Experiments on Adaptive Soft-Copy Color Reproduction

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Abstract

The perceived colors of an image seen on a self-luminous display are affected by viewing flare and perceptual phenomena, both of which vary with the ambient illumination. A framework for a display system that is capable of adapting its output to varying viewing environments is introduced. The proposed system uses a light sensor such as a CCD camera to estimate properties of ambient illumination around a display and then adjusts display colorimetry for those lighting conditions. The emphasis of this paper is on accounting for various illumination-dependent visual effects through color appearance modeling. The effects of different parameter choices in CIECAM97s were investigated in a series of visual experiments. Paired comparison technique was used to subjectively evaluate the appearance of pictorial images adjusted using CIECAM97s and viewed on an LCD display under three different ambient illumination conditions.

Introduction

Ambient light can affect the perceived color on a display in two ways: by causing reflections that change the display colorimetry or through visual phenomena connected to the adaptation state of the person viewing the display. In real-life situations both are likely to occur to some extent. An interesting case are reflective-type LCDs, which use ambient light and whose primaries are therefore colorimetrically displaced when ambient light changes.[1] In common CRTs, transmissive-type LCDs, or other types of self-luminous displays reflections of ambient light from the display faceplate are considered a nuisance and are minimized through display design and positioning of a display relative to light sources. Still, ambient light is bound to have an effect on the effective primaries as well as tone reproduction of a display in many situations. Color appearance phenomena refer to a set of perceptual effects by which two physically identical samples can appear to be remarkably different in color if they are viewed in two different viewing conditions. In TV systems, for instance, both the amount of flare and the perceptual phenomena associated with typical viewing conditions, as well as other issues such as preferred reproduction, are accounted for in the color encoding stage; the transformation from the colorimetry of original scene to the reproduction on monitor in conventional broadcast systems has been designed so that the picture appears to be of good quality despite the aforementioned physical and perceptual factors, whose net effect has therefore been approximately cancelled out by signal processing and system characteristics. Still, the fact remains that when illumination, or some other aspect of viewing conditions, is changed the perceived colors in a picture on display also change.

The motivation for the experiments described later in this paper was a scheme for automated adaptive color reproduction on displays used under varying lighting conditions. It is necessary to separate the physical effects of flare and the perceptual color appearance effects to systematically design a display system that is capable of automatically adjusting its output to any ambient illumination. The emphasis of this paper is on predicting and accounting for the color appearance phenomena encountered when viewing a self-luminous display under differing lighting conditions. One of the main reasons for developing color appearance models such as the current CIE-recommended model, CIECAM97s,[2,3] has been a need to maintain the appearance of images reproduced across media and varying viewing conditions.[4] In this context we wish to employ CIECAM97s in controlling the appearance of self-luminous images viewed on a single display but under varying lighting conditions. Automatic brightness control is known to be used in some commercial systems to adjust the display brightness according to the overall level of illumination. The goal here is to extend the adjustments to take into account other color appearance phenomena in addition to the illumination level adaptation.

In the recent past a number of studies investigating cross-media color reproduction have been reported. In some cases appearance comparisons between a hard-copy viewed under uniform illumination and a soft-copy viewed on a CRT under differing viewing conditions have been made based on memory matching, and matching images reported by test persons have been compared to the predictions of various color appearance or chromatic adaptation models, e.g. references 10 to 12. Other investigations concentrated on appearance comparisons between a hard-copy and a soft-copy viewed next to each other.[16-20]

In comparison, the experiments performed within this project differ from the aforementioned in that only images on a self-luminous display, seen under varying viewing conditions, were compared. Also, unlike in most other studies, the images shown to the observers were not surrounded by display area with constant luminance and chromaticity; here the images covered all of the visible display area. The experiments performed in order to improve the understanding of the use of CIECAM97s as a tool in adjusting soft-copy imagery are described after general description of the envisioned display system for automatically optimizing the display output to prevailing lighting conditions around the display.

Framework for Adaptive Display Color Management

A number of things are required to obtain the lofty goal of controlled color reproduction on displays viewed under varying light sources. First, the display system needs a light sensor to estimate properties of ambient light. Second, display colorimetry must be controlled; this requires colorimetric characterization of the display as well as estimation and modeling of reflections caused by ambient light, assuming they cannot be properly eliminated. Third, the effects of ambient light on color perception via illumination-related visual effects must be estimated and compensated for through color appearance modeling

In the test system under development a CCD camera is used in estimation of scene illumination. The illumination level is estimated based on readings from the CCD. A proper exposure is set based on the illumination level and an image of the scene is captured. The image is then analyzed to estimate the chromaticity of the illumination. Here we enter the field of white point estimation and computational color constancy.[24] The illumination estimate does not have to be based on a single image since the response of the system is best modified gradually; therefore temporal changes can also be analyzed.

The colorimetric characteristics of the display, preferably measured in a flare-free environment, must be known at reasonable accuracy to facilitate meaningful adjustments. In real viewing situations some ambient flare is bound to be present. The amount of flare can be estimated based on the ambient illumination. Suitable compensation for the effects of flare must then be made. Even if display colorimetry and the amount of flare are known the flare cannot be simply computationally cancelled since flare affects the effectual color space of the display. The evident effects of additive flare are decrease in image contrast and colorfulness; these effects must be appropriately compensated.[5]

At this stage we make the simplifying assumption that the properties of ambient illumination are known and its reflections from the display faceplate can be eliminated or, failing that, can be estimated and included in the display colorimetric characterization. The focus at this point is thereby on color appearance modeling for displays used in varying viewing conditions and the problem is to control display luminance level and relative colorimetry so as to optimize the reproduction for given viewing environment.

It is planned to perform the brightness adjustment conceptually before the adjustments based on CIECAM97s. Note that the "brightness adjustment" is performed independently and is not tied to CIECAM97s predictions of brightness or other appearance attributes; the aim is simply to set the display luminance level at a comfortable level compared to ambient illumination. Still, the absolute display luminance level naturally affects the appearance of the image and this needs to be considered when choosing parameters for a color appearance model. In standards and dealing with visual display terminals used in office environments various recommendations are given for the luminance balance between the display and the surrounding areas. ISO 9241-3,[7] for instance, states that the ratio of average luminances of task areas such as displays and documents should be lower than 10:1. By calculating CIECAM97s appearance correlates for picture elements, using the forward model, in certain assumed reference viewing conditions, the appearance of the picture in those conditions can be quantified. When the viewing conditions change, the model can be used in inverse direction to obtain the corresponding colors in these new viewing conditions. In the adaptive system the original image RGB data is typically assumed to be in the sRGB color space.[8,9] Based on the sRGB definitions for display characteristics and viewing conditions, CIECAM97s JCh values, that is, correlates for lightness, chroma, and hue, are calculated from the sRGB pixel values.

Choice of adopted white point XYZ values is not that straightforward in mixed-mode viewing environments with different white points and luminance levels for the ambient illumination and display. Other results suggest that D65 chromaticity is a decent choice for adopted white point in the case of sRGB,[15] this is used as the adopted white point for sRGB and the parameter D is set to 1.0 to indicate complete adaptation to the sRGB white point. However, in different conditions the monitor white point is not likely to be a good estimate of the internal adapted white point of the human visual system.[13–20]

In the case of an adaptive display system, two basic approaches can be envisioned. First one is to assume a constant white point for the display, and based on that white point and the ambient white point estimate suitable adopted white point and, incorporating incomplete adaptation, make adjustments to the image, supposing its background is made up of other areas of the display that are not affected by the adjustments.[16–20]

In the second approach, which is currently used in the system, a display is adapted to the given ambient illumination, assuming that the picture fills all of the display area. In this case the white point of the displayed image will effectively also be the white point of the display. The goal is then to set the display white point so that it appears neutral when viewed in the given viewing conditions. Reference white point of XYZ = (100, 100, 100), that of equal-energy source, of CIECAM97s can be used in totally dark environment; this is justified by the achromatic appearance of equal-energy stimuli to the dark-adapted eye.[21] Any other reference white point could be introduced by substituting corresponding values for reference white in CIECAM97s equations. The amount of departure from the reference white point towards ambient white point in brighter environments is controlled by parameter D. The degree of chromatic adaptation cannot be, in this case, estimated by the recommended equation[3] with parameters set according to the surround categories, however. This is because of different modes of visual perception used when viewing self-luminous soft-copies, or hard-copies and original scenes that are perceived to reflect prevailing illumination.

Experiments and Results

A single Dell 1701FP, a 17 inch active matrix TFT LCD display, was used in all the experiments. The display was calibrated in a dark room, with stray light minimized, such that the xy-chromaticity of the white point was (0.313, 0.329) and luminance was 214 cd·m^{-2}. The display was measured with a Minolta CS-1000 spectroradiometer at 0° viewing angle, i.e. normal to the screen. The average error of the characterization for 27 RGB triplets chosen from all parts of the color space was 0.89±0.51 ΔE_{ab}^*, the maximum being 1.93 ΔE_{ab}^*. Viewing angle dependency is evident on the display at off-axis viewing angles but due to the experimental arrangement, which forces observers to view a limited region of the display at angles very near to 0°, this was not thought to be an issue in this context.

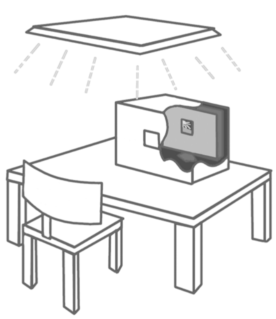

Figure 1. Viewing configuration for the experiments

The viewing configuration is shown in Figure 1. It was vital for the experiments to minimize flare. Thus the display was hidden inside a box and was viewed through an aperture. The observers were instructed to view the images from such a distance, about 60 cm, that only the image was visible in the aperture. All of the display face save the 6 cm by 6 cm image area was also covered to minimize stray light within the box. Although flare was negligible in the dark and dim conditions, ambient flare still caused a small increase in display luminance, high enough to possibly have an effect on the experiments, under the highest level of ambient illumination. This was compensated for by using different display profiles for each of the viewing conditions; the profiles for the dimmer conditions were modified by additive constants that made the black and white points equal under all viewing conditions.

The goal of the experiments was to test the usefulness of color appearance modeling in controlling appearance of soft-copy images under different illumination conditions and to identify the significant parameters in the adjustments. Different CIECAM97s parameters were varied to investigate their importance and to find optimal settings for the application at hand. Color reproduction of 4 different natural images on display was judged by 11 subjects with normal color vision in 3 different illumination conditions. The luminance and relative tristimulus values of the CIE 1931 standard observer are given in Table 1 for white at table level next to the display. In all the experimental phases a memory viewing technique was used;[25] 1 minute adaptation period was used whenever room illumination was changed. The experiments, divided into 3 parts, and their results are described below. The observers were familiarized with the types of changes they were to expect in each experiment.

Table 1. Viewing Conditions

	Ambient white point			
Conditions	X	Y	Z	L (cd·m^{-2})
A	100	100	53	153
B	113	100	25	2
C	100	100	100	0

As can be seen on the table, experimental viewing conditions had differences in luminance levels as well as light source chromaticities. The pictures used in the experiments are shown in figure 2. Let them be called *fruit, loaded, swan*, and *waterskier*.

Figure 2. Pictures used in the experiments

1st Experiment and Results

This experiment examined the chromatic adaptation by varying the D parameter under different ambient illuminations. Two sets of images were produced for the experiment, one for viewing conditions A and the other for viewing conditions B. The ambient white points for conditions A and B, from Table 1, were used as adopted white points in the respective sets. The set for conditions A contained six images produced with D parameter values 0.0, 0.2, 0.4, 0.6, 0.8, and 1.0, corresponding display white points ranging from XYZ values (100, 100, 100) to (100, 100, 53). Values of 0.0, 0.1, 0.2, 0.3, 0.4, and 0.5 were used in the set for conditions B. All other CIECAM97s parameters were kept constant for all images; display white point luminance was constant at 153 $cd \cdot m^{-2}$. The reference image was produced with adopted white point of (100, 100, 100). After viewing the reference in conditions A, i.e. a dark room, for an unlimited time, usually between 30 and 60 seconds, the room illumination was changed to either conditions A or B. The observers were then, after 1 minute of adaptation, presented the images in pairs, in random order, and asked to select the one that was closer in appearance to their memory of the reference. They were instructed to concentrate on the global color balance of the images in their judgements. The observers were allowed to alternate between the images in a pair, only one picture being displayed at a time, as many times as they wished. Five seconds of black screen was shown every time picture was changed; the observers were instructed to detach their view from the display area during these intervals.

The interval scale values calculated from the paired comparison data according to the Law of Comparative Judgement, Case V, are shown in Figure 3 with 95% confidence intervals. The z-scores for conditions A, peaking at D = 0.4, are shown as circles, while the squares, peaking at D = 0.1, are for conditions B.

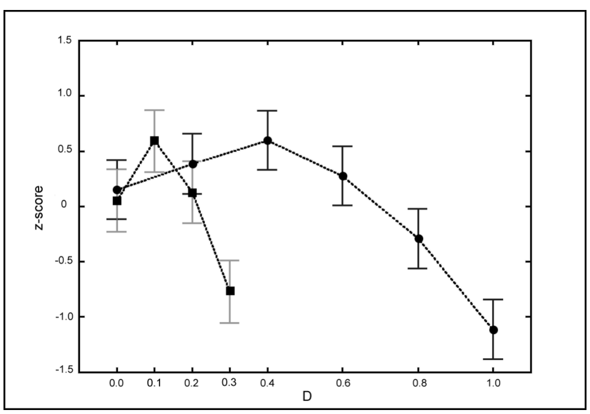

Figure 3. Results of the chromatic adaptation experiment

In the case of conditions B the results for D values 0.4 and 0.5 were excluded from the scale generation since their data columns contained zero and other very low proportions, indicating that their appearance was far from the reference. Although scale values were calculated using Morrisey's least-squares solution, which nicely handles this incomplete matrix problem, the failure in the Mosteller's chi-squared test when these proportions were included suggested that the Case V model did not properly represent the data. When these uninteresting low-proportion samples were removed from analysis the data passed the chi-squared test, as did the other data sets in experiments 1 and 2, these with all of the paired comparison decisions included.[22,26]

2nd Experiment and Results

This experiment examined the effects of the CIECAM97s surround parameters c and N_c. A set of images was produced by varying the c parameter; N_c was selected as a function of c as suggested by Fairchild.[23] Images adjusted for conditions A, i.e. those reproduced from sRGB originals using values 0.69 and 1.0 for c and N_c, respectively, were used as the references. These and reproductions with varying amount of surround compensation were judged using the paired comparison method in viewing conditions B and C. The procedure was the same as in the 1st experiment above, except that this time the observers were instructed to concentrate on image contrast; also, the reference images were viewed in conditions A. The resulting interval scales are shown below. Values for conditions B, peaking at c = 0.59, are again marked by squares; diamonds stand for results in conditions C, highest scale value being found at c = 0.56.

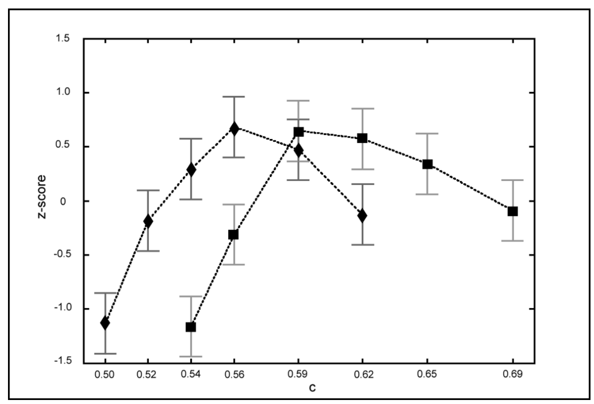

Figure 4. Results of the surround compensation experiment

3rd Experiment and Results

Finally, the quality of image reproduction using the optimal parameter values deduced from the 1st and 2nd experiments was judged under viewing conditions B and C. Here two pictures from the first two experiments, *fruit* and *loaded*, were used along with two other pictures, *lizard* and *beachvolley*, not shown here. Seven versions of each picture were produced with different CIEACM97s parameters listed in the table below. L_A, the luminance of the adapting field, was set to 20% of the display white point, L_{disp}. The VC column shows the viewing conditions for which each image version was intended. Picture version 1 was used as reference in conditions A. Both display luminance and CIECAM97s adjustments were used on picture versions 2 and 3, while display white point luminance was not adjusted for 4 and 5. In the case of versions 6 and 7 only display luminance level was adjusted; the white point luminance values for different conditions were based on an experiment, not described here, that tested the preferred display brightness, independently of color appearance, in each of the three viewing conditions.

Table 2. Adjustment Parameters for the 3rd Experiment

Version	White point	L_{disp} (cd·m^{-2})	c	D	VC
1	(100, 100, 53)	153	0.69	0.4	A
2	(113, 100, 25)	90	0.59	0.1	B
3	(100, 100, 100)	50	0.56	0	C
4	(113, 100, 25)	153	0.59	0.1	B
5	(100, 100, 100)	153	0.56	0	C
6	(100, 100, 53)	90	NA	NA	B
7	(100, 100, 53)	50	NA	NA	C

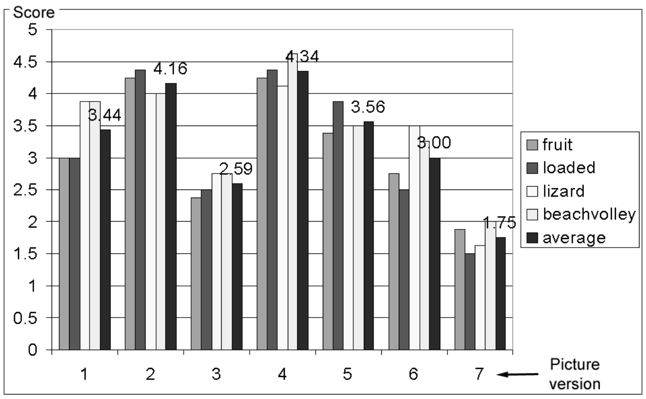

Figure 5. Average scores for viewing conditions B

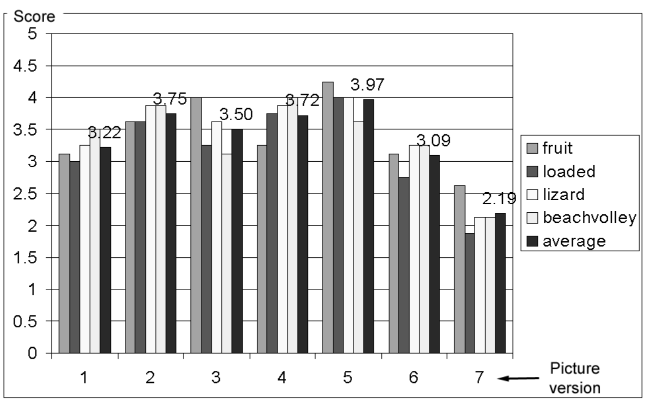

Figure 6. Average scores for viewing conditions C

The seven observers that took part in this part of the experiments were shown version 1 of the picture in conditions A as a reference. After 1 minute adaptation to conditions B or C they were asked to judge the quality of each picture version, shown in random order for five seconds, as a reproduction of the reference, paying attention to matching color appearance and comfortable brightness level.

The observers expressed their opinion using the following scale: 5 ("Excellent", no perceptible difference to the reference), 4 ("Good", slight difference), 3 ("Acceptable", easily perceptible difference but the picture is still an acceptable reproduction of the reference), 2 ("Poor", annoying difference), 1 ("Bad", very annoying difference). Figures 5 and 6 show the average scores for different versions of the four pictures. The right-side column in each group, with numerical value above, shows the average score of the corresponding version of all four pictures.

Discussion

The observers' judgements in the chromatic adaptation experiment indicate changes in their adaptation. As expected, the best match to the original viewed in a dark room was produced when the display white point was shifted towards that of the ambient illumination. In viewing conditions A the optimal display white point appears to be slightly below half-way from the reference white point towards the ambient white point. On the other hand, in conditions B only a slight shift towards the ambient illumination chromaticity was evident in the judgements, D=0.1 receiving the highest scale value, compared to D=0.4 in conditions A. This was also an expected result, low level ambient illumination having less effect on the observers' state of chromatic adaptation when viewing the display. It should be stressed that in these experiments the images filled all of the visible display area, and are therefore not directly comparable to investigations involving also the context of display background, which is likely to cause the observers to be more completely adapted to the display. In these experiments, using uniform color patches, the shift caused by ambient illumination was weaker, around 10-20%.[13-15] When soft-copy pictorial images were compared to hard-copies in mixed adaptation conditions the shift was more pronounced at 40-60%.[16-18, 20]

In the second experiment the need for surround compensation was evident. The results indicated closest match in conditions C when parameter c was set to 0.56, which is somewhat higher, corresponding to less surround compensation in dark surrounds, than recommended in CIECAM97s specification for the dark surround category. However, since other sources[11,23] suggest that the strength of surround effect is highly dependent on the particular viewing conditions and observational task this result does not seem very surprising, either.

For the relatively small set of observers used in the 3rd experiment the results show the benefit of using CIECAM97s when making soft-copy reproductions to be viewed in varying ambient illumination conditions. Also when adjusting display luminance level color appearance modeling significantly improves the quality of color reproduction. The color appearance seemed to be greatly affected when only display luminance level was lowered to a more comfortable level, resulting in low scores for picture versions 6 and 7; however, when also CIECAM97s was used (versions 2 and 3), much higher average scores resulted. Especially in dim conditions (B) the adjustments using parameters intended for those conditions resulted in better scores. In dark conditions (C) the versions specifically adjusted for those conditions significantly increased their scores, compared to conditions B, but the scores for all versions were closer together than in conditions B.

Conclusion

Appearance of pictures seen on an LCD display under varying ambient illumination conditions was investigated. A series of experiments was carried out to study the effect of CIECAM97s chromatic adaptation and surround compensation parameters in this context. The use of color appearance modeling was shown to improve color reproduction when ambient illumination around the display was changed. Although these results are encouraging, there are still some problems to overcome when thinking of the adaptive display system outlined above in real-life viewing conditions. One important issue is compensating for the reflection of ambient illumination from the display and seamlessly incorporating these flare adjustments into the system.

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Biography

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