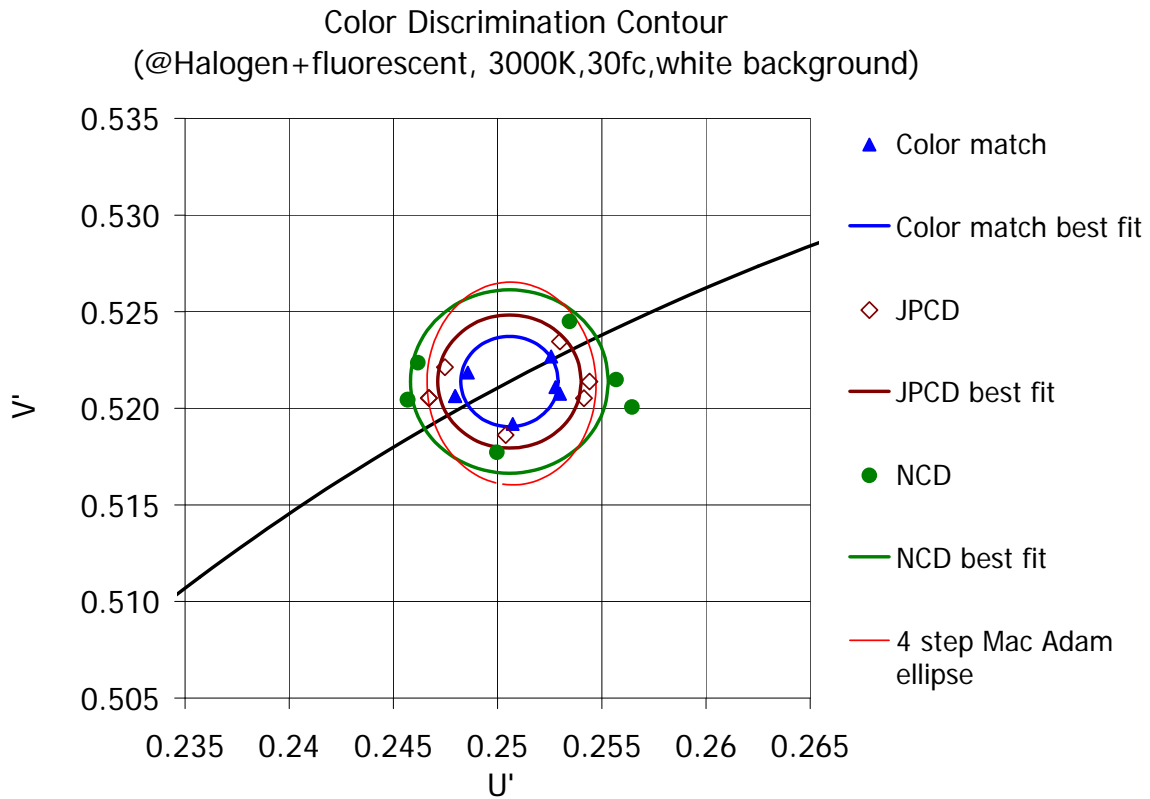
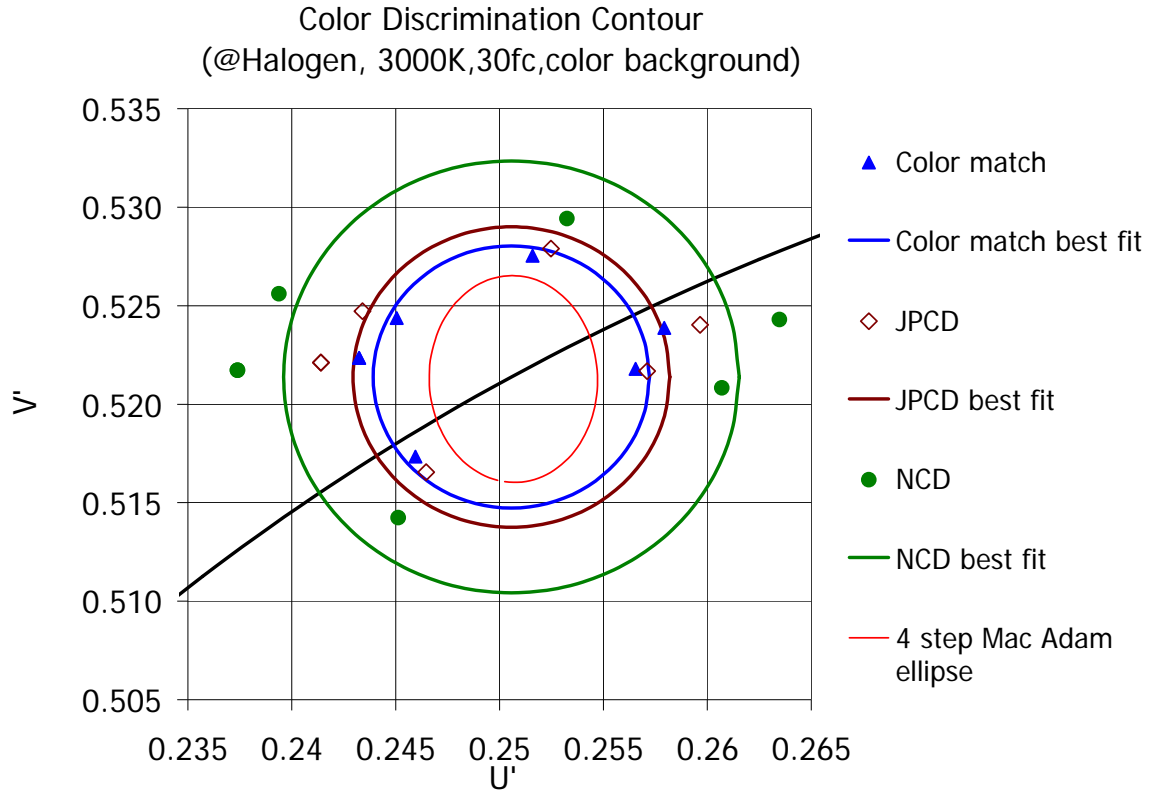
Color Discrimination Contour
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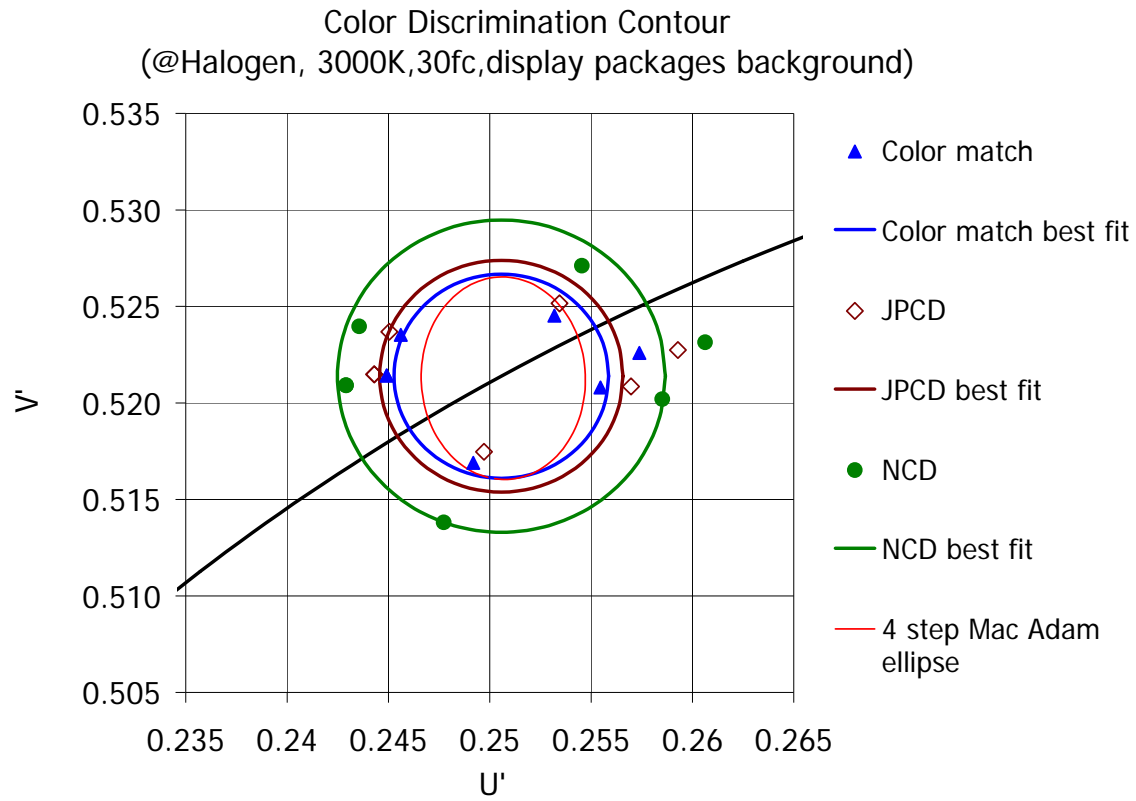


Color Discrimination Contour
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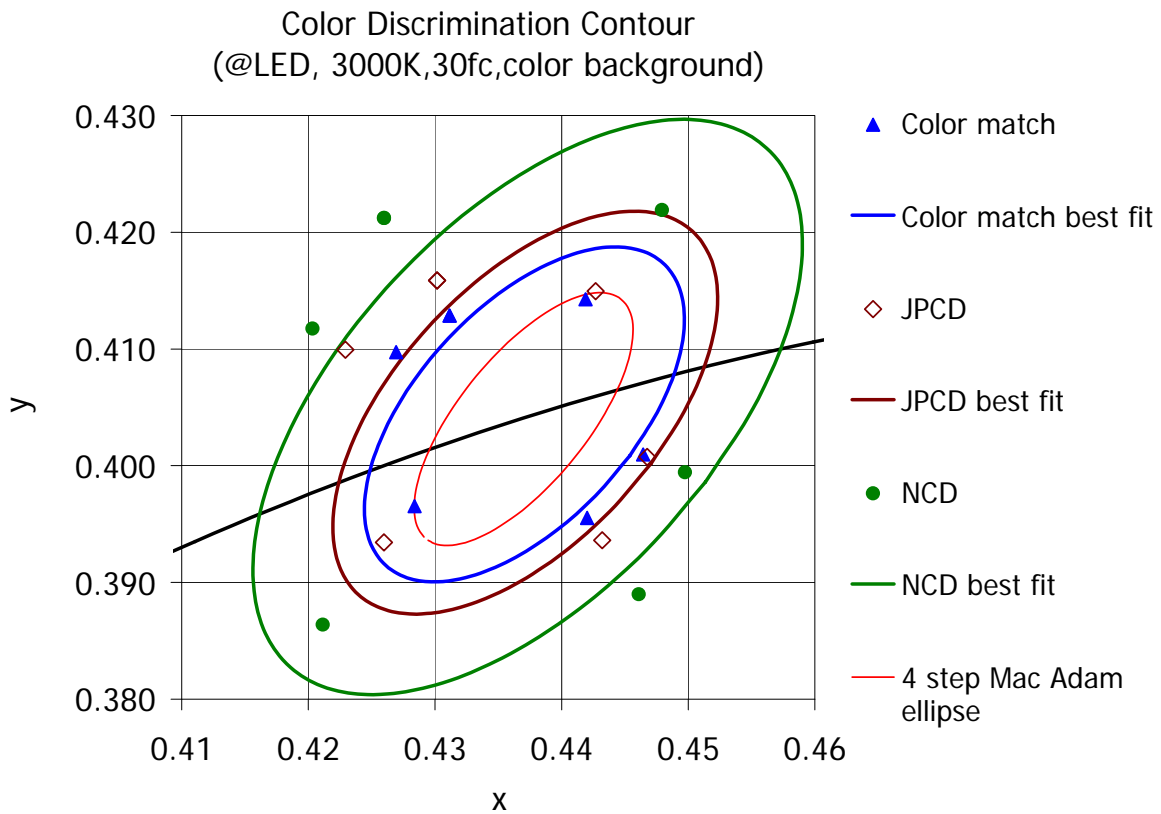
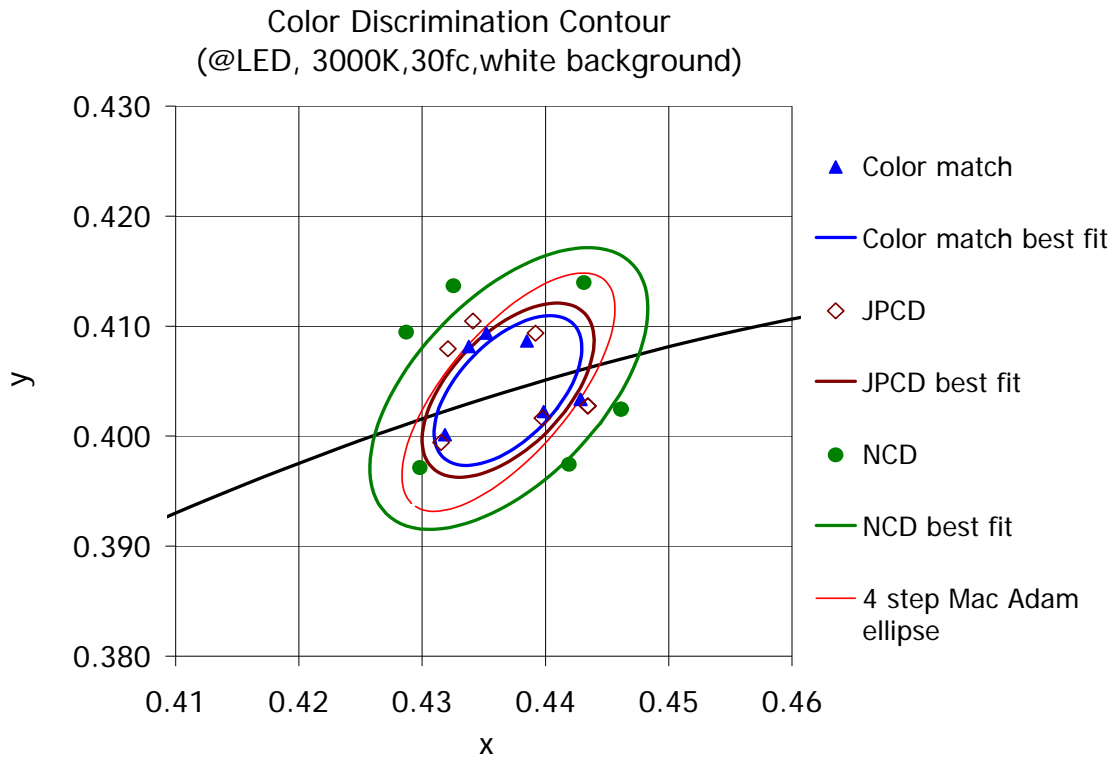




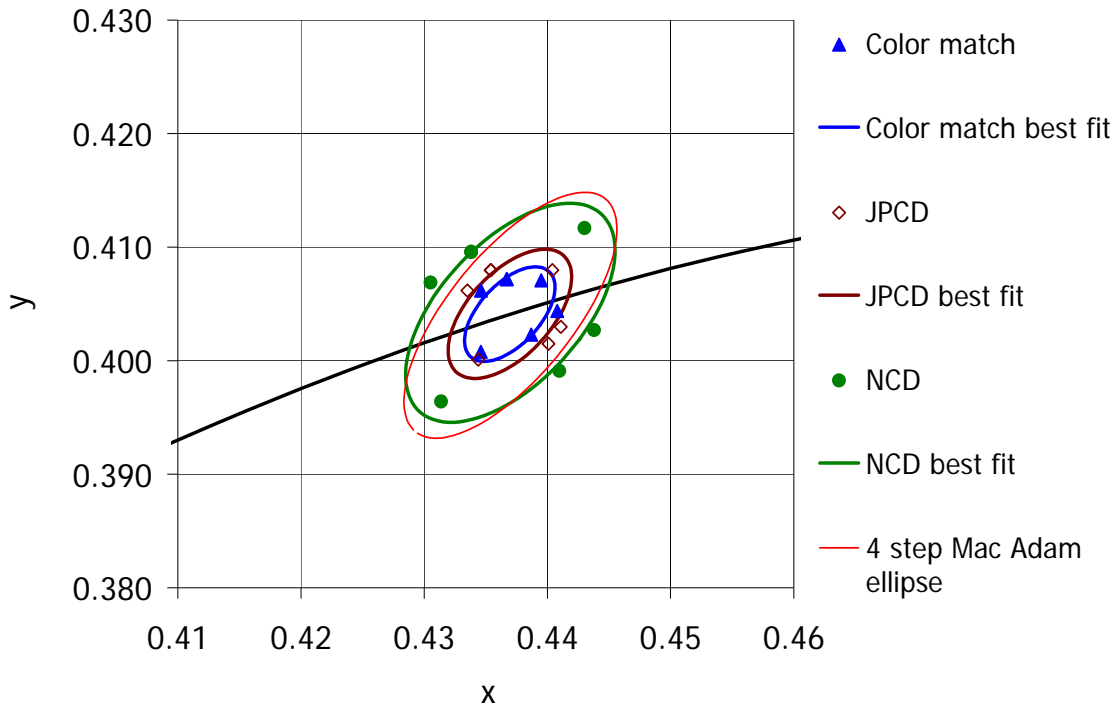


Appendix 2

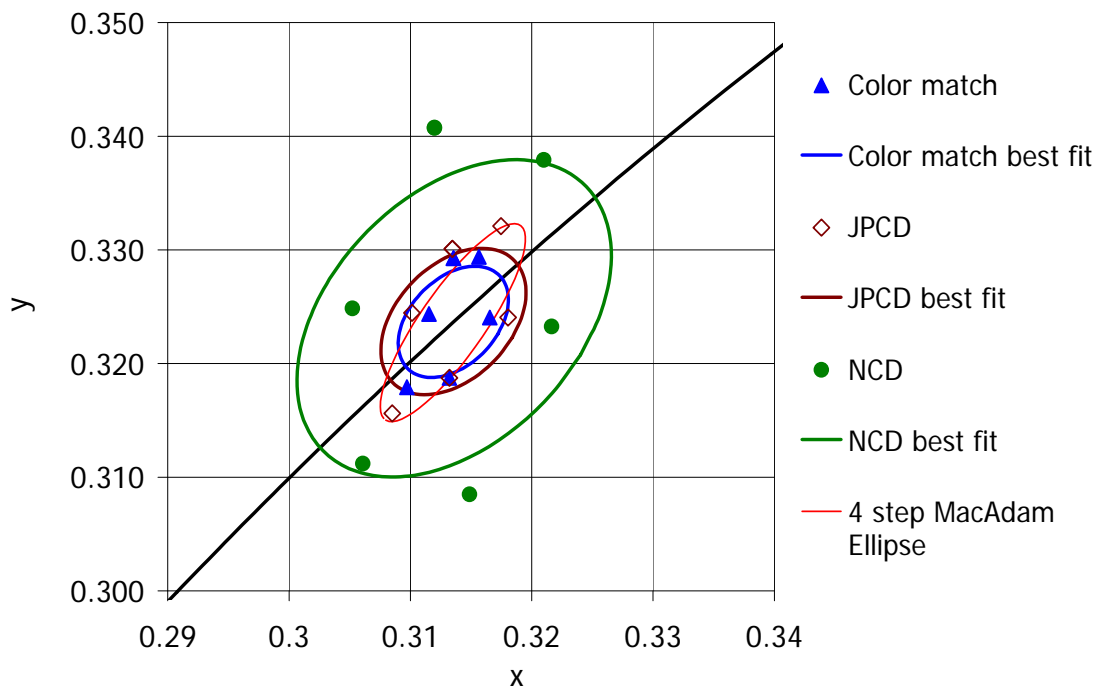
Results are shown on a CIE x, y chromaticity diagram. Data points indicate the mean values of the subject ratings for match, just-perceivable color difference (JPCD), and noticeable color difference (NCD) conditions. Best-fit circles for each data group and a reference 4-step MacAdam ellipse are also illustrated in each graph.

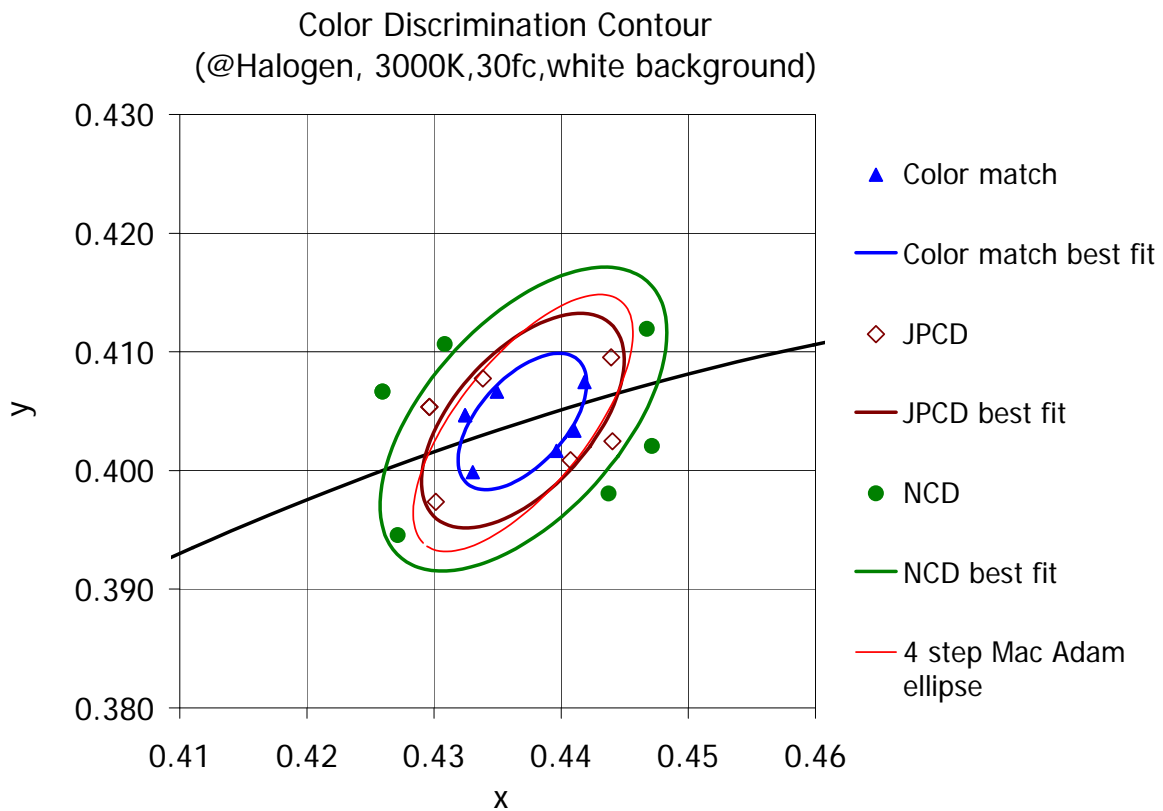
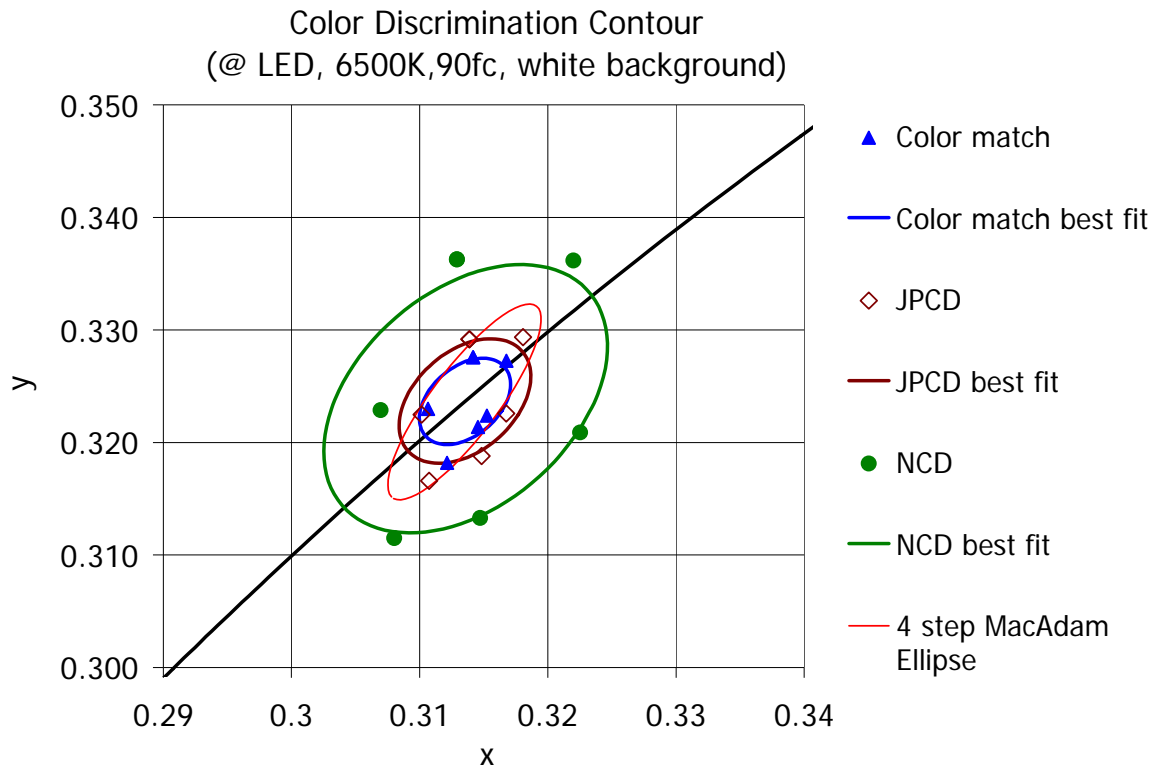


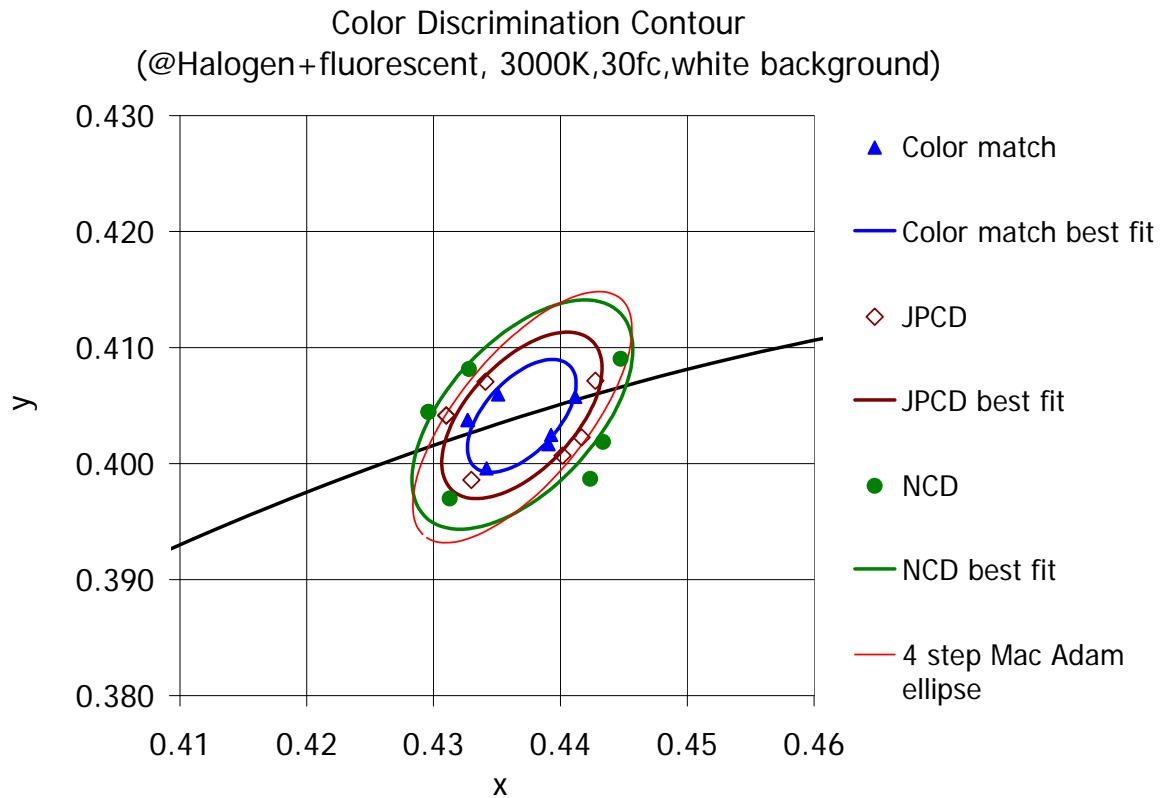
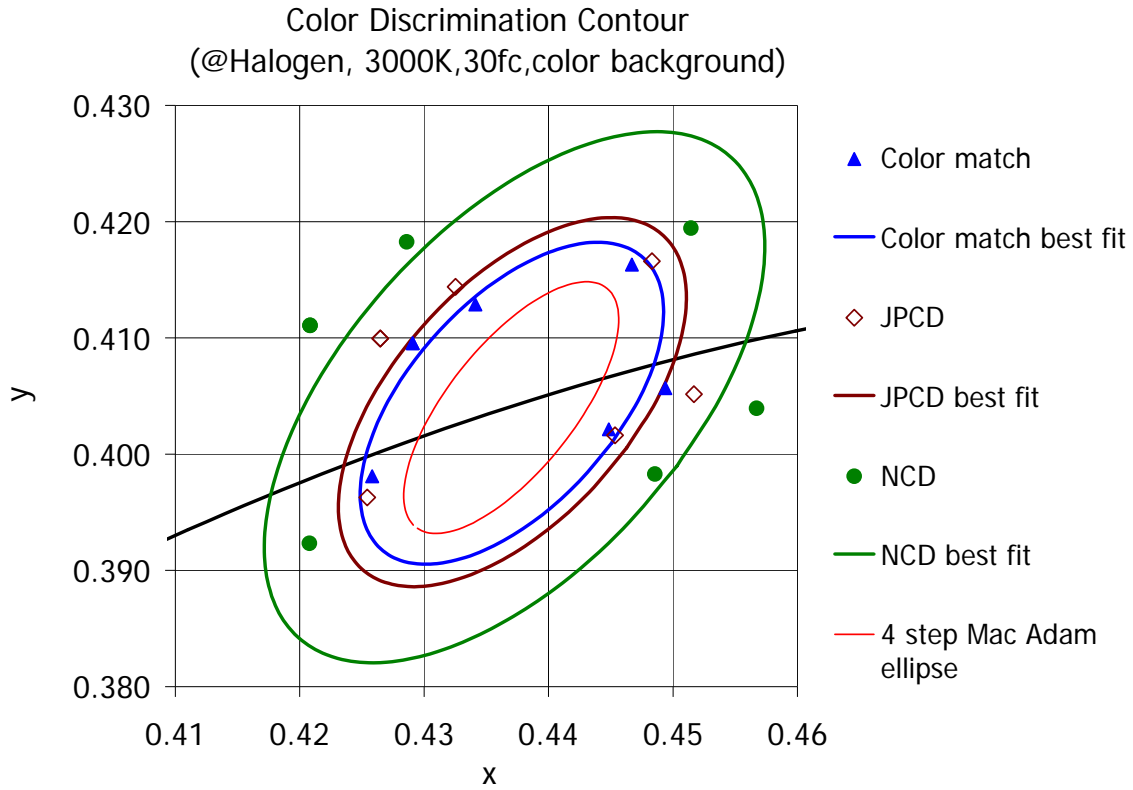
Color Discrimination Contour
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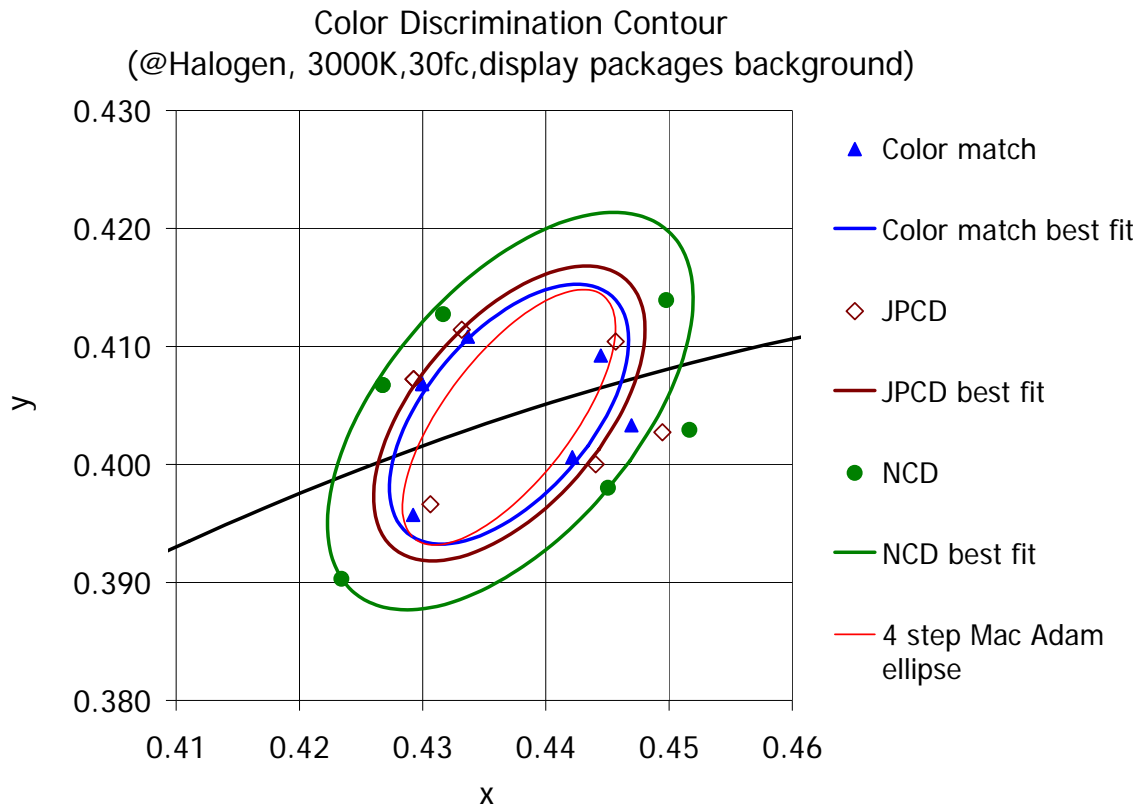


Color Discrimination Contour
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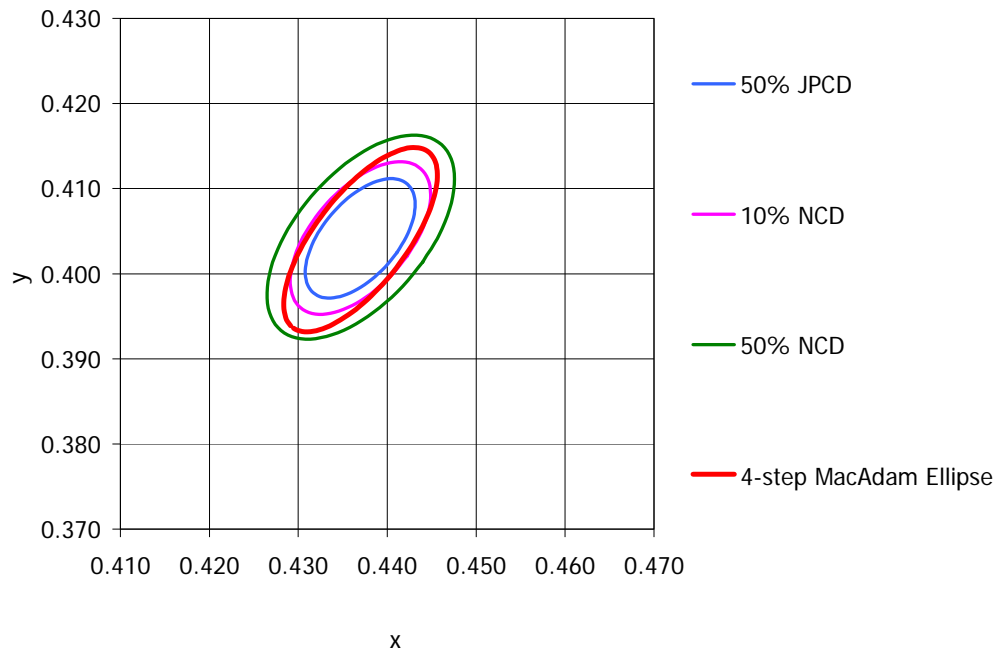




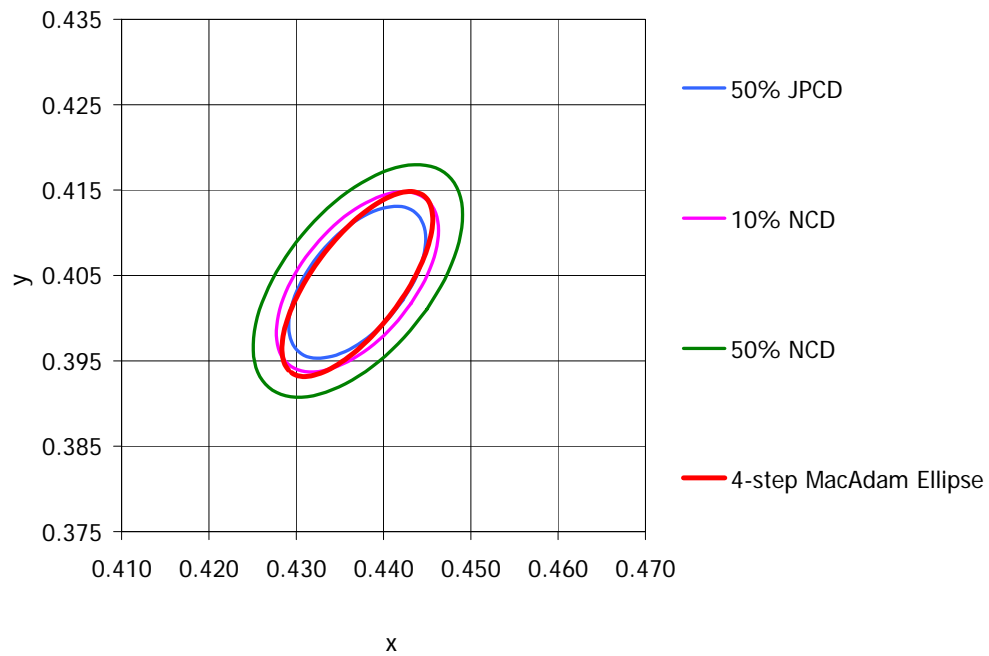
Appendix 3

Results are shown on a CIE x, y chromaticity diagram. Data points indicate the 50% just-perceivable color difference (JPCD), and 10% and 50% noticeable color difference (NCD) conditions. A reference 4-step or 8-step MacAdam ellipse is also illustrated in each graph.

Color Discrimination Contours
(for LEDs, 3000K, 90fc, white background)



Color Discrimination Contours
(for LEDs, 3000K, 30fc, white background)



Color Discrimination Contours
(for LEDs, 3000K, 30fc, multicolored background)

