# Quantifying Mixed Adaptation in Cross-Media Color Reproduction

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## Abstract

This paper describes an investigation undertaken to address the goal set by the CIE Technical committee TC8-04: "To investigate the state of adaptation of the visual system when comparing soft-copy images on self-luminous displays and hard copy images viewed under various ambient lighting conditions." A set of psychophysical experiments have been conducted for the determination of corresponding colors between printed stimuli under CIE Illuminant D50 simulators and CRT displayed stimuli with a D93 white point. The experiments were completed with 15 observers and 6 different viewing conditions. Analysis was completed to quantify any systematic effects of viewing configuration and to identify the extent to which existing adaptation and appearance models can predict the results. After examining a number of adaptation transforms, preliminary results showed how a simple von Kries type adaptation transform provided the best predictions for all conditions while subsequent iterations of the von Kries transform using simple ratios between the adapting and ambient illuminants improved upon these results. The results also indicated how the CIECAM97s model, given certain conditions, could provide results equal to or better than the von Kries model.

## Introduction

For a number of years now, many have used a softcopy device to reproduce the appearance of a hardcopy original. This is nothing new, nor is the mixed extent to which this has been accomplished successfully. But one thing is for sure and that is all successful appearance matches have been performed under strictly controlled viewing environments. Inherently such settings will not allow for any changes in viewing conditions without affecting the perceived match between the original and reproduction. What is new, nevertheless, is the desire to identify not only how appearance matching can be achieved in a more typical working environment but also how it can be modeled.

For reasons such as this color appearance models were developed, ranging from the most complex, predicting a whole array of appearance attributes, to the more basic, predicting simpler more common appearance attributes. More recently the CIE, after testing a number of color appearance models put forward CIECAM97s, a simple color appearance model for general use, as an industry standard. Unfortunately though, when testing the models, the work of the committee was limited to the color appearance of surface colors and did not include the color appearance of self-luminous colors, aperture colors or comparisons between different media or modes of appearance.[1]

The appearance of colors displayed on CRT devices has been studied by a wide array of people. Although much work has been written in relation to color appearance only a small amount has been published concerning adaptation under mixed illuminants. The contributions by Katoh[2-7], Fairchild[8-14], Braun[15-16] and Alessi[17-18] are considered the most relevant. Nevertheless this work still leaves much more to focus upon, as Katoh himself points out, softcopy images viewed under mixed chromatic adaptation have not yet been evaluated.

We know that appearance matching between hardcopy and softcopy images will be affected by the surround conditions under which it is viewed. Specifically, the perceived brightness contrast of an image changes depending on whether the image is viewed under a dim or a dark surround. In most matching experiments, a dark surround is used but because this set-up does not reflect normal working conditions the proposed experiment will also assess appearance matching in more normal surrounds.

It was the aim of this project to undertake experiments looking at the effect of mixed and incomplete adaptation, to identify how well existing adaptation transforms model this and to identify ways of improving the models. The work described in this paper is intended to contribute to existing knowledge and further the work of the CIE. It has been conducted under the guidelines of the CIE TC 8-04 committee and although complete in its own right the results can be used for further analysis and subsequent recommendations.

# Experimental

### Configuration of facilities

The experiment was conducted in a specialized room designed for cross-media image comparisons. This room currently exists within the MCSL facilities and is known as the *Color Modeling Laboratory*. The room is designed with neutral paint to control the state of adaptation and minimize flare reflected off the CRT face. The illumination in the room is quite flexible with 8 independently switched fluorescent fixtures. These were configured with CIE Illuminant D50 simulators to control the correlated color temperature and the number of tubes activated was used to control the luminance level. Printed stimuli were viewed in a small (GTI Soft-View) light booth that matches the D50 ambient illumination. A 21" Sony Trinitron controlled by an Apple Macintosh G3 system was used for the CRT display.

### Luminance and Chromaticity Specification of the Controlled viewing conditions

Only one monitor device was used, which was set up with a 9300K CCT white-point. The luminance of the CRT's white point was set at the maximum possible luminance, 62.4 cd/m2 (while still allowing for accurate colorimetric characterization and optimal image quality). The hardcopy was viewed in a booth set up with CIE Illuminant D50 simulators at a luminance of 61.6 cd/m2 to equal that of the CRT display. The D50 simulators are designed to correspond to daylight with a CCT of 5,003 K. The D50 stimulators were also used for the ambient illumination of the room, having a luminance of 64.1 cd/m2. When the ambient illumination was not used the luminance of the room dropped to 0.95 cd/m2 accounting for the flare from the monitor and the booth. A PhotoResearch-704 was used for all white point measurements either directly from the CRT, the hardcopy or from a halon tablet for the ambient illumination.

The neutral 9300K CCT background of the softcopy image provided the reference white-point for the CRT while the substrate provided the reference white-point for the hardcopy. In this case, the chromaticities of the white-point for the softcopy and the hardcopy were not the same. This allows for the testing of different color spaces and chromatic adaptation transforms across different color temperatures. The white background of the hardcopy illuminated in either the viewing booth or in the illuminated room was used to specify the chromaticity of the adapting stimulus of the reflection print.

### Monitor and Printer Characterization

Both the monitor and the printer were characterized and calibrated to their optimal settings. In this particular instance a PR-704 was used to measure both the monitor and the hardcopy print during the set-up of the experiment. Each observer match was also directly measured. For this reason device characterization was not found to be an issue.

### Gamut

For all intents and purposes, the gamut of the monitor and the hard copy output device proved not to be an issue. Colors for the test target were specifically chosen to fall within both devices' gamuts.

### Test Target

The test image consisted of a simple 9x9 array of square patches on a white background. Hard copy images were produced using a Kodak 8670 PS thermal printer, approximately 10 x 8 inches, at a resolution of 150dpi. For the hard copy out put, the main aim was to choose a device that is capable of reproducing the color gamut of the monitor. The softcopy version was displayed on the CRT monitor at 72dpi. This allowed for the softcopy image to be displayed at the same size as the hard copy image. Each patch subtends a visual angle of approximately 2° and is separated by 1°. This configuration serves to provide a simple stimulus that can be adjusted (on a patch-by-patch basis) on the CRT display to match the appearance of the printed stimuli in the various viewing configurations. The simple-patch configuration also minimizes any errors due to device characterization since the printed patches can be directly measured. The 9 test colors consist of 3 skin tones and 3 grays of various luminance factors (to allow for measurement of image-contrast effects) and 3 colors, including the important memory colors sky blue and grass green.

### Matching

The aim of the work was to focus upon cross-media color matching and for this reason softcopy - hardcopy comparisons were made. Table 1 lists the six viewing configurations investigated and compared in the psychophysical experiments:

Table 1. Experimental Configurations.

| Con. | Print Environment | Psychophysical Technique | Adaptation Time Delay |
|---|---|---|---|
| 1 | Ambient Illumination On | Successive Viewing | 1 min Time Delay |
| 2 | Ambient Illumination Off | Successive Viewing | 1 min Time Delay |
| 3 | Ambient Illumination On | Successive Viewing | No Time Delay |
| 4 | Ambient Illumination Off | Successive Viewing | No  Time Delay |
| 5 | Ambient Illumination On | Simultaneous Viewing | No Time Delay |
| 6 | Ambient Illumination Off | Simultaneous Viewing | No Time Delay |

The six viewing configurations consisted of an experimental design with three variables (print environment, psychophysical technique, and delay). The print environment was either in the viewing booth with a dark surround (ambient lights off) or in the viewing booth within a fully illuminated room (at the same luminance and correlated color temperature). The psychophysical technique was either simultaneous matching (both print and CRT visible) or successive matching in which only one display was visible at a time. For the successive technique, an adaptation time delay was also used. A sixty-second delay is often used in research studies to allow nearly complete adaptation to a display. However, this delay is rarely used in practical situations. Thus, the successive experiments were completed both with and without the sixty-second adaptation periods. In accordance to the CIE guidelines[17] for such experiments, the experimental design defines the reflection print as the reference original and the CRT monitor must be altered to match that reflection print original.

**Matching Method**

Two types of matching were employed, simultaneous and successive. The observer was presented with a hardcopy original displayed in the viewing booth. This image was constant throughout the duration of the experiment. The observer was also presented with a soft copy version of the same image, displayed on the CRT. The experiment was set up so that the illumination from the viewing booth is not reflected in to the CRT and vise versa. For all matches, the observer was asked to initially select one patch and to adjust three sliders on the monitor, chroma, hue and lightness, until they feel they had made a softcopy match to the hardcopy original. All of the target patches were matched in this way. The whole process was repeated for a total of six times to account for each of the six different viewing conditions. The IDL interface for the experiment was able to record the RGB values of each of the resulting matches, for retrieval and analysis at a later date.

**Instructions for Observers**

At the onset of the experiment, observers were given an overview of the matching task. In the cases where the matches were made using a time delay, the observers were given approximately a minute to adapt to the viewing conditions of the CRT and then the viewing booth each time they changed their focus from one device to the other. Although this part of the experiment proved to be a little tedious, it was not intended to assess memory colors and so the observers were encouraged to look back and forth between the two images as frequently as needed to make the matches so long as the adaptation time was adhered to.

The experiment was set up specifically so the observers could compare the images equidistantly; the observer was positioned approximately 50-60 cm in front of either of the images. In the case of the successive matching the images could not be viewed at the same time, this involved toggling between the target and a neutral adaptation screen on the monitor and by using a neutral mask over the hard-copy target when not being viewed. No time restrictions were placed on the observers. (The exact instructions can be found in the appendix of the thesis relating to this paper[18])

**Analysis of Data**

The data for each observer's matches were recalled and displayed on the CRT so that the spectral radiance of each patch could be measured. The targets were measured under the same conditions in which the original matches were made. Additionally the illuminated hardcopy original was fully characterized. This involved two characterizations; one with just the illumination from the light booth and the second with the illumination from the room and the light booth. Because the test target comprises colored patches, the measurement was straightforward because of the uniformity of the patches.

A comparison between the actual measured spectral radiance of the hardcopy and the measured spectral radiance of the softcopy was made for each observer's settings under each combination of viewing condition and adaptation. The analysis was performed as stated in the CIE guidelines[19], whereby the spectral radiances were initially reduced to absolute tristimulus values and luminance. This was performed by numerical integration, weighting each measurement by the appropriate CIE 2˚ color matching functions x,y,z from 380nm to 780nm in 2nm increments. These values were then be multiplied by a constant, 683 lumens/watt. The resulting X,Y,Z values could then be reduced to CIE x,y, and absolute luminance values ($cd/m^2$) using the Y-value of the target white of the CRT as the reference white. It was then possible to average these results, from all observers for each viewing condition.

## Results and Discussions

To see the measure of inter-observer variability, MCDM's[20] were calculated for each condition. These were calculated using CIE $\Delta E^*_{94}$ and can be seen in table 2.

Table 2. Mean Color Differences from the Mean (MCDM).

| | Con. 1 | Con. 2 | Con. 3 | Con. 4 | Con. 5 | Con. 6 |
|---|---|---|---|---|---|---|
| D. Brown | 1.12 | 1.43 | 0.83 | 1.78 | 0.73 | 1.04 |
| M Brown | 3.06 | 2.96 | 2.26 | 4.17 | 1.32 | 1.92 |
| L. Brown | 1.86 | 2.52 | 1.76 | 1.68 | 1.56 | 1.99 |
| Blue | 2.17 | 3.22 | 3.24 | 2.28 | 1.78 | 1.89 |
| Green | 4.14 | 2.43 | 4.12 | 3.30 | 1.58 | 2.25 |
| Red | 1.77 | 2.92 | 2.03 | 2.26 | 1.82 | 2.42 |
| L. Grey | 2.99 | 3.74 | 2.69 | 2.80 | 2.29 | 3.15 |
| M. Grey | 2.21 | 2.12 | 2.06 | 2.90 | 2.36 | 2.58 |
| D. Grey | 3.06 | 3.63 | 2.70 | 2.94 | 1.89 | 2.38 |
| Average | 2.49 | 2.77 | 2.42 | 2.68 | 1.70 | 2.18 |

These results are useful at showing the spread of observed matches, how certain colors have much smaller MCDM's and how the viewing conditions can also influence the results. Here it can be seen that the brown colors have slightly smaller MCDM's over all viewing conditions with not a great deal of variability between the light, medium and brown matches. The greys have higher MCDM's but again over all there is not a great deal of difference between the light, medium and dark greys except for the one outlier in the data. The red and the blue matches compare to the browns in terms of MCDM figures but green shows quite a high maximum MCDM value of 4.14 very large observer variability. The results show how the MCDM's tend to reduce in magnitude significantly for conditions 5 and 6 – the simultaneous viewing condition, an indication that a better match can be observed when both targets can be viewed at the same time.

**Single Adaptation Models**

The data was then analyzed using five known single adaptation transforms. All of these adaptation transforms were tested in the same way. That is, the input to the transforms were normalized tristimulus values for both the input device characteristics, i.e. the hard-copy and the output device, i.e. the soft-copy. When using these transforms the white point of the target in the booth and the white point of the target measured from the monitor were used as the first and second viewing conditions respectively. Because the models tested here are all single adaptation transforms the actual white point of the surround was not required. It was however necessary to know the type of surround, such as light or dark, for incorporation into some of the models.

All other model parameters were incorporated as recommended by the individual models themselves. For clarification, when selecting the D values for CIECAM97s, the model was allowed to choose its own D values. (D = F - F/[1 + 2(La^1/4) + (La^2/300)]). The hard-copy target data was then put through each of the models and the resulting adapted data was compared against the observer adjusted data for each condition. A summary of all the forward models can be seen in table 3 and figure 1.

Table 3. ΔE94 results showing differences between predicted matches and adjusted matches using single adaptation transforms.

| | Con. 1 | Con. 2 | Con. 3 | Con. 4 | Con. 5 | Con. 6 | Av. |
|---|---|---|---|---|---|---|---|
| Original | 15.6 | 16.9 | 15.0 | 17.0 | 14.3 | 17.0 | 16.0 |
| CIELAB | 6.00 | 5.12 | 4.44 | 4.46 | 4.11 | 5.28 | 4.90 |
| Von Kries | 5.01 | 4.56 | 3.30 | 3.68 | 3.56 | 4.66 | 4.13 |
| RLAB | 6.07 | 5.67 | 4.74 | 5.42 | 4.62 | 6.38 | 5.48 |
| LLAB | 5.49 | 5.68 | 3.71 | 5.38 | 3.5 | 5.83 | 4.93 |
| CAM97's | 6.34 | 5.22 | 4.59 | 4.54 | 3.7 | 4.72 | 4.85 |
| CAM97's solve for D | 6.25 | 4.95 | 4.49 | 4.11 | 3.46 | 4.39 | 4.60 |
| 3*3 | 3.26 | 2.83 | 2.24 | 2.41 | 2.38 | 3.03 | 2.69 |

The results as shown indicate that a simple von Kries adaptation transform, on average, performed the best for each of the viewing conditions. These results could perhaps indicate to us that often it is best to keep things simple rather than deal with more complicated models, or that the more complicated models overcompensate for various factors. CIELAB, LLAB and CEICAM97s performance in general was very similar to one another and one could not really distinguish between the results. However, although CIECAM97s in general did not perform best on average, for some of the conditions the results from CIECAM97s were not vastly different than the von Kries model. RLAB performed worst of all with an average $\Delta E^*_{94}$ color difference of 5.48 across all conditions. It is not entirely obvious why this was the case but it is expected that the defined constant variables could have been the cause.

The significant point to note however is the vast improvement that all the adaptation models have had on the data as compared to performing a simple color comparison by comparing tristimulus values (fig. 1).

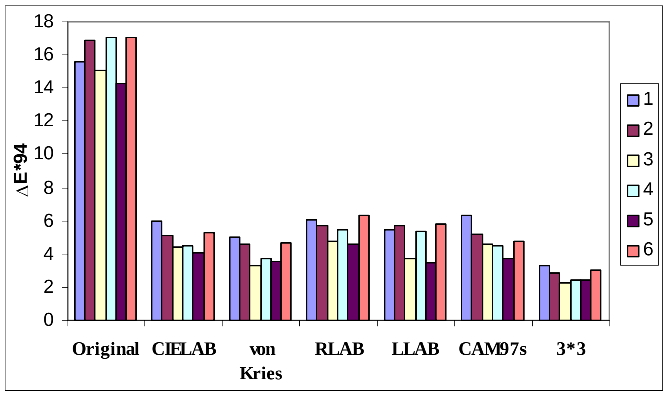


Figure 1. Summary of $\Delta E^*_{94}$ values for all single adaptation transforms

The improvement on average spanned 10.52 to 11.87 $\Delta E^*_{94}$ values which overall provide very encouraging results for all the single adaptation transforms used. As a control an empirical fit of a 3*3 adaptation transform for each condition was also performed on the data with results indicating that there is room for improvement in existing models in the order of approximately 1.5 to 3 $\Delta E^*_{94}$ values. Knowing this improvement could possibly be made proved promising when looking at the use of mixed adaptation transforms.

**Mixed Adaptation Models**

The testing of the mixed adaptation models was no different than the testing of the single adaptation models except for the fact that the white point of the surround was taken into consideration. A ratio between the two illuminants was taken to be the adapting illuminant and this adapting illuminant was fed in to the adaptation transforms. In all the procedure was very simple and straightforward, the only problem of course was repeating the tests for all possible adapting ratios, which again did not prove to be so difficult as it was time consuming. The ratios were optimized for each condition and not for each color. For the testing of mixed adaptation it was decided to test CIELAB because it is simple, CIECAM97s, Katoh's model because it is specifically designed for mixed adaptation, and the model that performed the best in the single adaptation mode, i.e. the von Kries model. It was felt that testing all of the models in the mixed adaptation mode would not be necessary, especially since it is mainly CIECAM97s people wish to use and thus need to know how it performs in such circumstances and furthermore how it could be improved if it does not perform well. As with the single adaptation model, the parameters used were those suggested by each of the models and the only thing altered was the adapting ratio. Although it has been shown that the results from CIECAM97s could be improved by solving for D it was decided that in mixed adaptation mode the model should be left to determine D for each part of the transform. Finally the resulting adapted data was compared against the observer-adjusted data for each condition. A summary of the results from the mixed adaptation transforms can be seen in table 4.

Table 4. ΔE94 results showing the best ratios between predicted matches and adjusted matches using mixed adaptation transforms.

| | Con. 1 | Con. 2 | Con. 3 | Con. 4 | Con. 5 | Con. 6 | Av. |
|---|---|---|---|---|---|---|---|
| Original | 15.6 | 16.9 | 15.0 | 17.0 | 14.3 | 17.0 | 16.0 |
| Mixed CIELAB | 5.47 | 4.89 | 4.21 | 4.42 | 3.94 | 4.99 | 4.65 |
| Mixed von Kries | 4.29 | 4.31 | 2.85 | 3.48 | 2.91 | 4.05 | 3.64 |
| Mixed CAM97s | 6.30 | 4.89 | 4.57 | 4.35 | 3.56 | 4.72 | 4.71 |
| Katoh's | 6.03 | 6.52 | 4.51 | 6.33 | 3.67 | 7.55 | 5.76 |

The results again show how the simple von Kries transform, this time incorporating mixed adaptation, provides the best prediction of the observed color matches between the booth and the CRT display. But more interesting is the fact that the incorporation of a mixed adaptation ratio between the illuminant of each viewing condition has improved the results in all cases when comparing these against the equivalent single adaptation model. Additionally the optimized ratios have shown how the observers are adapted very differently between the two sets of viewing conditions, for all of the mixed adaptation transforms tested. It is perhaps unfortunate that there is a fairly large amount of observer variability especially with the greens and the blues which is perhaps keeping the predicted values fairly high. All in all, any model would find it hard to predict such a spread of data points. Even so, it has been shown through all of the models tested that reasonable predictions can be made through a very simple model. And perhaps this might bring back the thought that keeping things simple is perhaps best, for it has been shown how some of the more complicated models, with their inclusion of many constants can alter the results, and not necessarily for the better. Of course, each and every model could be improved through further optimization, but if you were to optimize a model through the constants then you could just as easily build a tailor made model to suit the data, which of course would highly unlikely hold for additional data.

## Conclusions

An experiment has been designed and completed to test how well appearance models can be used to predict observed matches in a cross-media color reproduction environment. The data was initially analyzed using 5 known single adaptation transforms. When using these transforms the white point of the target in the booth and the white point of the target measured from the monitor were used as the first and second viewing conditions respectively. The results, as shown in table 5.11, indicate that a simple von Kries adaptation transform, on average, performed the best for each of the viewing conditions. For some of the conditions though, when plotting error bars, the results from CIECAM97s were not statistically different than the von Kries model. As a control an empirical fit of a 3*3 adaptation transform for each condition was also performed on the data with results indicating that there is room for improvement in existing models in the order of approximately two $\Delta E^*_{94}$ values for each condition.

After identifying the von Kries method as producing the best results for the single adaptation transforms this method was then adjusted to account for mixed adaptation. This involved including an adaptation ratio between the booth and the surround for the forward part of the model and another adaptation ratio between the monitor and surround for the inverse part. The ratios selected are those obtained when the $\Delta E^*_{94}$ value between the adjusted and the predicted matches was minimized. The results for the mixed adaptation models were illustrated in table 5.15, show how, in all conditions, the results can be improved by using a mixed adaptation ratio between the adapted and surround illuminant.

The CIECAM97s model was also tested using a ratio for mixed adaptation. In this instance it can be seen that the incorporation of the ambient illumination did not improve upon the original results by more than a fraction of a $\Delta E^*_{94}$ value. The significant point to bear in mind with regard to using CIECAM97s is the initial selection of the D factors (used to determine the degree to which the illuminant is discounted). Changing this figure by even a fraction of a point can alter the results significantly. When using the CIECAM97s model with out the ratio factor but optimizing for D the results are improvements upon the original values and can be seen to be virtually equal to if not better than the results produced by the mixed von Kries method. In this case D was altered again minimizing $\Delta E^*_{94}$.

A mixed adaptation method published by Katoh was also examined. At present it is not fully obvious why the results are poorer than most but it is expected that, as with the CIECAM97s model, the choice of initial constant variables incorporated in the model could have a detrimental effect in this case.

All of the models here have been shown to be promising, that is they can all generally be used to reliably predict appearance matches in cross media reproduction. The von Kries model gave surprisingly good results for what appear to be a very simple adaptation model. Even an empirical fit of a 3*3 adaptation transform would only reduce this figure by about 2 $\Delta E^*_{94}$ values. For this reason alone one should never fail to use it as a starting point from which to compare other adaptation models.

Promising results have also been shown for the use of CIECAM97s, with one of the most significant findings in this research highlighting the extreme care needed when selecting the constants to be used in any of the available adaptation models. In particular with CIECAM97s the correct selection of the D factors is crucial in the determination of the adapting XYZ values.

Although the use of an adaptation model has improved the results for each model compared to the single adaptation mode of the same model, it was not possible to accurately predict the ratios to use. Trends were shown in the data sets but this is not enough to set a standard ratio factor and thus further work could possibly be carried out to obtain more data in order to further clarify this point.

Other possible ongoing work relating to the results found here could be to look at optimal ways of selecting the D values in the CIECAM97s models as well as looking further at an algorithmic approach to the incorporation of mixed adaptation ratios.

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## Biography

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