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# Just-Perceivable Color Differences between Similar Light Sources in Display Lighting Applications

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## ABSTRACT

Some light source technologies are notorious for being inconsistent in color between lamps of the same nominal type. Producing the same type of lamp with no apparent color differences depends on the manufacturing process and its tolerances. These requirements directly impact the cost of the final product. Therefore, the manufacturers want to know how much color variation can there be between lamps of the same nominal type. An experimental study was conducted to investigate at what point observers perceive a color difference between similar lamps when used in display lighting applications. A mock-up refrigerator display case with two side-by-side cabinets was used as the experimental setup. A novel fiber-optic lighting system with color tuning capabilities was developed and used as the light source in the display cabinets. Human subjects made comparative judgements between the reference cabinet and the test cabinet when the color in the test cabinet was changed in a systematic manner. Several types of colored displays were used in this study. The results indicate that a color tolerance criterion such as the four-step MacAdam ellipse, recommended by ANSI, for a given lamp type is too generous for display lighting applications where the scene has white objects and little visual noise. On the other hand for lighting multicolored displays with lot of visual noise, the four-step MacAdam ellipse criterion seems adequate. The conclusion that can be drawn is that a single criterion for a lamp type will not satisfy all applications. Therefore, it might be better to set different ranges that can cover the various application categories.

## INTRODUCTION

There are many types of lamps available in the market place for general lighting applications. In the lighting industry it is customary to describe the color of a lamp by its Color Temperature (CT) or the Correlated Color Temperature (CCT) both of which are measured in Kelvin degrees. For most commonly used lamps, the CCT value varies from 2700 K to 5000 K. The CCT does not completely describe how a lamp appears. Alternatively, representing the lamp color as x, y values on the CIE chromaticity diagram provides more information regarding the appearance of the light source. Lamps are considered white light sources, if the CIE x, y values fall on or close to the blackbody locus.

The variety in lamp colors greatly helps lighting designers create visually appealing environments. On the other hand, having lamps of 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. Light source technologies such as metal halide, end-emitting fiber optics and some reflectorized lamps are known for their color differences between lamps of the same nominal type. Producing the same type of lamp with no apparent color differences depends on the manufacturing process and its tolerances. These requirements directly impact the cost of the final product. Therefore, a commonly asked question by the manufacturers is "how much color variation can there be between similar lamps?" There is no simple answer to this question. At present, the lighting industry uses MacAdam ellipses for color discrimination. ANSI specifies four-step MacAdam ellipses as the tolerance criterion for color, for certain types of fluorescent lamps[1]. 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. Therefore, setting a general criterion for acceptable color variation such as the four-step MacAdam ellipse for a lamp type may not be appropriate, because it could be excessive for certain applications while being inadequate for others.

For the past five decades, several researchers have conducted studies to understand how sensitive the human visual system is to small color differences. Most of these studies are based on color matches about a color center under controlled conditions. In 1942, D. L. MacAdam studied the visual sensitivities to color differences in daylight using a monocular arrangement, where the observer viewed a 2-degree comparison field that had a split circular target[2]. The 2-degree test field had a luminance of 48 cd/m$^2$ and a 42-degree diameter field having a chromaticity similar to that of standard illuminant C (average daylight) and a luminance of about 24 cd/m2 surrounded it. A single observer made over twenty-five thousand trials matching the color of the two halves in the field of view by turning a single control knob while the luminances of the two fields were automatically held constant. The standard deviations of the distribution of the color matches made were denoted in terms of distances on the 1931 CIE Chromaticity diagram. The loci of the points representing the standard deviations form an ellipse around the color center. Thus the study resulted in a family of ellipses on the CIE Chromaticity diagram around 25 standard color centers that denote equally noticeable color differences.

In 1949, Brown and MacAdam studied trichromatic color matching using a similar monocular colorimeter with a split 2-degree viewing field and a dark surrounding field[3]. The equal luminance restriction that was present in the earlier study was removed in this study. The two observers in the experiment adjusted the amount of mixture primaries in the variable field. The spectral composition of the test and fixed fields were the same for an ideal match. The luminances varied from about 1 to 30 cd/m$^2$. Although the cross sections of the ellipses obtained from Brown and MacAdam's study generally resembled the ellipses obtained by MacAdam in 1942, more than fifty percent of them had marked discrepancies under close examination.

In 1957, Brown, conducted another study with 12 observers to understand the variation between their ellipses and to obtain mean-discrimination ellipses at 22-color centers[4]. These color centers extended over a wide range of chromaticities and the luminance varied between 9 to 18 cd/m$^2$. Brown used a binocular colorimeter with a 10-degree matching field surrounded by a broad near-white field, to mimic the condition under which color matching is generally performed. Brown's study showed that there is significant variation between observers. The study also showed that there is a pronounced learning effect in the results for given observers for repeated measurements.

All of the studies mentioned above were conducted using a limited field of view and low target luminance Furthermore, the viewing target was a luminous field. None of the studies were performed under real application situations. Therefore, the main motivation for the study explained in this manuscript is to understand how color discrimination varies when they are examined under real application conditions and to determine at what point observers perceive a color difference between similar lamps in a given application. The target application selected for this study is the refrigerated display cabinet lighting commonly found in supermarkets.

## EXPERIMENTAL SETUP

Since the goal of this experimental study is to determine the points at which human subjects observe a just-noticeable color difference between light sources in refrigerated display cabinets placed side-by-side, an experimental setup that mimicked a real-life situation was needed. Of all the components in the experimental setup, the capabilities of the lighting system were the most demanding. The color of the light source inside the display cabinets had to be changed systematically in chromaticity space, such that the color in one display cabinet was held constant while changing the color in the second cabinet in a predictable manner. The details of each major component of the experimental setup and the subjects used in this study are described next.

### Display Cabinet

Prior to building the experimental setup, the authors conducted a brief survey of vertical freezer cabinets found in local supermarkets. On an average, the vertical illuminance on the front face of the displayed objects inside the freezer cabinets was 32 footcandles and the horizontal illuminance on the floor in front of the cabinets was 50 footcandles. The freezer cabinet configurations varied significantly. Some of them had a back wall while the others did not, to allow access for re-stocking from the back rather than from the front doors. The interior wall finishes varied from bare metal to white enamel. The majority of vertical freezer cabinets had continuos transparent glass doors and fluorescent lamps placed one on either side of the glass panels. A small number of them had fluorescent lamps placed above and below the glass panels. The lamps found in our survey were cool white, high output fluorescent tubes (F60T12 CW-HO). The freezer cabinets had several horizontal racks depending on the kinds of products being stored in them (five to six racks). The racks were made from either metal or vinyl coated wire. In general, the products stored in these freezer cabinets were frozen food items (TV dinners, frozen vegetables, ice creams, etc), plastic or glass bottles (milk, soda, beer, etc) and cans (soda, or beer).

Figure1 illustrates the experimental setup constructed for this study, which is a half-scale mock-up. The size criterion was dictated by the amount of light provided by the lighting system developed for this study. An internal wall to create two side-by-side cabinets divided the display area of the mock-up freezer case. This allowed each chamber to be illuminated separately without light leakage from one display cabinet to the other. There were only three horizontal racks per display cabinet due to its size. The cabinets had a back wall and the interior was spectrally neutral white in color. The cabinets were not cooled and also they did not have glass doors in the front. The authors felt that the lack of these two features would not affect the results of the study. The experimental setup recreated light levels of typical freezer cabinets, and it was placed in a room that had ambient lighting similar to that of a supermarket.

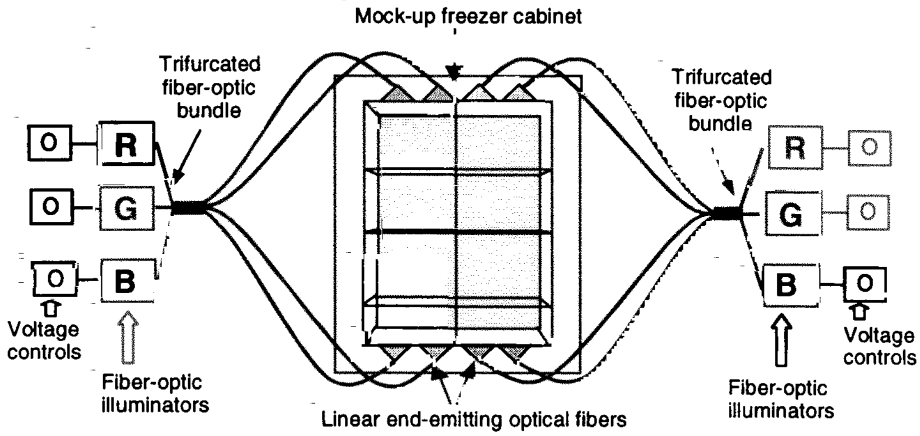


**Figure 1:** Experimental setup

Lighting System

It is a well-known fact that combining the light from three primary color sources in the proper proportions can produce any color stimulus. Based on this principle, a novel fiber optic lighting system was developed for this experiment. Three fiber optic illuminators with halogen lamps and color filters (red, green and blue) became the tunable light sources for the display cabinets. The halogen lamps were selected because they had a continuous spectrum in the visible range and also they could be dimmed easily. The three color filters chosen were broadband. The combined filtered spectrums of the three illuminators represented the spectrum of a single halogen lamp. In other words, there were no dead bands in the combined spectrum, which is an important consideration for color rendering. This also ensured that there wasn't wasted energy, which again was important since the light output from the three illuminators was just sufficient to reproduce the required light levels inside the display cabinets.

As shown in Figure 1, a trifurcated fiber-optic bundle was utilized to accept the light from each illuminator. Combining the individual fibers (red, green, and blue) systematically at the output end allowed color mixing to produce the required white light. By adjusting the light output of the halogen lamps using voltage regulators, the color of the light was varied. The combined fibers at the output end were split into four equal parts and each part was configured to a linear light source. The four linear light sources were placed above and below one cabinet aperture as illustrated in Figure 1. The light distribution inside the cabinet proved to be more uniform when the linear sources were placed above and below than if the sources were placed on either side of the cabinets. Since optical fibers provide a directional beam, they had to be aimed so that the light was distributed more evenly within the cabinets. These linear sources inside the cabinet were not directly visible to the observer. An identical lighting system with three other halogen fiber-optic illuminators were built for the other case aperture. Finally, there were six control knobs, three (R, G, B) for each side, that allowed the color of the light to be changed at very fine intervals. Since each freezer cabinet had its own control, we were able to tune and fix the color of the light source at any color center while changing the color in the second cabinet very finely around this color value.

Displayed Objects

There were two kinds of objects used inside the mock-up freezer cabinets. One was a mix of red, green, blue, white and black colored paper cups, see Figure 2(a); the other was a mix of different frozen food boxes, see Figure 2(b). The paper cups were selected because they were available in the colors needed for this study. During human subject measurements the objects inside the freezer cabinets were displayed in three different configurations, as listed below.

Display 1: Red, green, blue and white cups stacked regularly.
Display 2: Red, green, blue and black cups stacked regularly.
Display 3: The frozen food boxes stocked within each freezer cabinet.

Subjects

The subjects who participated in this experiment were employees and graduate students of the Lighting Research Center (LRC). There was a total of 15 subjects, three in Experiments 1 and 2 (three females), and 12 in Experiment 3 (six males and six females). Their ages ranged from 20 to 50 years old. All subjects had normal color vision. The knowledge about lighting (technology, human factors and aesthetics) varied among the subjects. Of all the subjects 56% had little or no formal knowledge about lighting, 19% had some kind of lighting knowledge through other means such as a study of architecture, and 25% were trained in lighting, therefore they were very knowledgeable about lighting in all aspects. Although a larger number of subjects would have an impact on the results in terms of precision, the purpose of this study, however, is to establish trends of color discrimination tolerances. Therefore, the number of subjects used in this study is sufficient.

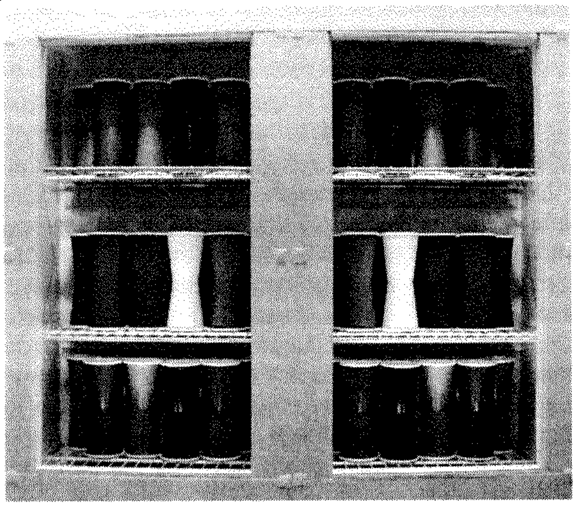

Figure 2(a): Example of the paper cups display


Figure 2(b): Example of frozen food boxes display

In all display configurations, one stocked freezer cabinet would be the mirror image of the other. This meant that if observers looked at the right corner of one cabinet and saw a red object, they would see the same exact red object on the left corner of the other cabinet.

## EXPERIMENTAL PROCEDURE

Altogether, there were three experiments. The goal of the first experiment was to replicate MacAdam's study[2] as closely as possible under the current experimental conditions and verify that the results were comparable to MacAdam's results. The second experiment was conducted with different displayed objects to understand what impact object colors have on the light source color discrimination task. The third experiment was conducted to determine color discrimination contours with typical display objects in the scene, at various color centers, and compare the results with MacAdam's ellipses.

As illustrated in Figure 3, a spectrometer (Photo Research PR-703A) was used in all three experiments to measure the luminance and the CIE x, y values of the light inside the freezer cabinets. The spectrometer was set on a tripod, about eight feet away from the front of the freezer case and 56 inches above the floor. It was aimed about 10° down from the horizontal axis towards a point close to the center of the freezer cabinet's back wall.

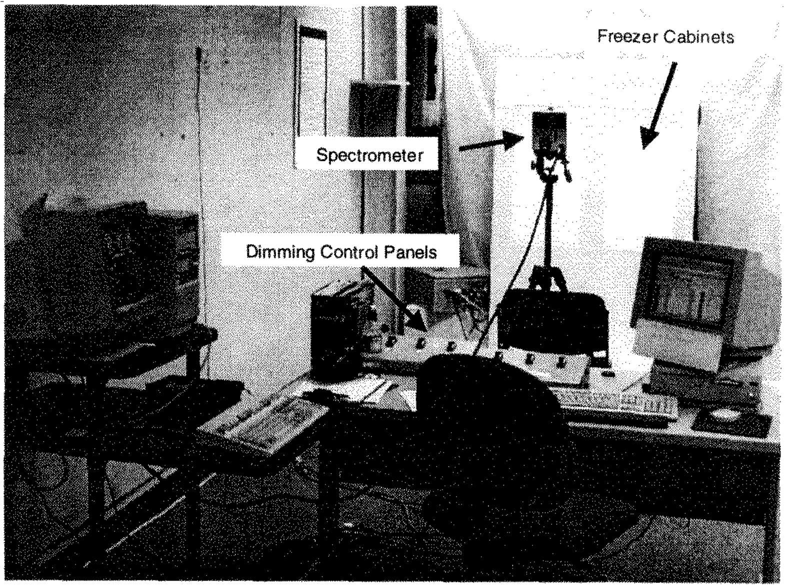


**Figure 3:** Experimental Setup

The illuminators were switched on, one at a time, and the corresponding CIE x, y values were measured using the spectrometer. Figure 4, illustrates the measured chromaticity coordinates of these six illuminators, plotted on the 1931 CIE chromaticity diagram. The chromaticity coordinates of the three light sources in each cabinet form the corners of a triangle on the chromaticity diagram. Mixing the light from the illuminators would result in a color whose chromaticity coordinates fall within this triangle.

Prior to starting any tests, the lighting in the two empty freezer cabinets were set to a particular color temperature by adjusting the dimmer dials. At this point the luminance and color of the two cabinets were matched and the two cabinets appeared the same. Starting at a particular color center and adding or subtracting a single color using the dimmer controls will result in shifting the chromaticity value along the line joining the color center and the apex on the triangle corresponding to that color, as shown in figure 5. As an example, starting at 3077 K and adding some red will move the chromaticity value towards the red apex along the axis joining the color center and the red apex. Likewise removing red will move it away from the red apex from the 3077 K center, along the axis joining the color center and the red apex.

Adding or subtracting an amount of red, green or blue light would change the average color inside each cabinet. Making spectrometer measurements, at a fixed point off the cabinet's back wall, while stepping through the voltage control dial setting at regular intervals, allowed the dial settings to be calibrated to read CIE x, y values. Initial luminance values for both freezer cabinets were between 140 and 155 cd/m$^2$. The lighting system used in this experiment did not have feed back control to maintain the luminance of the visual field constant. Therefore, the luminance changed whenever a color was added or removed. However, in the entire experiment the luminance change was very little. The average luminance values were between 131 to 164 (± 15% about the mean: 146 cd/m$^2$), 132 to 170 cd/m$^2$ (± 16% about the mean: 146 cd/m$^2$), and 145 to 150 cd/m$^2$ (± 3% about the mean: 143 cd/m$^2$), while adding or subtracting red, green or blue light respectively. The luminance ratio between the two averages is small especially at these high luminance levels and is within the range of the earlier studies by MacAdam and Brown[3]. Future work may provide an opportunity to modify the setup so that luminance levels could be kept constant while changing the chromaticity values.

All subjects were screened for color deficiency prior to beginning the experiments. As shown in Figure 6 the subjects sat on a chair in front of the freezer cabinets 6 feet away.

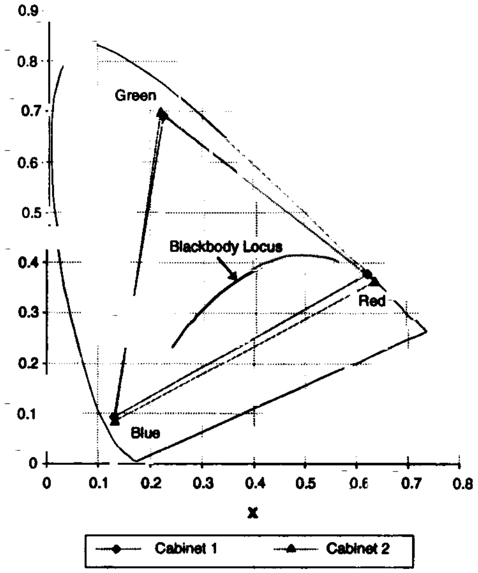


Figure 4: Chromaticity coordinates of each individual color filter

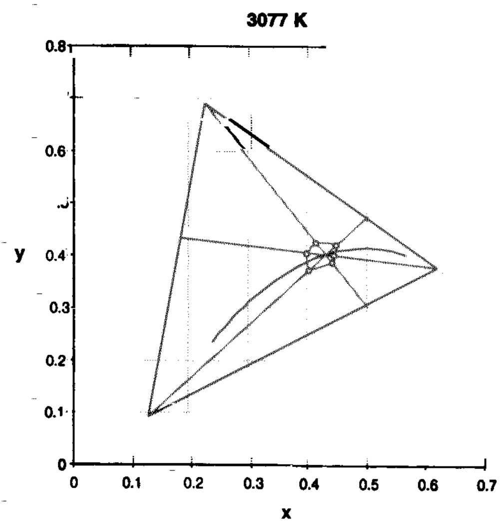


Figure 5: Color axis for the three primary colors used in the study

The total field of view of a cabinet aperture was about 10 degrees. The subjects were asked to compare the left freezer cabinet (test) against the right cabinet (reference) for just-noticeable color differences when red, green or blue color light were independently added or taken away from the test light source. Subjects were specifically instructed to view the cabinets in general and compare color differences between them and not to look at individual objects. The subjects kept their sight focused on a white surface on the floor for visual adaptation until they were asked to compare the color of the two cabinets. When subjects were asked if the two cabinets matched in color, they brought their eyes up towards the cabinets, had two seconds to make the visual comparison, brought their eyes back down and answered. The two second visual exposure was selected to compromise between chromatic adaptation, caused by long exposure time, and interference caused by spatial and temporal integration, due to short exposure time. If their answer was 'no' then they had to make a judgement of the difference and pick one of the following: 1=not different, 2=just-perceptible, 3=noticeable and 4=obviously different. When the colors of the two cabinets were sufficiently close in appearance, the subjects found it difficult to assess a color match and said there was a color difference on some trials while on others they said there was no color difference, even when the dial had not changed. To overcome the uncertainty of the subject's answers, we used a psychophysical measurement technique known as the random double staircase method[5,6]. Using this method, the subject was exposed to an average of 50 presentations per color. These presentations included addition and subtraction of the color in question. Within those two categories, the experimenter showed the subject examples of obvious, noticeable, just perceptible and no color differences. The presentations began with obvious differences and moved towards no differences while switching between addition and subtraction of the color randomly.

Once the subject arrived at a match after addition of a color, the experimenter would systematically subtract that color until the subject saw a color difference. Every time there was a reversal on the subjects' answer the experimenter added or subtracted the color accordingly. This procedure was repeated until there was a total of 12 reversals per addition and 12 per subtraction. The average of the last nine reversals was calculated. All together there were 6 averages for each subject, two per RGB color (addition and subtraction) in a given test. Figure 5, shows an example of the six data points mapped on the three color axis. Each average represented an RGB color at a particular dial setting. These dial setting numbers were converted to CIE x, y values and luminance values using the prior calibration.

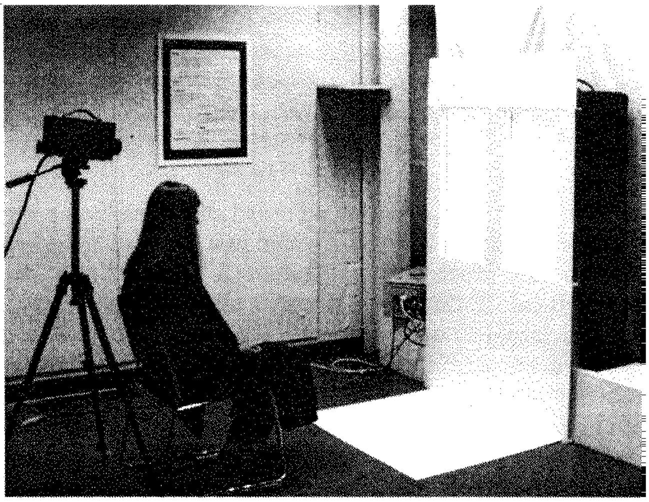

**Figure 6:** Subject viewing the freezer cabinets

Once the necessary data were gathered, the subject was dismissed and the freezer cabinets were emptied. The dials were reset to their original values. The color and luminance of the freezer cabinets were measured using the spectrometer to determine the variance between the chromaticity coordinates before and after the test.

## RESULTS AND DISCUSSIONS

A presenter conducted all three experiments by adjusting the color of the lights inside the mock-up freezer cabinet while asking the appropriate questions to the subjects. The first two experiments were conducted at one CCT value and the third experiment was conducted at four different CCT values. The details of each experiment and the associated results are explained in this section.

<u>Experiment 1: MacAdam Replica</u>

The goal of this experiment was to conduct a study very similar to MacAdam's experiment but for the current experimental conditions and to compare the results to MacAdam ellipses. Since MacAdam's study compared the colors in a circular 2-degree field, we covered the empty mock-up freezer cabinets completely with two white foam board screens with two small circular apertures that allowed a view to the inside of cabinets as shown in Figure 7. The apertures formed a 2-degree field of view for the observing subject. The two apertures were centered on the board in the vertical direction and the distance between their centers was 10 inches. Prior to starting the experiment, the lighting in the two cabinets was set at 4000 K by adjusting the dials of the dimming panel to the appropriate chromaticity coordinates. Both cabinets matched in luminance and color in the absence of ambient lighting.

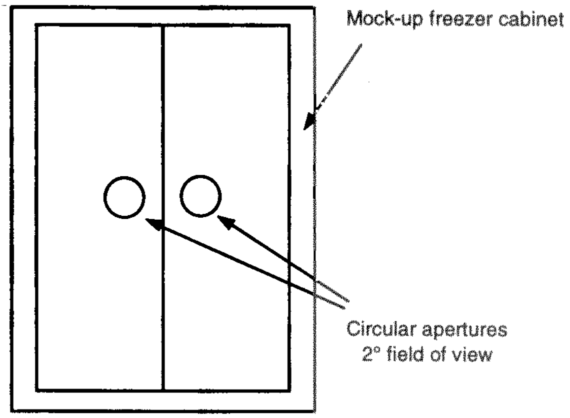


**Figure 7:** Setup used for repeating MacAdam's study

Three subjects participated in the first experiment that lasted about one-hour per subject. This experiment was conducted without ambient lighting. A practice round was included at the beginning of each session to make the subjects familiar with the procedure and to minimize any learning effects. Each session was divided into three for the RGB colors. Data collection took place according to the procedure explained in the previous section. From each subject we obtained six average CIE x, y values, each value being an added or subtracted RGB color. An average from the three subjects for each color was then calculated obtaining six final CIE x, y values, which represented the boundary for the color discrimination area. These six CIE x, y values are illustrated in Figure 8, and they are connected with a line to create a contour and are referred to as "MacAdam replica" in the graph. A first standard deviation MacAdam ellipse (one-step MacAdam), which represents color discrimination by 66 percent of the population, is also plotted on the same graph for comparison.

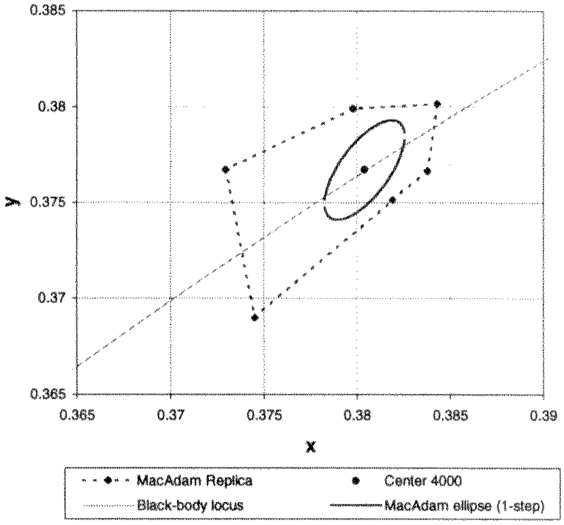


**Figure 8:** Comparison between the one-step MacAdam ellipse at 4000 K and the corresponding color discriminaion contour (MacAdam replica)

The average color discrimination contour determined in our experiment was larger than the first-step MacAdam ellipse at the same color center. This is not surprising because the conditions for Experiment 1 were somewhat different than MacAdam's experiment. In our case there were two separated 2-degree fields of view instead of one, and the luminance of the target was substantially higher while the surround was dark. However, it is interesting to note that if we used the six data points to draw an ellipse, the major and minor axes of the two ellipses would have coincided. Within our data analysis we did not fit ellipses to the data point because it was unclear that the contours were indeed elliptically shaped. For all practical purposes, the area covered by the data points is sufficient to make the judgement whether the tolerance for color variation is larger or smaller.

Experiment 2: Multicolored Displays

The second experiment was conducted with different types of colored objects placed within the mock-up freezer cabinets. Refer to displays 1, 2, and 3 explained earlier. The goal here was to understand the difference in the color discrimination ranges when comparing different stocked colored objects. Unlike Experiment 1, the field of view for this experiment was the size of the cabinet apertures, the cabinets were filled with objects, and there was ambient lighting (50 fc. on the floor). The CCT value of the lighting in the mock-up freezer cabinets was set at 4000K. Prior to starting the experiment the lighting in the two cabinets were matched to the specific color temperature following the procedure used in Experiment 1. After calibration the cabinet shelves were stocked with displays 1, 2, or 3. Data collection was identical to Experiment 1. The same three subjects participated in this experiment. The results for the chromaticity coordinates for each display condition are illustrated in Figure 9. The results obtained from Experiment 1 are also plotted on this graph for comparison.

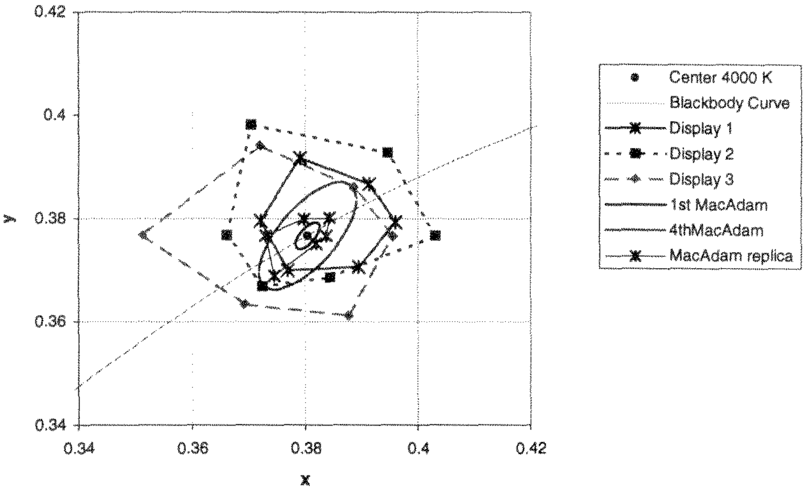


**Figure 9:** The average color discrimination contours at 4000 K for the three displays and MacAdam ellipses

The following observations are made from Figure 9:

1. The average color discrimination contours with the display objects inside the cabinets are bigger than the first-step MacAdam ellipse and the replicated MacAdam study results. Unlike a white interior, colored objects inside the freezer cabinets make color discrimination more difficult and therefore the contour areas are larger.

The color discrimination contour from display 2 is larger than the one from display 1. The presence of white cups in display 1 among other colors provided a better clue to the subjects regarding the color of the light source and therefore eased the color discrimination task.

3 The color discrimination contour from display 3 is larger than the one from display 1 but similar in size to display 2. The presence of white among multicolored objects would make it similar to the display 1. But, these frozen food boxes have more visual noise due to different patterns and lettering on them. This makes color discrimination more difficult and therefore the range is greater than the one obtained from display 1. However, one would expect this range to be smaller than the range from display 2, which did not have any white regions. This suggests that visual noise in a scene can make color discrimination as difficult as a scene that does not have any white patches of color in it.

4. The four-step MacAdam ellipse (almost all can see a color difference) is bigger than the MacAdam replica. The four-step MacAdam ellipse is of the same size as the color discrimination contour from display 1, which indicates that 50% of the subjects see a color difference. This seems like a generous criterion. Therefore, the four-step MacAdam ellipse is an inadequate requirement for applications where there is little visual noise and has white objects in the scenery.

Experiment 3: Typical Display Objects under Different CCT Light Sources

The goal of the third experiment was to verify that the color discrimination contours obtained for cabinets stocked with typical objects, such as the frozen food boxes, is larger than MacAdam ellipses at several color centers along the black-body locus. The tests were carried out at four-color temperatures across the blackbody locus, including 3077K, 3636K, 4000K and 4444K. Once again the field of view was the size of the cabinet apertures and there was ambient lighting. The cabinets were stocked with frozen food boxes. There were twelve subjects in this experiment. The data collection process was similar to the previous experiments.

The results for the twelve subjects varied significantly. The color discrimination contours at various CCT values for the twelve subjects are illustrated in Figure 10. These contours are drawn at 10-percentile intervals from 0 to 100. A problem that was encountered during this experiment was that the amount of blue light that was needed for color matching became insufficient for a few subjects. This is evident on the color discrimination contours, for CCT values 4000 K and 4444 K. The color discrimination contours appear pushed-in on the blue axis at the two CCT values at higher percentile values, 80 to 100. Figure 10 also shows four-step MacAdam ellipses at each CCT value for comparison.

Figure 11, shows the comparison between 50$^{th}$ percentile color discrimination contours and the corresponding one-step MacA

dam ellipses at each color temperature. The 50$^{th}$ percentile color discrimination contours represent an area where 50 percent of the subjects notice color difference, similar to the one-step MacAdam ellipse that represents an area where 66% of the population notice a color difference.

The following observations are made from Figures 10 and

It is clear from Figure 11 that the 50$^{th}$ percentile color discrimination contours are much larger than the one-step MacAdam ellipse at all four CCT values.

The four-step MacAdam ellipses are about the size of 10 to 20 percentile value contours, suggesting that 80 to 90 percent of the observers will not see color difference. In this case the four-step MacAdam ellipse criterion seems reasonable.

From these results one can conclude that the color variation between similar lamps placed inside supermarket refrigerated display cases can vary significantly before observers start noticing a color difference.

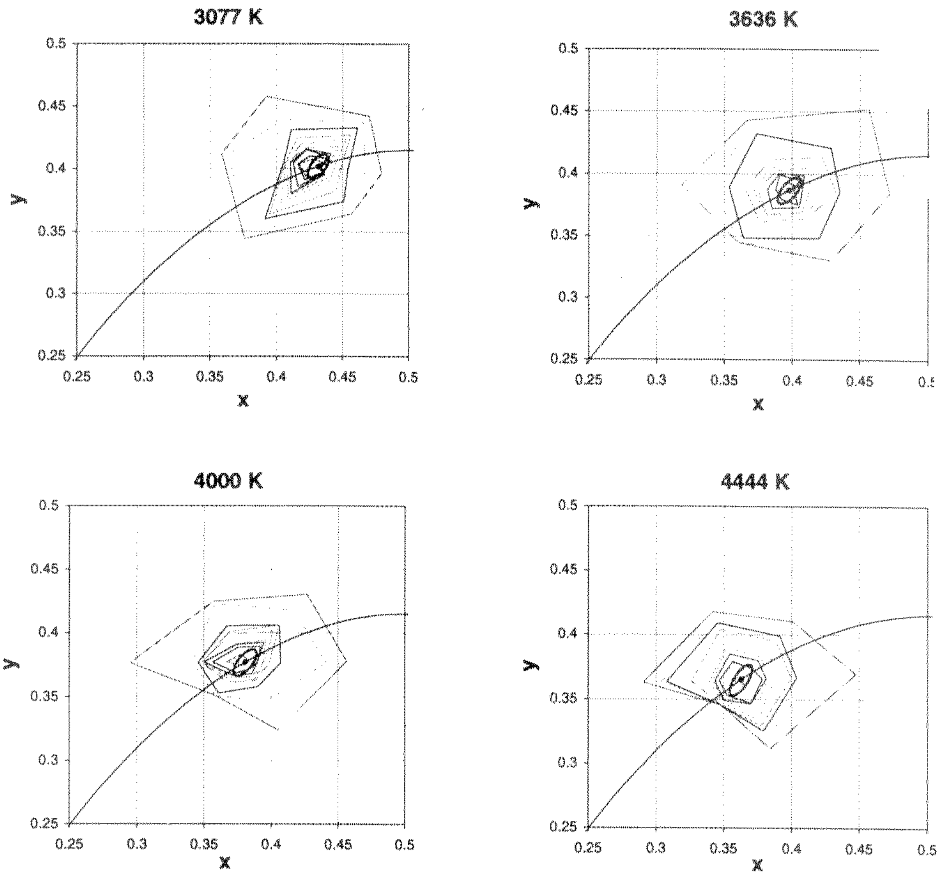


**Figure 10:** Color discrimination contours plotted at 10 percentile intervals for the 12 subjects

## SUMMARY

An experimental study was conducted to investigate at what point observers perceive a color difference between similar lamps when used in display lighting applications. This study was triggered from a commonly asked question by lamp and lighting system manufacturers, "how much color variation can there be between similar lamps?" The results from this study show that there is no easy way to set a general criterion, since color discrimination between light sources depends on the application. It is shown that a criterion such as the four-step MacAdam ellipse for a given lamp type is too generous for display applications where the scene has white objects and has little visual noise. In a situation like this, the requirement should be more like one-step MacAdam ellipse instead of the four-step MacAdam ellipse. From the results one can also infer that the same requirement may hold true for down lights on white ceilings. On the other hand, for lighting multicolored displays with lot of visual noise, the four-step MacAdam criterion seems adequate, since only 10 to 20 percent of the subjects notice color difference. The experimental study explained in this manuscript could be very useful for setting color tolerance ranges of lamps for a variety of lighting applications and not just display lighting.

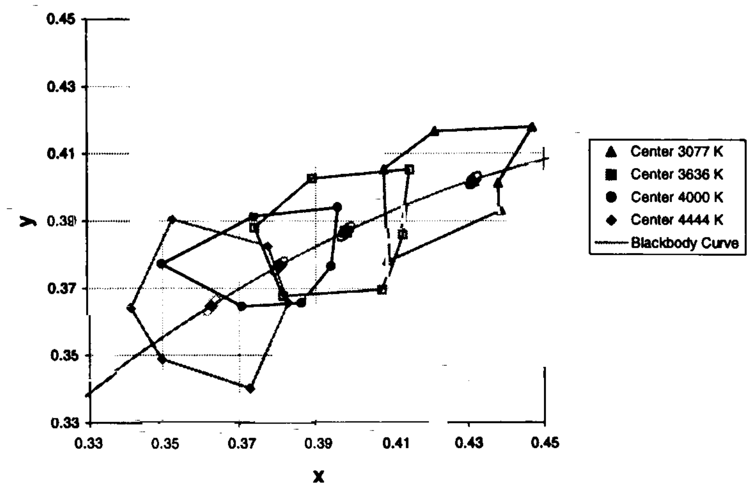


**Figure 11:** The 50-percentile color discrimination contours at four CCT values and the corresponding one-step MacAdam ellipses

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