Dynamic Correction of Color Appearance on Mobile Displays

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Abstract

Technological advances in mobile devices have made them attractive for many previously infeasible image synthesis applications. Mobile users may roam between a wide range of environmental lighting including dim theaters, lit offices, and sunlight. Viewing images in diverse lighting situations poses a challenge: while our eyes can adapt to environmental lighting, changes in lighting can affect the perceived hue, brightness contrast and colorfulness of colors on electronic displays or in print. Consequently, colors in displayed images may appear bleached or be perceived differently from one lighting scenario to another. If these adverse lighting effects are unmitigated, the fidelity of color reproduction could suffer and limit the use of mobile devices in sensitive applications such as medical imaging, visualization, and watching movies.

Many mobile devices currently include simple compensation schemes, which adjust their display's brightness in response to the environmental illumination sensed by built-in light sensors. These displays compensate for brightness but neglect the changes in perceived color and contrast caused by environmental lighting. We propose a novel technique to dynamically compensate for changes in color, colorfulness, and hue as mobile users roam. Our adaptation technique is based on the iCam06 color appearance model and uses the mobile device's sensor to continuously sample and feed back environmental lighting information.

Index Terms: I.3.3 [COMPUTER GRAPHICS]: Picture/Image Generation—Display algorithms; I.4.0 [IMAGE PROCESSING AND COMPUTER VISION]: General—Image displays; K.m [MISCELLANEOUS]: Mobile Graphics—; K.m [MISCELLANEOUS]: Mobile Computing—

1 Introduction

The progression toward smaller, more powerful computing devices equipped with programmable graphics hardware, higher resolution displays, and improved color depth has facilitated a plethora of mobile graphics applications. Mobile users can now play computer games, watch movies or view pictures of friends while commuting to work. Surgeons can now view patient's charts to diagnose ailments at remote locations. The increasing popularity of image synthesis on mobile devices makes the accurate image presentation on mobile displays crucial. While viewing rendered images, a mobile user may roam into a wide range of lighting situations such as dim theaters, artificially lit offices, moonlight and bright sunlight. Changes in environmental lighting can adversely affect the perceived visual quality of images on mobile displays and can degrade the graphics experience if not mitigated.

Drastic increases or decreases in environmental lighting can shift the perceived hue (Abney Effect and Bezold-Brcke Effect), contrast (Stevens Effect), colorfulness and brightness (Hunt Effect) of viewed images. Figure 1 shows bleaching of displayed colors when a mobile user transitions from low office lighting into bright sunlight. Some mobile devices uniformly adjust the brightness of their display to compensate for such lighting changes. However, current adaptations are naive since they typically neglect color shifts and changes in color contrast sensitivity. It is also important to note that perceived color and contrast shifts are not uniform, but differ from color to color. More sophisticated adaptation techniques should also compensate for color-specific shifts in colorfulness and hue while preserving the original intention of the image.

Figure 1: Sample images showing bleaching of displayed colors by bright sunlight. The left column row contains original images viewed under moderate indoor light. The right column contains the same images viewed in bright sunlight.

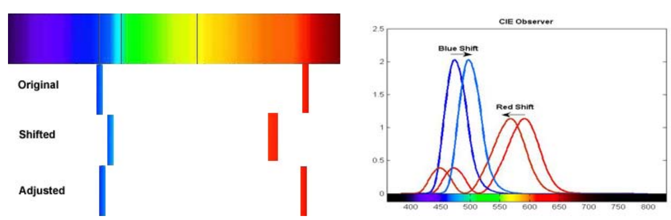

Figure 2: The wavelength of colors increase as incident illumination increases. The left figure shows a spectrum with original colors, shifted wavelengths due to illumination changes, and adjusted wavelengths after applying our technique. Right is a spectral curve shifted by environmental illumination.

Color preservation is vital when the mobile devices are used in high-fidelity applications such as medical imaging, visualization, or viewing a movie. In certain medical imaging applications, values of measured physical quantities are depicted using colors. For instance, in Doppler Flow Echocardiagrams (see figure 3), differences in a patient's blood pressure and velocity are displayed using different colors. Fast moving blood is colored red, while slow moving blood is colored blue. Trained physicians assume this color-coding and routinely make life-preserving decisions based on observed colors. If environmental lighting bleaches an intended red color or changes it to orange, a physician's inference could be wrong. Many other examples exist where color or contrast shifts

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in rendered colors can seriously affect high-fidelity graphics, visualization and medical imaging applications. Physicians have widely adopted the use of handhelds for their work due recent HIPAA regulations and to make their work more convenient. A 2005 survey found that more than 50% of physicians already used handheld devices regularly[16]. With such widespread PDA adoption, the fidelity of image representation on mobile displays becomes more important.

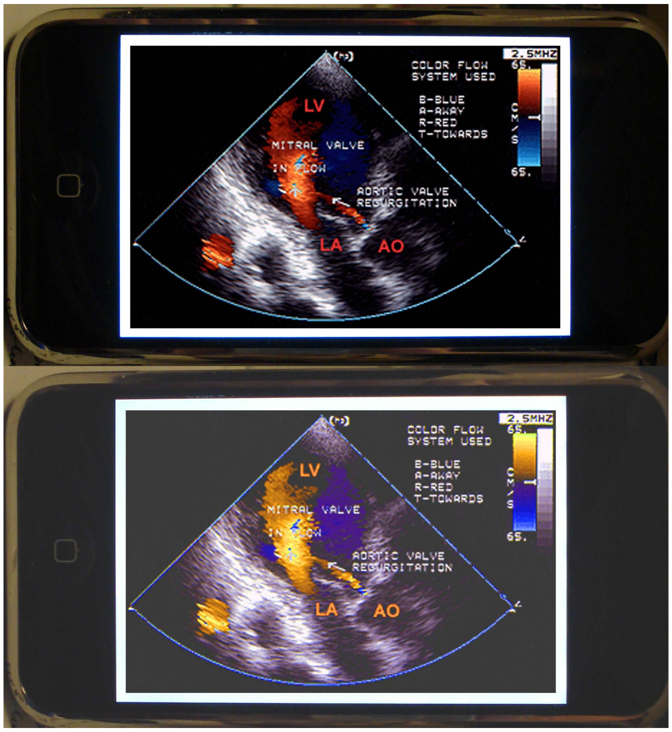

Figure 3: An Apple iPhone displaying a Doppler Echocardiagram; top image shows correct colors in normal office lighting and bottom image is viewed under outdoor lighting conditions.

Our work proposes a modification to the iCAM06 color appearance model that preemptively adjusts the hues of colors in an image before rendering to compensate for anticipated hue shifts caused by the bleaching effects of high environmental luminance. We accomplish our adjustment by adding an inverse-bleaching multiplier during the chromatic adaptation phase of the iCAM06 model, which shifts the hues in a direction that is opposite to the anticipated shift due to environmental lighting. Figure 2 illustrates this idea on spectral curves (right) and on a spectrum rendering (left), showing the original hues, the shifted hues and final perceived colors after adding the effects of environmental illumination. .

The rest of this paper is as follows. First, in section 2, a background on how humans experience color and color appearance is presented. Next, in section 4, we discuss related work leading up to ours, starting with a brief history of color perception. We introduce the concept of Color Appearance Models (CAMs) outlining how they evolved from our understanding of human color perception. These CAM models provide a framework to understand and manipulate displayed colors that humans experience in a given environment. Then in section 5, we describe our solution to the problem of color fidelity on mobile devices by using a CAM to guide pre-emptive color manipulation before rendering images to compensate for environmental illumination. In section 6, our results are presented and in section 7, future directions are discussed.

2 Background: How Humans Experience Color

Humans perceive colors when the light reflected off object surfaces is translated into stimuli in the Human Visual System (HVS). Our color experience is shaped by how we perceive the brightness, hue and the color purity of light, which are Colormaking attributes commonly used to describe colors. Hue names a color. Brightness and lightness describes how bright or dark a color may be and color purity relates to how much of a named color is present in its pure form. The verbal descriptions of color are just human descriptions of the physical stimuli experienced. Thus, Colormaking attributes are only loosely correlated to the physical quantities of light and color. As a foundation for our work, an understanding three ways in which the HVS adapts to input stimuli are now introduced. In section 3, we shall describe how these HVS adaptations are modeled in Color appearance Models that we then modify in our work.

White Point: In addition to the Colormaking attributes, our color experience also depends on the context in which we view the color. The contextual dependence of color is complex and encompasses many factors such as the incident light's intensity and color, what colors surround the color of interest, and the ability of HVS to adapt to changes in color and light. The color and intensity of illumination affect the amount of stimulation our eyes receive. When a surface reflects a more intense light source, its colors appear brighter. Similarly, the color of the light source can affect how we perceive the color of surfaces that it reflects off. This is evident when the same surface is viewed under artificial light compared with sunlight. These are both sources of white. However, sunlight produces all wavelengths of light equally, while artificial light sources produce different wavelengths unequally. Consequently, the color we experience as white under artificial light will be completely different from what we consider white on a bright sunny day. Our perception of the color "white" remains constant even though the actual light values can be completely different. The HVS adaptation to these ranges of physical white light is called a White Point. While the HVS, adapts easily, subtle differences in incident white light is evident in picture. A common example is the case where a photo is taken indoors under artificial illumination. The perceived white light of illuminant might actually have fair amount of red color in it, which requires a correction of "redness" of the picture even though when taking the picture the light seemed white (red if the light was an incandescent tungsten light). On a mobile display, white point adaptation is relevant because we would like to account for the fact that a mobile user can experience different types of incident white light.

Chromatic Adaptation: Another contextual element that has a profound impact on how we perceive color is the color of objects surrounding the surface we are looking at. Humans can pinpoint subtle color differences that are surrounded by colors of almost similar hue Similarly; we are less able to discern subtle color differences in regions that also contain large color changes. This phenomenon is an example of Chromaticity Adaptation. Figure 4 demonstrates this effect. When the surrounding colors are close to those of the middle ovals we easily see that the three ovals are slightly different shades of gray, but when the surrounding colors are very different from those of the ovals, we are less able to notice that the ovals are slightly different shades of gray. On images rendered on mobile displays, chromatic adaptation is important because since images are essentially blocks of pixels, we would like to be cognisant of how a pixel's neighbors affect its perceived color.

Tone Compression: Lastly, our visual system has the ability to adapt to changes in light (Luminance Adaptation) via a mechanism called Tone Compression (Also called post-chromatic adaptation response, or non-linear response compression). This has the effect of reducing initial brightness over time after walking from dark lighting to bright lighting, during an adjustment period. For example, immediately after walking out of a movie theatre, every object in daylight appears excessively bright, colors appear more vivid, and reflections of the sun seem very bright until our eyes adapt. Conversely, a reduction in light can make an environment dark and reduce our ability to see color, making everything look gray and black until our eyes adjust. In summary, our eyes can adapt to a large range of light intensities. In deal with wide ranges of illumination, the HVS compresses incident ranges. However, unlike our eyes, electronic displays, print, paper and other output devices cannot adapt to ranges of impinging light intensities. Tone mapping algorithms have been developed to mimic the how the HVS compresses extreme ranges in incident light. They essentially map light intensity ranges found in the real world to displayable values while trying to preserve the look of objects viewed with the original range.

3 Color Appearance Models

Over the years scientists have developed mathematical models that try to capture some of the findings above in translating physical light quantities to a contextually based perception of color. These models are called Color Appearance Models (or CAMs). In general, CAMs use environmental parameters to predict how a given color will appear to a user. These input parameters typically include the Colormaking attributes in some form and involve steps to simulate the visual process of a standard observer. The two main steps common to all CAMs is Chromacity Adaptation and Tone Compression and each CAM distinguishes themselves by how they model these two features.

CAMs are generally used in applications where color reproduction is needed, such as print media, color correction for film, and scientific applications. CAMs can model the complexity of certain parts of the HVS but fall short in predicting others. Time-varying and spatially varying stimuli [10], such as those seen in electronic images and video, are features that previous appearance models lack. For example, the classic CIELAB color model provides a perceptually uniform hue and chromacity that is unable to reach the same chromacity level exhibited in CRT screens [10]. Therefore a new class of CAMs called Image Color Appearance Models (iCAM) were developed to address these shortcomings [14, 15]. Fairchild et al. developed an iCAM framework comprising of two such models called iCAM02 and its successor iCAM06 to deal specifically with issues related to digital image and video rendering. These models add significant improvements to color modeling on digital displays as well as support for High Dynamic Range (HDR) imaging.

The iCam06 differentiates itself from its predecessor by closely modeling the features of the HVS while remaining relatively simplicity. For example, the iCAM06 model separates the input image into two layers, a base layer and detail layer that allows compression without losing vital information (more details in the next paragraph). Also, the iCAM06 model updates previous models by replacing a simple gamma correction term with a function that better mimics photoreceptors. The iCAM06 model also incorporates a large range in luminance to better accommodate Scotopic (dim light, roughly 10^{-2} to 10^{-6} cd/m^2) and Photopic(normal lighting, roughly 1 to 10^6 cd/m^2) vision. Finally, the new iCAM models the HVS changes in colorfulness, contrast, and gamma due to luminance changes.

The Base and Detail Layers in the iCAM: The first step in the iCAM models filters the input image using a Gaussian filter. The iCAM06 model replaces the previous single layer Gaussian filter with a dual-layered approach, a base layer for global features and a details layer for local features. The motivation for the separation stems from the fact that the HVS is more sensitive to local features like reflectance and local contrasts and less sensitive to global features [4] like illumination. iCAM06 takes advantage of this by aggressively compressing the base layer during the tone compression step, which contains the larger variations, while preserving the fine-grained details in a separate layer without compression. To accomplish the separation, an edge preserving filter, called a bilateral filter [4], is applied to the input image to produce the base image. The bilateral filter uses a 2D Gaussian blur with one dimension in the spatial-domain *f()* and the other in the intensity domain *g()*. For pixel s and its neighbors p, the bilateral filter J_s can be calculated by equation 1 where I_s and I_p are the intensity values for the pixel and its neighbors and k(s) is a normalization factor.

$$J_s = \frac{1}{k(s)} \sum_{p \in \Omega} f(p-s) g(I_p - I_s) I_s \tag{1}$$

The overall benefit of using the Bi-lateral filter versus other decomposition techniques is that other filters produce a halo effect [4], which causes ”leaks” that spills color across boundaries, while the bilateral filter does not. Finally, the detail image is obtained by subtracting the base layer image from the original input.

Chromatic Adaptation in the iCAM: Chromatic adaptation in the HVS occurs in the photosensors of the human eye where the sensitivity of the cones is adjusted based on the amount of stimulus it is receiving. This can be modeled by normalization of the RGB values using the white point with a gaussian filter applied. This normalization is often called the von Kries normalization [5]. The normalization is a function of the adaptation luminance (L_A) and the surround factor.

$$D = 0.3F \left[1 - \left(\frac{1}{3.6}\right) e^{\frac{-L_A - 42}{92}} \right] \tag{2}$$

$$C_c = \left[\left(C_{D65} \frac{D}{C_W} \right) + (1-D) \right] C \tag{3}$$

The adaptation in equation 3 is applied separately for the red, green and blue channels.

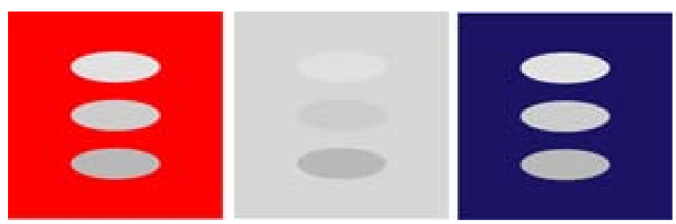

Figure 4: An example of Chromatic Adaptation; The three ovals in the middle have slightly different colors. These differences only become apparent when the context in which they are viewed are similar enough to the original color (middle image). Against red or blue backgrounds the ovals appear to have the same color.

Tone Compression in the iCAM: In reality, the range of light values can span several orders of magnitude making it difficult for the HVS to make color consistent from one lighting level to another. In order to accomplish this consistency in color the input luminance range needs to be compressed. This is also true for CAMs as well, and has led a to wide range of research in tone-compression and tone-mapping which is especially important when dealing with High Dynamic Range (HDR) images. Care must be taken within the CAMs (traditional CAMs as well as iCAMs) to make sure compression is accurate, since improper compression of illumination ranges can have an impact on the viewers perception.

Equations 4 - 7 deal with the tone compression technique developed for iCAM06. These equations convert the post-adapted color values from CIECAM02 [6] space to the Hunt-Pointer-Estevez space using transformation matrices before tone compression as in equation 4.

$$\begin{bmatrix} R' \\ G' \\ B' \end{bmatrix} = M_{HPE} M_{CAT02}^{-1} \begin{bmatrix} R_c \\ G_c \\ B_c \end{bmatrix} \quad (4)$$

$$R'_a = \frac{400(F_L R'/Y_W)^p}{27.13 + (F_L R'/Y_W)^p} + .1 \quad (5)$$

$$G'_a = \frac{400(F_L G'/Y_W)^p}{27.13 + (F_L G'/Y_W)^p} + .1 \quad (6)$$

$$B'_a = \frac{400(F_L B'/Y_W)^p}{27.13 + (F_L B'/Y_W)^p} + .1 \quad (7)$$

Each color channel is compressed using a reducing power function (5-7). The power function, where p ranges from 0.6 - 0.85, serves to mimic the cones response to luminance levels where Y_w is the luminance of the local whitepoint and F_L is the luminance adaptation factor. A similar treatment for the rods response, A, is also calculated. The total compression response is then the sum of the response of the cones and rods.

$$RGB_{TC} = RGB'_a + A_s \quad (8)$$

4 Related Work

Bezold-Brucke Effect: As colored light becomes more intense, the perceived hues on the light can change. This phenomena was first noticed by Johann Friedrich Wilhelm von Bezold and Ernst Wilhelm Ritter von Brcke in the early nineteenth century. In 1931, Purdy demonstrated that the luminance values of a monochromatic light affects its perceived hue [21] and thus generated the first dataset that quantified the Bezold-Brucke effect. Then to preserve a constant perceived hue, the wavelength of the light must be changed to compensate for changes in the luminance [5]. He also discovered that adding white light to monochromatic light causes the same shift in hues. This observation is what directly affects the rendering of displays. By adding environmental luminance to the emitted light from the screen the perceived hue is shifted for the viewer. In addition to Purdy's experiments, Pridmore used color matching experiments to further refine the work of others who replicated Purdy's early work by more precisely matching the shifts in wavelength especially in the red wavelength [19, 20].

CAMs: The minimum objective of any CAM is to predict lightness, chroma, and hue [5] but CAMs try to accomplish more by also predicting other color appearance attributes as well as effects such as the Bezold-Brucke (hue shift), Abney, and Hunt (colorfulness and brightness shifts) effects. One of the first CAMs developed was the Nayatani Model [17, 18]. This model was an extension to their previously published chromatic adaptation method and was designed primarily for simple stimuli with uniform backgrounds. The most comprehensive CAM till date is the Hunt model []. The Hunt model was developed over several years ranging from 1982-1995 and predicted a plethora of effects and phenomena such as luminance levels, bleaching, and every effect mentioned thus far. The Hunt model doe not try to model some of the more complex spatially-varying or temporally-varying images.

iCAM, An Extension to CAMs: The iCAM framework is an extension of CAMs that was primarily developed for use with spatially and temporally varying images, such as electronic images, movies, and animations. Kuang, Johnson, and Fairchild developed this framework to also include tone-mapping operations and perceptual modeling [10, 6]. The iCAM framework models the HVS by adding spatial processing components to their color appearance model, which enhance local details as well as predict many appearance phenomena, such as white point, chromaticity and luminance adaptations. As described in section 3, the latest version of the iCAM models is the iCAM06 model [10].

Color Appearance On Digital Displays: There has been other work that has focused specifically on the effects of color display on CRTs. Brainard and Ishigami [3] ran initial experiments in 1995 to develop a theory to accurately predict the color appearance and contextual effects of color rendered on CRTs. Choh et al [8] studied and modeled the effects of various types of ambient illumination on colors rendered on CRTs. The results of these experiments were then used to develop color profiles for the manufacture of CRTs. More recently, Akyz and Reinhard [1] developed a technique that augments iCAM in order to optimize viewing of rendered HDR images on CRTs under various environmental lighting scenarios. Although their technique is similar to ours, we note important differences: their technique requires a priori knowledge of the environmental illumination and does not permit dynamic (on-the-fly) adaptation of rendered images on mobile displays when surrounding light changes as users roam. In addition to Akyz and Reinhard work, Lee et al. [12] proposed a color correction method based on Choh et al's model of the Bezold-Brcke (B-B) effect with user experiments on high luminance displays. Color matching experiments were used to compare normal and high luminance display colors but not including environmental illumination.

To summarize our key contributions, none of the above techniques are able dynamically adapt to lighting changes as a mobile user walks from one lighting environment to another. Previously proposed models implicitly assume that while displays may experience extremely bright or dim lighting, they assume that displays have a fixed location such that compensation for adverse light conditions need to computed in advance once and remain valid for the lifetime of the running application. We propose a dynamic model that uses estimates of surrounding environmental lighting from sensors as input to the iCAM framework. Additionally, none of the models, with the exception of Akyz and Reinhard, no previous work attempts to compensate for changes that affect the displays due to surrounding illumination. We also note that Akyz and Reinhard compensate for changes in appearance but do not try to overcome glare, ambient light, glare or additional illumination from the display itself. We propose a modification to the iCAM06 model that will account for all of these factors dynamically.

5 Our Technique

Our system involves a set of modifications to the iCam06 color appearance model that uses a) the mobile device's light sensor b) the original parameters to the iCAM06 model, and c) the image, in a feedback system. As shown in figure 1, bright light can have a bleaching effect on displayed colors. Applying our improved model in such a case would generate an over-compensated (more colorful) image, which when viewed under (washed out by) bright light, would closely resemble the intended image. We focus on re-adjusting the iCam06 features that respond to changes in hue. The first modification is with the Bartleson-Breneman power function that adjusts the levels of surrounding illumination in perceptual space. Second, the degree of chromatic adaptation for the post cones response is also modified in perceptual space. Finally, we compare resulting RGB values to calculate a difference threshold in order to add weight if the RGB values go beyond the threshold (equation 9 and 10).

The values from the light sensor give an estimate of the current surrounding luminance under which the image is being viewed. We feed this estimate into the modified iCam06 model as a parameter for calculating the color appearance of the image in IPT space. Bartleson-Breneman [5] predicted that as environmental illumination increases so does contrast and colorfulness. In our work, we found (as well as other researchers [5]) that this is not entirely true for CRTs and other electronic displays. Our eyes adapt to environ-

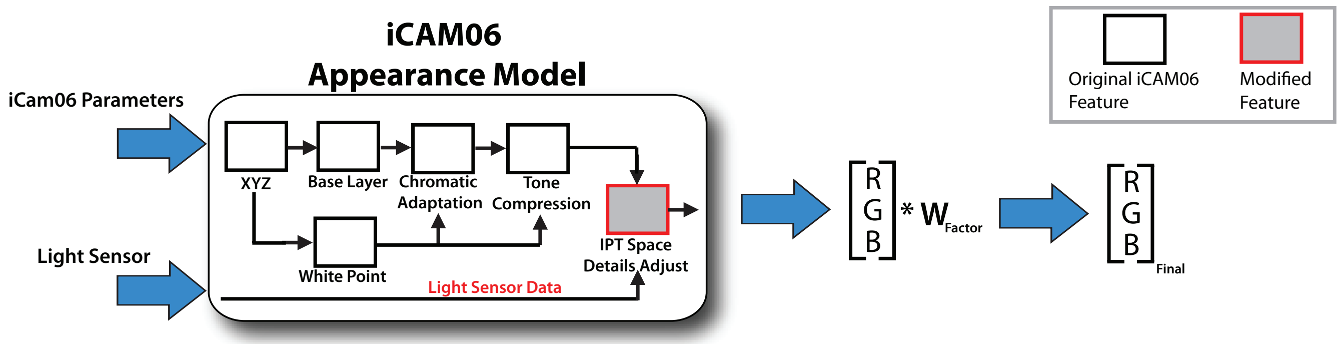

Figure 5: Overview of our technique showing the inputs, the iCam06 model, and the weighted correction of the final RGB values. Our modifications to the iCAM06 model (in red) are in the IPT perceptual space where detail adjustments are made and the weight factor W from equation 9 and 10.

mental illumination, glare, and display brightness, which overpowers the changes in contrast, and colorfulness. A simple experiment proves this, as viewing a CRT in the dark is relatively better than viewing the CRT with lights on. The value from the mobile device's light sensor is used to determine the surrounding condition under which the image is being viewed. For bright environments we can adjust the degree of chromatic adaptation, which is generally considered dark, dim, or average by the Bartleson-Breneman experiments outlined in [5]. But we consider that even in average lighting, the level of adaptation may be beyond average due to the aggregation of illumination from the ambient light, reflection and glare from light sources reflecting off the mobile's screen, and the light emitted from the screen itself. The degree of adaptation is then used to calculate the response cones after they have adapted to the stimuli.

The second modification to the iCam06 model comes during the image attribute details adjustment. These image adjustments are responsible for predicting the Stevens and Hunt effects in the iCAM06 model. Neglecting the adjustments will preclude the image from displaying aspects of either effect. What we need is to increase the contrast and colorfulness to overcome any color bleaching that may occur from additional luminance. Then each pixel's color is then adjusted to compensate for additional contrast sensitivity to environmental lighting levels and mild amounts of glare on the screen. Since our eyes are continuously adapting to the changes in intensity of what we are looking at, this final color adjustment outside of the iCAM model can compensate for additional light reflected off the screen into our eyes.

The final RGB values calculated by the model, RGB_{final}, can sometimes be too different from the original color values RGB_{orig}. We bound this difference such that it never exceeds an error term, RGB_{error}. In other words, after the iCam06 model has completed its appearance calculations, we adjust RGB_{final} if:

$$RGB_{final} - RGB_{orig} > RGB_{error} \tag{9}$$

where,

$$RGB_{final} = W * RGB_{final} \tag{10}$$

Then a correction factor must be applied in order to keep the values from shifting beyond what is necessary for colorfulness preservation. Within the iCAM06 model there are two equations responsible for modifying the appearance of the color, they are listed as equations 11 and 12. The color channels listed in these equations (IPT) are a perceptual color space where the terms P and T roughly translate to red-green and blue-yellow respectively. The C value represents the chroma or color, and is where adjustments can be made to adapt the color. There is a luminance dependence that is incorporated into equations 3 and 4 represented by FL. The color adjustments we make beyond what the iCAM06 model is done during the IPT/Details adjustment phase from figure 5.

$$P = P\left[(F_L+1)^{.2}\left(\frac{1.29C^2 - .27C + .42}{C^2 - .31C + .42}\right)\right]B^{-1} \tag{11}$$

$$T = T\left[(F_L+1)^{.2}\left(\frac{1.29C^2 - .27C + .42}{C^2 - .31C + .42}\right)\right]B^{-1} \tag{12}$$

Where B is a bleaching factor similar to the version used in the Hunt color appearance model [5, 9]. The inverse will affectively reverses the bleaching caused by high luminance levels. The differences between this bleaching factor and one used in the Hunt model is that we use a value that is proportional to that of measured luminance factor L_s obtained from the mobile devices light sensor.

$$B = 10^7 / \left[10^7 + 5L_s(Y_w/100)\right] \tag{13}$$

6 Results

Figure 5 shows our results. In the images, our adjustments to the iCam06 model shows preservation of the colorfulness of the Macbeth color checker under above average environmental illumination. The left column of images is viewed in average (office) lighting, while the right column is viewed under bright sunlight. The top left image shows the original image and the top right shows the image under simulated outside ambient illumination, glare, and display brightness. The bottom left image is the over-compensated image viewed under average illumination neglecting extreme light and glare effects. The bottom right shows the image rendered under the aggregate of effects. Notice the change in colorfulness, the shift of the hues, and the loss of contrast from the image on the top right compared to the original image. Even though an increase in illumination is theoretically supposed to increase the contrast and colorfulness, the end result is that it does not. This is due to competing glare from the added environmental illumination and glare. To counter this problem we produce the over-colorful and over-contrasted image on the bottom left when rendered under the extreme environmental illumination will retain the original experience (bottom right).

Figure 6 shows similar results using an image of a cathedral as the input image. Figure 6 shows the results of rendering the original image on the left and the same image under a sunlight illuminant on the right.

7 CONCLUSION

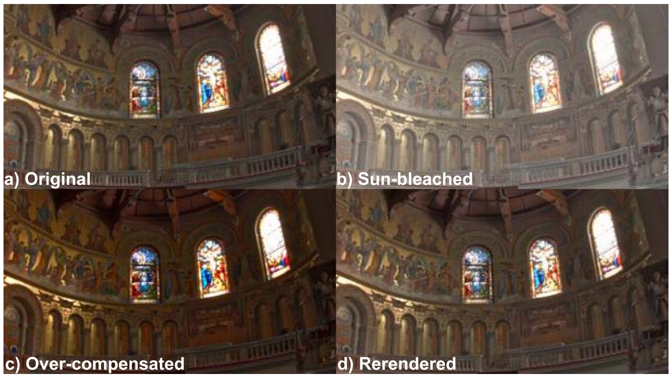

Figure 6: Our technique viewed under simulated bright daylight incident upon the screen. Top left is the original image. Top right is the original image under environmental ambient light and glare. Bottom left is the image viewed under low ambient light after over-compensating. Bottom right is the over compensated image viewed under high environmental ambient light and glare.

We have shown that current color appearance models lack the features to preserve color experience on mobile displays under extreme environmental lighting conditions. Previous techniques compensate for brightness levels but neglect the effects of environmental lighting on displayed colors. To fill this need we developed a technique that compensates dynamically for environmental factors to preserve the original image's rendered experience. Our work extends that of Akyz and Reinhard to add dynamic adaptation and to compensate for an aggregation of environmental illumination including ambient light, mild glare, and display emission. Without our color preservation technique, environmental lighting can modify the appearance of color and potentially change the way colors are perceived. Although our technique is proposed in the context of mobile displays, our technique can be used in wide variety of displays that have incorporated light-sensing technology to preserve color under varying illumination. Applications for our technique include mobile medical devices, devices that use color to convey information to heads-up-displays used in vehicles, and digital cameras.

CAMs provide the base functionality for preserving color but are not intended to counteract dynamically changes in color. Our modification of the iCAM06 model in our technique highlights the need for dynamic adaptation. In the future we would like to incorporate CAMs in real-time rendering applications that can account for perceptual changes in color in real-time. Also, we are currently planning extensive user studies to further validate our method under various conditions. We also feel that these techniques could be useful for other areas of mobile computing, such as Virtual and Augmented Reality and mobile games. We plan to adapt our methods to fit the rendering constraints of these domains.

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Figure 7: The result of our feedback mechanism for adapting the color appearance of an image. Top left is the original image viewed under normal lighting conditions. Top right is the image viewed with outdoor environmental illumination. Bottom right is the over-compensated image from our system. Bottom right is the re-rendered image.