Color Reproduction Using “Black-Point Adaptation”

Sun Ju Park and Mark D. Fairchild
Munsell Color Science Laboratory
Rochester Institute of Technology
Rochester, NY/U.S.A.

Abstract

Based on the current state of CIECAM97s, there is a missing adjustment associated with a black-point unlike a white-point. As an attempt to improve the performance of CIECAM97s for color reproduction, six algorithms focusing on “black-point adaptation” were generated based on previous work on white-point adaptation methods and gamut mapping methods. The six algorithms were used to reproduce four original images targeted to four simulated hard-copy viewing environments that were only differentiated by their black-point settings. Then, the six algorithms were tested in a psychophysical experiment with 32 observers. As a result, linear lightness rescaling under the luminances of white and black of a specific setting was demonstrated to be the best color reproduction method across different black-point settings. The adapted black-point was defined as having the lowest lightness value with its default chromatic appearance correlates predicted by the current state of CIECAM97s under the input viewing environment and was reproduced accordingly with the same appearance correlates.

Introduction

As a small step towards the goal of improving the performance of CIECAM97s, an investigation related to dark color reproduction across different media and under practical viewing conditions has been undertaken. In this paper, the new term “black-point adaptation” is used to explain an observer’s stable visual state which is controlled by the displayed black-point and displayed neutrals in the complete field of view.

The basic idea of the research is as follows. When people look at images, either on a self-luminous display such as CRT or on the reflection print, they adapt to the given setting, which is determined by various parameters such as illuminants, white-points, surroundings, and state of adaptation. As a part of the visual response, the human visual systems rescale the tones between the adapted two extremes - black and white-points. Therefore, it is possible that dark grays or very dark reds appear to be black, and they are called black under some viewing circumstances. Because of various viewing conditions and reproduction devices, black could be very different from an ideal black or the traditional assumption that black does not have chromatic values in it and that it carries the lowest physical luminance in the complete field of view. For instance, according to the measurement made by Nakabayashi,[1] the black on the CRT screen viewed under the fluorescent light F6 was reported as L* of 42.7, a* of 3.8, and b* of 23.8, yellowish gray. If this black source were represented on the printer device using the current state of CIECAM97s, the reproduced black on the printer would be far off from the achromatic axis and could be no longer called black in the target environment. In the current state of color appearance model which lacks a black anchor in setting the tone scale and without application of gamut mapping, black is reproduced in a manner similar to all other colors without being considered and treated as black. Another example would be the text on the newspaper print. The text color on a newspaper, which is called black, has very high L* value of about 40. These examples demonstrate that even though the current appearance indication of black is far from black in the general sense, it sometimes can appear to be black to an observer depending on the viewing conditions and devices.

Colors under a specific setting are not predicted well and are not reproduced correctly because a fixed black-point for color reproduction is missing. Therefore, it is necessary to discover a stable visual black-point under a specific setting and define it as an “adapted black-point” that sets the other extreme point on a tone scale with an “adopted white point.” The “adopted white-point” is the term used in CIECAM97s referring to the observer’s effective visual adaptation to the white-point.[2] Additionally, it is necessary to discover a good mapping technique to describe adapted neutrals under a specific setting and to be used for color reproduction across different media. The above idea of the adaptation transform of a black-point using various models is a very similar approach to that applied in white-point mappings[3-5]. Additionally, in the current practice of color reproduction, a poor black treatment in a color appearance model is handled in a gamut-mapping step using various techniques[6] such as compressions and expansions of color attributes compensating for different device limitations.

The project has evolved from the hypothesis that incorporating "black-point adaptation" into the color appearance domain might result in more efficient and effective color reproduction systems. The three goals of the project are summarized as follows. The first goal was to improve CIECAM97s by introducing an adapted black-point. The second goal was to find a good way to map adapted neutrals for color reproduction across different media and viewing conditions. The third goal was to provide a good basis for color gamut mapping which is a next step in color reproduction process.

Experimental

Configuration of Facilities

The experiment was conducted in a dark room in a laboratory setting. The display system consisted of an Apple Cinema Display (22'', 1600x1024, LCD) driven by an Apple Power Macintosh G4 System. Such a display system was utilized since it has a significantly higher luminance at 176 cd/m^2 and dynamic range of 1:293 than typical CRTs. These measurements were made using a LMT L1009 photometer that gave readings in absolute terms using absolute units of cd/m^2. These advantages made the LCD system ideal for simulating output systems with a wide variety of black-points. In order to isolate the given black-points from other color appearance parameters and evaluate various "black-point adaptation" models, the simulation of various target environments was preferred. In that way, an LCD was used as both original and destination devices, concentrating on various black-points generation. In addition, its wide-screen aspect ratio and spatial uniformity allowed the experiment to be completed on a single display with appropriate physical division. A physical partition was put in the middle of the display screen in order to simulate various hard-copy viewing environments.

Display System Characterization

The LCD display system was characterized by a two-stage model[7,8]: linear and non-linear. Based on the verification of its primaries' additivity and scalability without including the internal flare, the linear part of the model was characterized using a simple 3x3 matrix. For the non-linear part of the model, three one-dimensional linearly interpolated look-up tables for each channel were separately developed and used. These look-up tables were generated based on 52 measurements for each channel. All color measurements for the LCD system characterization were made using an LMT C1200, a high precision colorimeter.

Reproduction Systems (Target Black-Points)

The original images were presented using the system's default setting which consists of the full dynamic range and gives white and black points of the LCD system. The only different parameter between the original and reproduction systems was the systems' black-point set-ups. White-points of both the original and reproduction sides of the display were held constant and equal to avoid complicating the experiments on "black-point adaptation" models with changes in white-point. Disparate black-points were generated by varying the luminance and chromaticity of the black-points. These changes produced limitations in both dynamic range and black-point chromaticity, and no element on the reproduction side of the display was allowed to exceed these limits. Four various dynamic ranges and black-point chromaticities were produced based on the measurements of black patches printed on the selected papers by selected printers and viewed under various illuminants in order to simulate several hard-copy display technologies. For the adaptation to the specific simulated viewing environments, gray scales tied to the chosen black-points were generated and used for the experiment. The neutral maps were presented to the observer during the experiment to provide them with the reference tone scale for the given environments.

Models and Approaches for "Black-Point Adaptation"

Three different "black-point adaptation" models were developed each based on a different assumption of how "black-point adaptation" occurs in the visual system. Each of these assumptions is described below.

The first model is based on the assumption that people adapt fully to the given black-point consisting of its luminance and chromaticity under the given setting, which is the identical concept applied in the von Kries model or other color appearance models for the white-point transform. Therefore, the adapted black-point is equal to the given black-point in this model, and the way to identify and set the black-point in this model is very similar to the common way to identify and set the white-point. Based on the complete adaptation to the given black-point setting, the "black-point adaptation" model uses a physiological approach and is realized in a LMS cone sensitivity space. Under this model, the perception of blackness consists of three cone responses. Each has a different starting point that is set by a given black-point under a given setting, and they work independently. Other colors are generated as relative heights for white and black that can be different. Like the white-point, if people adapt to "paper black," the color of the paper black is recognized as "black" in a perceptual sense even though the black is "bluish-black" under fluorescent light in a physical sense. Additionally, when the appearance of "black" is reproduced targeted to tungsten light, "reddish-black" in a physical sense is reproduced, which appears "black" in a perceptual sense under tungsten light.

The second model is based on the assumption that people adapt fully to the luminance of the given black-point and rescale the tone scale under the given setting. Based on the complete adaptation to the luminance of the given black-point setting, the "black-point adaptation" model uses a perceptual approach and is realized in a color appearance space, CIECAM97s. The human visual system rescales the tone scale under the given two extremes - black and white-points - to preserve the contrast. Therefore, the adapted black-point is defined and reproduced as the lowest luminance point in the complete field of view, and other colors are defined and reproduced using various lightness rescalings in CIECAM97s. The adapted black-point is located in the lowest point in a lightness scale and has a zero value for lightness in CIECAM97s. In this model, two different lightness rescaling methods between the adapted white and black points are tested. The two methods - linear and sigmoidal lightness - are chosen in order to discover an appropriate rescaling method for the adapted neutrals. This model demonstrates that as long as an appropriate contrast using the luminance of a given black-point is defined and reproduced under a specific setting in the current state of CIECAM97s, other chromatic appearance correction is not necessary to predict and reproduce dark colors which include a black-point.

The third model is based on the practical assumption which occurs when people look at reproduced images, and the full story of the assumption is explained in the following. When people are presented to the original image, they totally adapt to the original setting which includes the given black-point and given neutrals. Under the original setting, the given black-point and given neutrals become the adapted black-point and adapted neutrals that should fall onto the achromatic axis which represents "perfect neutrals" observed under a specific setting. However, when people look at the reproduced images, they do not adapt to the reproduction setting, but rather to "perfect neutrals" which exist in their minds and which are determined under the original setting. Therefore, under the reproduction setting, people do not have any adaptation to the given black-point and given neutrals. The third model is expected to reproduce colors with a perfect tone scale that exists in people's minds under the reproduction setting, and it is expected that the perfect tone scale found in a color appearance space under the reproduction setting might yield better neutrals for color reproduction. The third model also includes the lightness rescaling for the given tone scale.

Unlike the first and second models that are based on adapting to the given black-point on both the original and reproduction sides, the third model is based on adapting to all the given neutrals only on the original side. At this time, a full adaptation to the given black-point and given neutrals, which occurs in the original setting, and a full adaptation to the perfect black-point and perfect neutrals that exist in peoples' minds, which occurs in the reproduction setting, use a perceptual approach and is realized in a color appearance space, CIECAM97s.

One point that should be clarified here is that in the third model, device black and device neutrals are used to correct colors as they appear under the original setting. Off-appearance amounts of the device neutrals from the achromatic axis observed in CIECAM97s are obvious appearance correction amounts needed for all colors under the original setting. These appearance correction amounts generated using the device neutrals would be used later based on a lightness scale. Therefore, all colors are corrected using their corresponding lightness appearance correlates the same way as to correct the device neutrals to fall onto the achromatic axis in a color appearance space. In that way, all colors were correctly positioned relative to the perfect tone scale under the original setting. Consequently, the original image is reproduced on a perfect tone scale that exists in people's minds under the reproduction setting.

For the purpose of reproducing images with a perfect tone scale, the appearance correction technique using the chromatic appearance correlates of device neutrals is performed under the original setting and is used for the "corrected Jab," "corrected JC," and "corrected L*a*b*" algorithms.

Definition of Algorithms

Six algorithms for color reproduction focusing on "black-point adaptation" models were generated based on the expectations and previous color reproduction results of white-point chromatic adaptation in cross-media image reproduction [3-5] and gamut mapping [6].

Three different criteria were considered when the six algorithms were chosen to be tested.

a. Color Space
b. Adapted Black-Point
c. Neutral Mapping Method

The "scale LMS" algorithm was based on the first model, a complete adaptation to the given black-point and its model in a LMS cone sensitivity space. As a result, neutrals and other colors were identified and reproduced relatively between the adapted black and white points.

The "linear J" and "sigmoidal J" algorithms were generated based on the second model, a complete adaptation to the luminance of the given black-point and its model in CIECAM97s. These algorithms were built on the same techniques currently practiced as lightness rescaling in gamut mapping. Linear and sigmoidal lightness rescalings were chosen to be tested among other lightness rescaling methods. The "linear J" and "sigmoidal J" algorithms rescaled the original tone scale targeted to the reproduction tone scale linearly and using a sigmoidal function, respectively. The "sigmoidal J" algorithm was similar to the sigmoidal lightness remapping, performed in the CIELAB color space using L* value and developed by Braun *et al.* [9,10] This was proven to be useful in gamut mapping application in order to preserve the contrast of images.

The "corrected Jab," "corrected JC," and "corrected L*a*b*" algorithms were developed based on the third model. This comprises a complete adaptation to given neutrals under an original setting and a complete adaptation to perfect neutrals determined under a reproduction setting in a color appearance space. In order to define colors correctly under the original setting and reproduce colors correctly under the reproduction setting for the third model, a color appearance correction[11] using a look-up table that stored chromatic appearance correlates of device neutrals that appeared neutrals under the original setting, was performed first. Lightness appearance correlates (J or L*) and chromatic appearance correlates (a and b or a* and b*) of device neutrals were computed and stored in a look-up table. The a and b values (or a* and b* values) demonstrated off-chromatic appearance amounts of the device neutrals from the achromatic axis, which would be used to correct all color appearances as being relative to the device neutrals. Chromatic appearance correction values required for colors were determined and were found in the look-up table based on their lightness appearance correlates. Therefore, each color was corrected using the same value and in the same manner as the device neutral having the same lightness value allowing it to fall onto the achromatic axis. Then, the original image was reproduced using correctly determined colors where gray balance throughout the scale had been idealized ("perfect neutrals") under the original setting.

The least color change after the reproduction was observed in the "corrected L*a*b*" algorithm, and the most color change after the reproduction was observed in the "corrected Jab" algorithm. Allowing for solutions on preserving hues for the color reproduction, two alternative algorithms were developed based on the same appearance correction idea applied in the "corrected Jab" algorithm; the "corrected JC" algorithm performed chroma appearance correction instead of chromatic appearance correction, and the "corrected L*a*b*" algorithm performed the appearance correction in CIELAB instead of CIECAM97s.

In this study, the LCD's device neutrals were reported as bluish and reddish. Therefore, when the bluish and reddish device neutrals were used to correct colors throughout the whole lightness scale in order to reproduce the original image with a perfect tone-scale under an output setting, all colors were shifted to the opposite directions (yellow and green). Bluish and reddish appearance correction amounts that were produced by the device neutrals in CIECAM97s were found to be excessive, especially in a middle lightness range. As a result, red became duller, and blue became gray. The severe hue shift occurred in the blue region, turning the blue sky to gray. Therefore, the device-neutral-based color correction technique is not recommended in CIECAM97s.

The chroma correction based on the device neutrals reproduced the original images with slight hue shifts and with duller chromatic colors in the "corrected JC" algorithm. The "corrected L*a*b*" algorithm reproduced satisfactory images, which did not have hue shifts. Even though the original images were poorly reproduced by the "corrected Jab" and "corrected JC" algorithms, these images were included in the experiment to be compared with other reproduced images.

It was found later that the perfect tone-scale under the given setting in CIECAM97s did not match to a perfect tone-scale that existed in people's minds. For the purpose of examining a perfect tone-scale under the given setting, one example image was reproduced using only grays, and the image was again regenerated using red, green, blue colors using Photoshop. As a result, the final image consisted of only neutrals, and these neutrals consisted of the same digital counts for all three red, green, blue channels. The gray image was reproduced using the "corrected Jab" algorithm, and the reproduced image was expected to have a full scale of perfect neutrals. However, the perfect neutrals of the reproduced image were not close to perfect neutrals that existed in people's minds. It has been found that colors in a middle lightness range were predicted with too much chromaticness under the original setting, which indicates the poor performance of CIECAM97s, when the device neutrals were plotted in CIECAM97s. Consequently the inaccurate appearance prediction of the current state of CIECAM97s has failed to test the third model developed for the "black-point adaptation." Therefore, major solutions to improve the performance of CIECAM97s are necessary.

Experiment Methods and Procedures

Figure 1. Experimental Screen for "Black-Point Adaptation" Study

An observer was asked to select the "better" reproduction of the original image between two alternative reproductions. In other words, the observer made a selection of one reproduction based on which image was a "closer" reproduction of the original image. The original image was presented on the left side of the display with a physical partition, and the two reproductions were presented on the right side, one at a time, by toggling between the two. There was no time limit on this experiment. When the observer had done half of the experiment (the comparison of 120 pairs), s/he was asked whether s/he wanted to continue the experiment. The experimental screen is shown in Figure 1.

Results and Discussion

A total of 32 observers with a variety of backgrounds and experience participated in the experiments. The data obtained were preference frequencies for all pairs of algorithms. The data were analyzed using Thurstone's law of comparative judgments to produce interval scales of algorithm performance along with estimates of uncertainties in the predicted scale values. The results were analyzed in three different ways: total observations, black-point dependent observations, and image dependent observations. The following plot was generated by Case V which is the simplest case using the assumption of equal dispersions for all stimuli. Therefore, the assumption for the following data analysis was that the two response variances were equal, and there was a zero correlation between the observers' selections of the samples.[12]

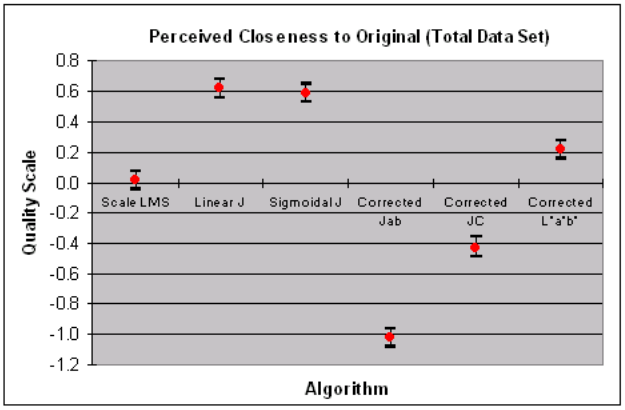

Figure 2. Experiment Results for Total Data Set

The results with the total data were summarized in terms of interval scales reflecting the relative performance of the various "black-point adaptation" algorithms, as seen in Figure 2. Error bars in the plot indicate estimated uncertainties in predicted scale values. The error bars were produced using 95% confidence interval. Even though the plots for each case showed image and black-point dependencies, the algorithm performances throughout all cases were very consistent. Overall, it has been observed that experimental results can be divided into three algorithm performance groups. The "linear J" and "sigmoidal J" algorithms form the best performing group. The "scale LMS" and "corrected L*a*b*" algorithms form the middle performing group. Lastly, the "corrected Jab" and "corrected JC" algorithms form the worst performing group. The results report that the "linear J" and "sigmoidal J" algorithms perform the best in general. The two different lightness rescaling methods used in the "linear J" and "sigmoidal J" algorithms do not report any significant outstanding performance over the other. This indicates that as long as lightness rescaling is applied properly for given settings, color reproduction focusing on "black-point adaptation" is considered the best.

One more point to mention for the overall performance is that even though the "linear J" and "sigmoidal J" algorithms are not significantly different and belong to the best performing group, the "linear J" algorithm is ranked first in 6 out of 9 performances. The only difference between the two algorithms is the lightness rescaling technique. The "linear J" algorithm uses a simple linear lightness rescaling method, and the "sigmoidal J" algorithm uses a sigmoidal scaling method. The better performance of the simple linear rescaling over the sigmoidal rescaling is not the expected result because better performance of the sigmoidal rescaling over the linear rescaling was observed previously[9,10] .

The best performing algorithm to model "black-point adaptation" for color reproduction has been shown to be the "linear J" algorithm that uses a simple lightness rescaling between original and reproduction systems under the luminances of black and white under a given setting. In other words, lightness appearance correlates are redefined under the assumption that people adapt fully to luminances of black and white under a specific setting, which might match the visual responses that are controlled by the black based on the results of this study. A method to improve CIECAM97s to better reproduce colors using the "black-point adaptation" model has been developed across different media, and the actual application of "black-point adaptation" for color reproduction consisting of forward and backward models is described in Figure 3. The objective and steps for the "black-point adaptation" model is also stated.

The lightness scale should be rescaled from 0 to 100 under the luminances of the white and black of the original system. Therefore, color appearance prediction will be determined after the lightness rescaling under the original system. After the color appearance values of the original system is determined, the color reproduction should be performed for the reproduction system being relative to the luminances of the white and black of the reproduction system.

In Figure 3, J_{input} , J_{output} indicate lightness appearance correlates determined and used in the current state of CIECAM97s, and $J_{adapted}$ indicates lightness appearance correlations after considering "black-point adaptation." Subscripts of 1,2,B,W indicate original (input) system, reproduction (output) system, black-point, and white-point in this order. J_{B1}, J_{B2} are computed the manner same to white using the measured black tristimulus values (X_B, Y_B, Z_B) using CIECAM97s. For better color reproduction, additional measurement of the blacks of the original and reproduction systems, additional appearance computation of these blacks, and an additional computation for "black-point adaptation" are needed as additional processes in the current state of CIECAM97s at this point (Figure 3).

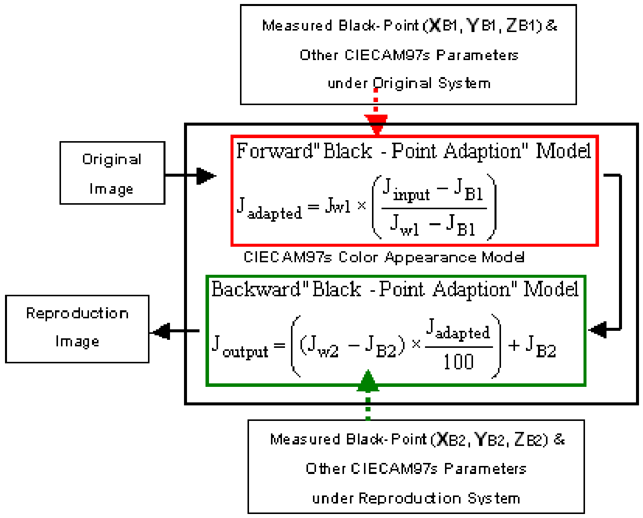

Figure 3. "Black-Point Adaptation" Model for Color Reproduction

Conclusion

Even though lightness rescaling techniques have been practiced in a gamut mapping stage due to limitations of devices, it is suggested that the lightness scale for a given setting be corrected in color appearance models. This recommendation is made because the "black-point adaptation" model is a given setting specific transformation.

Color reproduction based on being relative to the black and white in a complete sense using chromatic and lightness values is not preferred (tested by the "scale LMS" algorithm), which works for a white-point. Additionally, a big lesson learned is that any appearance correction techniques are not desirable and are not recommended to be practiced in the current state of CIECAM97s due to the poor performance of the appearance model. Too much chromatic expansions of color appearance in a middle lightness range are suspected to be the cause in failing to reproduce the originals based on the perfect tone scale observed under the reproduction settings. Thus, continuous efforts to improve the performance of CIECAM97s are necessary. This study has been a good starting point investigating black-points and the generation of a tone scale for color image reproduction.

Acknowledgements

The author would like to thank Canon R&D Center Americas, Inc. for the support for this study.

References

1. Kiyotaka Nakabayashi, Research Proposal, 2000.
2. Nathan Moroney, Usage guidelines for CIECAM97s, *PICS 2000: Image Processing, Image Quality, Image Capture Systems Conference,* Portland, 164-168 (2000).
3. M.D.Fairchild, *Color appearance models*, Reading, MA: Addison-Wesley; 1998. p 176, p 197-214, p 384-389.
4. Sharron A. Henley and Mark D. Fairchild, Quantifying mixed adaptation in cross-media color reproduction, *IS&T/SID 8th Color Imaging Conference,* Scottsdale, 305-310 (2000).
5. N. Katoh, K. Nakabayashi, and M. Ito, Effect of ambient light on the color appearance of softcopy images: Mixed chromatic adaptation for self-luminous displays, *Journal of Electronic Imaging*, **7**, 794-806 (1998).
6. Jan Morovic, On to develop a universal gamut mapping algorithm, Ph.D.Thesis, University of Derby, 1998.
7. Mark D. Fairchild and David R. Wyble, Colorimetric characterization of the apple studio display (flat panel LCD), *Munsell Color Science Laboratory Technical Report,* 1-22 (July, 1998).
8. Jason E. Gibson and Mark D. Fairchild, Colorimetric characterization of three computer displays (LCD and CRT), *Munsell Color Science Laboratory Technical Report,* 1-40 (January, 2000).
9. Gustav J. Braun and Mark D. Fairchild, Image lightness rescaling using sigmoidal contrast enhancement functions, *Color Imaging: Device Independent Color, Color Hardcopy, and Graphic Arts IV, Proc. SPIE 3648,* 96-107 (1999).
10. Gustav J. Braun and Mark D. Fairchild, General-purpose gamut-mapping algorithms: evaluation of contrast-preserving rescaling functions for color gamut mapping, *IS&T/SID 7th Color Imaging Conference,* Scottsdale, 167-192 (1999).
11. Todd Newman and Elizabeth Pirrotta, The darker side of colour appearance models and gamut mapping, Conference Proceedings, *Colour Image Science 2000*, 215-223 (2000).
12. Peter G. Engeldrum, Psychometric scaling: A toolkit for imaging systems development, Reading, MA: IMCOTEK Press; 2000. p 93-121.

Biography

Sun Ju Park received her BS degree in Computer Information Systems from Drexel University in 1995 and her first MS degree in Software Development and Management from Rochester Institute of Technology in 1997. After graduation, she worked for LG-EDS Systems in Korea as a systems engineer for about two years. She returned to R.I.T. in 1999 to study Color Science and completed the study in 2001. Now, she works for Canon R&D Center Americas, Inc.