# Post-Post-Modern Photography: Capture-Time Perceptual Matching For More Faithful Photographs

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**Figure 1:** *Photographs of the same cake taken under three different color-balance settings. Each makes the cake look like it has a different frosting (coffee, whipped cream, or buttercream), but which one is correct? From left to right: the original photo from a Nikon D50 camera, the photo with Photoshop "Auto Color" applied, and the photo adjusted to match the photographer's perception of the original scene (it was in fact buttercream). Best viewed on a high-quality color monitor.*

## Abstract

Perceived color and lightness are ephemeral qualities dependent on many psychological factors which are difficult to measure, yet photographers often know immediately from the preview image if the captured photograph does not match their perception of the scene. However, by the time the photographer processes the photograph at home this information has already been lost. We bring the user back into the loop at the time of capture by allowing them to quickly adjust color and lightness *in situ* to achieve a better match between the captured image and the perceived scene. To this end we present a simple image capture and editing system designed to assist photographers in obtaining more perceptually accurate representations of photographed scenes, as well as a psychophysical validation of our *in situ* method. User testing of our application in a variety of real-world lighting environments indicated a significant improvement in the validity of the captured image both within and across subjects.

**CR Categories:** I.4.1 [Computer Graphics]: Image Professing and Computer Vision—Digitization and Image Capture

**Keywords:** photography, image adjustment, perception

## 1 Introduction

The goal of a photographer is to capture a moment – a specific viewpoint of a particular location in time. In the early days of photography each captured image incurred a high penalty due to film and processing costs and therefore required a significant initial investment in calibration and set up. Typically a photographer would load a specific film speed (ISO) for the shooting environment (e.g., indoor/outdoor), then measure the scene using a light meter to determine exposure, possibly with a grey card hidden in a corner of the scene. Finally, after carefully adjusting the shutter speed, aperture, and focus, he or she would take a deep breath and press the shutter [Adams 1948].

Today's post-modern photography process is very different. Virtually limitless memory, ubiquitous high-quality displays, and rapid information transfer have reduced the cost of capturing and sharing photographs to almost nothing. Instead of shooting just one or two photos of a scene, the post-modern photographer typically takes many more photographs per scene often with minimal settings adjustments and with the intention of sorting and editing the images at a later date.

Although some aspects of the post-modern capture process are certainly convenient, it has its drawbacks. Perhaps most importantly, adjustments are performed later when the user is no longer present in the scene and he or she may not remember what the scene actually looked like. In many cases automatic algorithms such as auto-focus, auto-exposure, and auto-white balance have become sufficiently advanced so as to provide a good approximation of the scene. However, due to the variety of contributing perceptual factors that devices are unable to measure, the difference between the captured image and the perceived scene may still be significant. Figure 1 depicts three possible white balance parameters for this photograph of a raspberry cake. Although one might argue which of the three is most aesthetically pleasing, there is also the question of which one is actually closest to reality. Is the cake covered in coffee icing, buttercream frosting, or whipped cream? Furthermore, even if one might remember the type of frosting, is it possible to recreate the exact color after the fact?

Although a photographer's perception of a given scene may be difficult to ascertain through automatic methods, most capture devices are now paired with displays that provide instant feedback on the capture process. We propose to make use of this information by providing a post-post-modern capture process that brings the user back into the loop in real time and allows them to adjust the captured image so that it more accurately matches their perception of the scene.

We offer two novel contributions:

- A simple touch-based interface for perceptually grounded photo adjustments, allowing users to obtain a better representation of their view of the scene in just a few seconds.
- Verification that our *in situ* photo adjustment consistently produces more perceptually accurate results based on a user study conducted using real-world scenes and lighting environments.

# 2 Related work

Efforts to obtain accurate representations of human perception have largely fallen into two categories: automatic adjustment based on perceptual modeling and user-guided adjustment.

## 2.1 Perceptual modeling and automatic methods

Human perception of color and lightness is complex and dependent on many physiological and psychological factors. At the retinal level, light and dark adaptation and color adaptation due to rapid changes in viewing conditions may strongly influence perceived color and contrast [Norton et al. 2002; Jameson et al. 1979]. Additionally, under moderately low lighting conditions humans perceive a blue color cast known as the Purkinje effect [Shin et al. 2004]. These two effects have been modeled with some success by Pattanaik, et al. [2000] and Kirk & O'Brien [2011]. However, such models rely on ground truth knowledge of both scene luminance and the observer's adaptive state – neither of which are available under normal viewing conditions – and the difference between five seconds and twenty minutes of adaptation is likely to be significant [Rinner and Gegenfurtner 2000]. Neurological and perceptual effects in the visual cortex are even more difficult to measure and simulate. For example, related colors such as grey, black, navy, and brown appear dramatically different depending on their surroundings[Shevell 2003]. Although color constancy may help observers estimate the underlying reflective properties of objects under varying illumination, the degree to which constancy occurs is dependent on the color of the illuminant [Pearce et al. 2014], the complexity of the scene [Radonjić et al. 2015], and even the intention of the observer [Arend and Reeves 1986].

All of these perceptual phenomena are impossible for capture devices to measure, even in principle, without constant and sophisticated monitoring of the user. As a result, automatic methods have been largely unsuccessful at capturing the user's perception of the scene.

## 2.2 User-guided adjustment

An alternative route to perceptually accurate image capture is user-guided adjustment of photographs. Post-processing has been an important part of photography nearly since its inception. Film photographers extensively used *dodge* and *burn* techniques to adjust the relative brightness and contrast in their images both for artistic effect [Adams 1950] and as a way of compressing the dynamic range of the scene [Durand and Dorsey 2001]. More recently, digital photographers have been able to employ an almost limitless range of tools including white balance, saturation, brightness, contrast, gamma, shadows, and highlights adjustment, to name a few[1].

In our paper we specifically focus on real-time adjustment at the time of capture. There are a significant number of existing mobile photo adjustment applications on the market, although most are proprietary and very few have been accompanied by published papers detailing their methods or evaluating their performance. We found the applications we surveyed were lacking in usability either due to poor interfaces or a lack of integration with the capture process. Here we discuss just a few examples. Adobe Photoshop was recently ported to a mobile platform[2]. While it provides an impressive degree of control for a mobile device, the application is still completely divorced from the capture process and requires a significant amount of time and expertise to use. Apple's iOS 8 also includes a native photo adjustment application[3]. The application includes advanced controls for light and color, but we found the advanced interface to be extremely complicated and difficult to use. The linear mapping for color cast is also restrictive and there is no way to apply changes to future captures. The Olympus Color Creator[4] is the most similar to our application. The dial controls are somewhat more difficult to use than our touch based interface, and the inability to quickly switch between color and lightness adjustment is problematic. It is known that human color perception is non-linear with changes in luminance [Pointer et al. 1977], and in our study we found that users often interspersed color and lightness adjustments during the editing process.

In terms of published results, Lischinski, et al., [2006] also incorporated user feedback as part of an interactive, scribble-based tone mapping application. There are two important differences between their work and ours. First, they present a method for obtaining the most visually pleasing tone mapping result rather than an accurate one. Second, their method allows expert users to obtain a satisfactory result in a few minutes, whereas expert users of our application are able to obtain the final image in just a few seconds, and in less than a minute even for a novice. Based on research conducted at one camera manufacturer, users are typically only willing to invest approximately 10 seconds toward processing and sharing their captured images [citation removed for review]. Additionally, in the case of real-time *in-situ* image adjustment (capturing the colors of a beautiful sunset, for example), the difference between minutes and seconds makes all the difference.

# 3 Photo capture and adjustment interface

To enable *in situ* image editing, we created a user interface for white balance and lightness adjustment on a tablet computer (although our method could easily be implemented on any image capture device with a touchscreen display). We sought to smooth the initial learning curve for novice users by employing a touch-based interface that encourages exploration in the space of potential edits.

Our capture and editing processes are fully integrated. Both the captured image and the image preview may be edited, and after capture any further edits which are applied to the captured image are also propagated back to the image preview as a starting point for the next capture. We find that in static lighting environments the initial edits applied to the first capture serve as a relatively good estimate for the rest of the scene, requiring only minimal adjustment for subsequent captured images. This workflow is analogous to that of a professional photographer who might set the initial parameters for a given scene at the beginning of a shoot and perform slight adjustments as needed later on.

We also provide several standard image editing features. "Reset" returns to the default adjustment settings. "Undo" reverts the state of the image to that of the previous edit. "Save" allows the user to save the image (original and adjusted), and "Gallery" allows the user to open a saved image for editing.

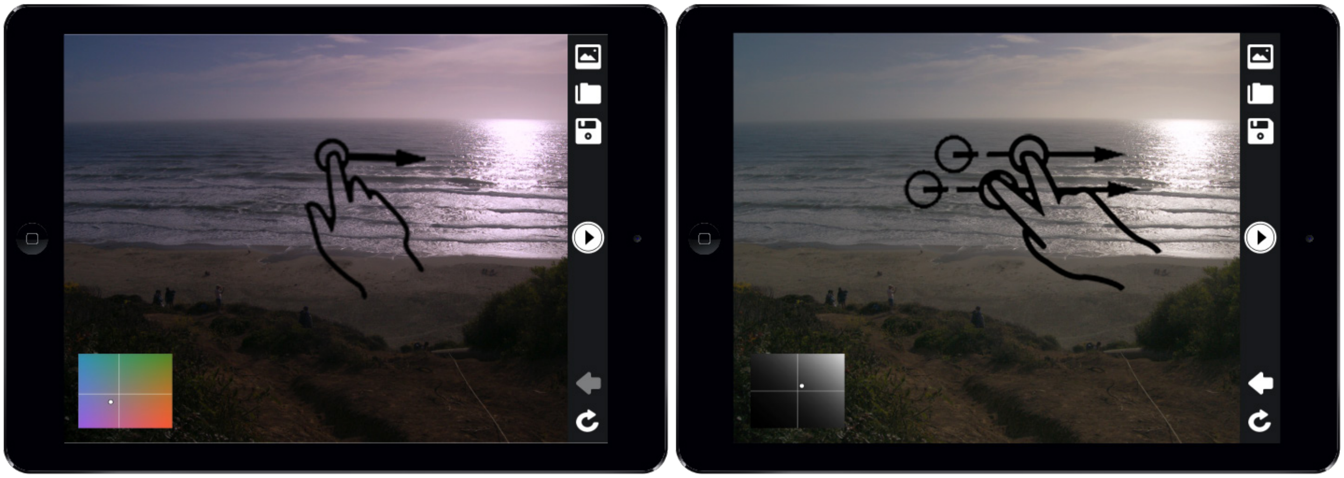
Due to the limitations of our device we used only low-dynamic-range (LDR) images in our study. Although we anticipate that high-dynamic-range (HDR) content would more accurately reflect human perception of HDR scenes, our user-based adjustment method should be viewed as dynamic range agnostic, able to use additional information when it is available.

[1] http://helpx.adobe.com/photoshop/using/color-adjustments.html

[2] http://www.techradar.com/us/reviews/pc-mac/software/graphics-and-media-software/image-editing-software/adobe-photoshop-touch-1031970/review

[3] https://www.apple.com/ios/whats-new/photos/

[4] http://robinwong.blogspot.ca/2013/09/olympus-om-d-e-m1-review-color-creator.html



**(a)** *color controls* **(b)** *luminance controls*

**Figure 2:** *White balance may be adjusted using one-finger scroll in any direction. Color tint is on the y axis, while color temperature is on the x axis. Luminance may be adjusted using two finger scroll in any direction. Overall gamma adjustment is on the y axis. On the x axis, leftward motion decreases highlight luminance, and rightward motion increases shadow luminance.*

### 3.1 Editing controls

A crucial aspect of our application is the design of the image adjustment interface. Editing is split into two modes: one-finger scroll for color and two-finger scroll for luminance (see Figure 2). The ability to rapidly switch between color and luminance adjustment offers an important advantage over previous designs. Human color perception is known to be non-linear with changes in luminance; as a result, luminance adjustments frequently require color adjustments and vice versa. Our method removes the need to press a button or navigate a menu to switch modes, so we find the gesture-based editor to be both faster and more intuitive for novice users.

Color may be adjusted using one-finger scroll, where the starting position is zero color adjustment and the degree of color adjustment is proportional to the distance from the start in any direction. The vertical and horizontal axes correspond to temperature and tint, respectively, as described in section 4. Movement along the cardinal axes results in pure temperature and tint adjustment, while intermediate positions combine both temperature and tint adjustment in proportion to the distance from the origin in each axis.

Luminance may be adjusted using two-finger scroll. The vertical axis is global luminance and the horizontal axis is local luminance (leftward motion makes highlights darker and rightward motion makes shadows lighter). Note that the horizontal axis configuration is only possible because we discard the ability to make highlights lighter or shadows darker, however these edits are typically not recommended because they are equivalent to clipping. Additionally, we treat darkening of highlights and lightening of shadows as opposite ends of a continuous spectrum such that it is impossible to do both simultaneously. This is similar to the way in which color temperature variation from blue to orange must pass through neutral white. Treating local luminance edits in this manner is consistent with our intention to only allow natural looking edits that mimic the behavior of the human visual system.

## 4 Adjustment filters

We use a total of four filters (temperature, tint, luminance, and highlights/shadows).

### 4.1 Color filters

Two independent controls are provided for color adjustment (i.e., white balance): temperature and tint. Our goal was to use color axes that best reflected the types of lighting environments users are most likely to encounter, temperature for natural illumination variation and tint for artificial illumination. Most natural illuminants are encompassed by the 40,000 K (blue) to 3,000 K (orange) range of correlated color temperatures along the Planckian Locus, a curve through CIE XYZ color space (see the black curved line in Figure 3a). The tint axis is the line perpendicular to the Planckian Locus in xy chromaticity space at the white point illuminant D65 (6500 K) as shown by the black diagonal line in Figure 3a. Tint corresponds roughly to the green-magenta axis, which accounts for many commonly found artificial illuminants. The white point illuminant D65 was chosen because it is both the CIE standard daylight illuminant and is also the standard white point for the sRGB color space common to most display devices.

To acheive perceptually uniform color adjustment parameters, we converted these color values to CIE $L^*\alpha^*\beta$ color space and calculated the increment between each tick mark as one just-noticeable-difference (JND) equal to the CIE76 energy value $E$ in the equation below [Sharma 2002].

$$E = \sqrt{(L_1^2 - L_2^2) + (\alpha_1^2 - \alpha_2^2) + (\beta_1^2 - \beta_2^2)} \qquad (1)$$

The resulting uniform temperature and tint axes are shown in Figures 3b and 3c. Since the axes are meant to be a color adjustment value, we scaled both temperature and tint by their respective values for the D65 white point such that the proportion for each color channel at the white point was equal to 1 and applied that proportion adjustment to the red, green, and blue channels respectively.

### 4.2 Luminance filter

There are several possible methods for adjusting the global luminance of an image. The three most common are exposure, brightness, and gamma. Here we discuss the relative merits of each and

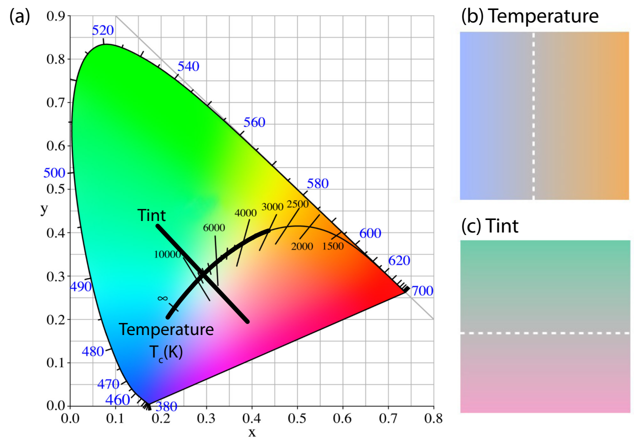



**Figure 3:** *Illustration of temperature and tint color adjustment axes. (a) The CIE 1931 Chromaticity diagram with the Planckian Locus shown by a thin black line (Figure adapted from image courtesy of Wikipedia user PAR). Bolded lines indicate the range of adjustments for temperature (curve) and tint (line) used in our method. (b) The RGB colors associated with traversing the temperature and tint axes in a perceptually uniform manner. The D65 white point is shown as a dotted white line in each image.*

why we ultimately chose to use gamma as our overall luminance adjustment.

**Exposure** is the range of luminance values that are displayed in an image. An under-exposed image will only contain pixels with luminance values in the mid to low range, while an over-exposed image will only contain pixels with luminance values in the mid to high range. Ideal exposure generally means that the image uses the entire range between zero and one, but without clipping any pixels on either end. Post-capture exposure adjustment typically refers to adjusting the black point or white point (the luminance value limits outside of which pixels are clipped to black or white). On mobile capture devices such as an iPad the exposure value is usually automatically selected given the overall luminance of the scene (and occasionally also based on user input). Because the automatic exposure settings are often quite accurate and the low dynamic range of the camera sensor usually causes clipping on one or both ends of the luminance spectrum, it is not generally advantageous to adjust the exposure in post-processing.

**Brightness** is the average luminance of an image. Brightness adjustment is usually equivalent to multiplying each pixel in the image by a constant value (although in some cases the terminology can be switched, e.g. the “Brightness” adjustment in iOS seems to actually be gamma). Although brightness adjustment preserves relative luminance differences within the dynamic range of the image, changes in brightness usually result in clipping on one end of the luminance spectrum, effectively compressing the dynamic range of the image even further.

**Gamma** is a non-linear tone mapping that expands the relative difference between one range of pixels (usually shadows) while compressing another range (usually highlights) according to a gamma curve. The formula for gamma adjustment is $p^{\gamma}$ where $p$ is the pixel luminance value [Shirley and Marschner 2009]. A gamma value of 1 therefore corresponds to a linear mapping with no gamma adjustment, while a gamma value greater than 1 compresses highlights and a gamma value less than one compresses shadows. The benefit of using gamma as an overall luminance adjustment is the fact that

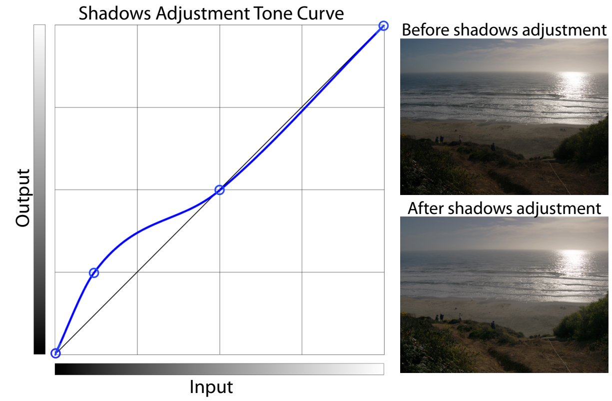



**Figure 4:** *Lightening shadows is done by applying a tone curve which increases the lower pixel values.*

the black and white points remain stationary and only the median luminance is adjusted. This allows the appearance of overall luminance changes without any clipping or dynamic range compression.

### 4.3 Local luminance adjustment

In addition to global color and luminance adjustments, we also provide local luminance adjustment to shadows and highlights. For lightening shadows, the adjustments are made on a per-channel basis using a tone curve (inspired by standard curve editing operations in Adobe Photoshop and Gimp) such that shadows are those values lower than 0.5 and highlights are those values above 0.5. We found that contrast was best preserved by gamma adjustment. We defined three fixed points on the tone curve $(0.0, 0.0)$, $(0.5, 0.5)$, and $(1.0, 1.0)$ and used a variable point beginning at $(0.25, 0.25)$ adjusted linearly to $(0.1, 0.25)$ depending on the user input. The shape of the resulting curve is interpolated using a monotonic spline (See figure 4), which provides a smooth transition between shadow and highlight values while keeping the highlights nearly the same.

Highlights adjustments were made on a per-pixel basis only to those pixels with luminance values above 0.5. Luminance was calculated using a perceptually accurate weighting of the RGB values [Anderson et al. 1996], shown here:

$$L = 0.21 \cdot R + 0.72 \cdot G + 0.07 \cdot B \tag{2}$$

We found that the best results were obtained by multiplying each pixel by a scalar value between one and the maximum highlight brightness. In other words, pixels with a luminance value equal to 0.5 were multiplied by a highlight adjustment value of 1 and remained unchanged, while pixels with a maximum luminance value of 1 were multiplied by a highlight adjustment value based on the user’s input. We set the range of the highlight adjustment to a maximum of 1 (no change) and a minimum of 0.6 (so that the brightest pixels would still remain the brightest.

## 5 Qualitative results

A few examples of the qualitative results achieved using our method during the user study are provided in Figure 5. Each row illustrates several adjustment parameters for a particular scene. The first column shows the original captured images with a “grey world” white balance applied. The second column shows the “white-point” white

**(a)** *Grey world white balance* **(b)** *Original image (white-point white balance)* **(c)** *Perceptually matched user-adjusted image*

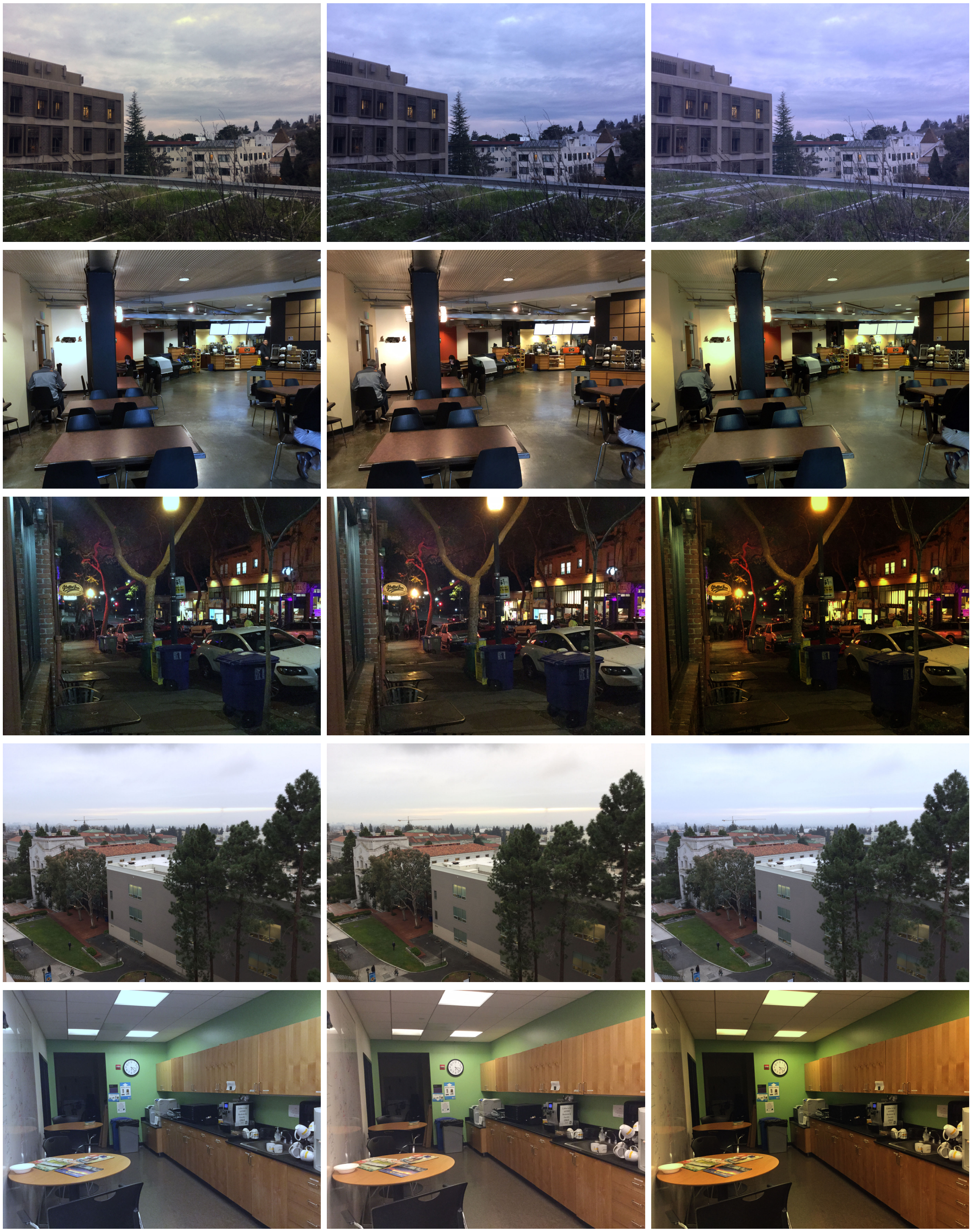
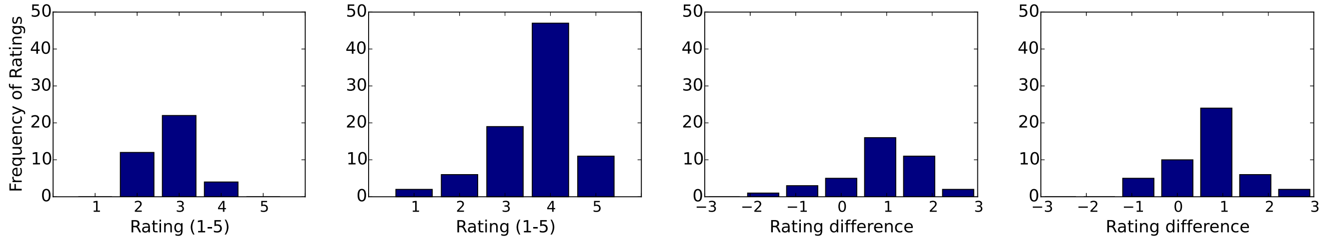


**Figure 5:** *Qualitative results from the perceptual user study. Each row illustrates several adjustment parameters for a particular scene. (a) The left column shows the original images with a "grey world" white balance applied. (b) The middle column shows the "white-point" white balanced images (equivalent to the original images). (c) The right column shows the images resulting from perceptual matching adjustments made by the user.*




**(a)** *Original overall ratings* **(b)** *User-edited overall ratings* **(c)** *Self-rating - original rating* **(d)** *Cross-rating - original rating*

**Figure 6:** *Results of the perceptual user study. Overall average rating (out of 5) for (a) original images was 2.78 $\pm$ 0.622, while overall average for (b) user-edited images (of which there are two for each original) was 3.69 $\pm$ 0.873. A significant difference was found between original ratings and corresponding (c) self-ratings, and (d) cross-ratings, with an average rating change of +1.02 and +0.79, respectively.*

balanced images (which are equivalent to the original captured images due to the default white balance settings on the device). The white-point and grey world methods were derived from Bianco, et al. [2007]. Finally, the third column shows the resulting images from our perceptual matching study.

## 6 Perceptual user study

Quantifying the degree to which an image matches a given scene is a difficult task. Although many psychophysical methods for color matching exist, we found that these designs precluded testing in real-world scenes with uncontrolled lighting environments. We decided instead to use a rating task to assess users' subjective experience. Subjects were asked to rate how well each image matched their perception of the scene on a 5-point scale, where a rating of 1 indicated that none of the colors in the captured image were a good match, and 5 indicated that all of the colors in the captured image were a good match. Due to the limited dynamic range of the device, we asked subjects to primarily focus on the hue and saturation of the colors and only rate the lightness for the unclipped areas in the image. Subjects were unaware of each others' ratings throughout the experiment. The experiment was repeated with 24 subjects in 12 different scenes (3 outdoor, 9 indoor).

Because most automatic algorithms are able to successfully capture the apparent color and lightness of a scene illuminated by diffuse, wide-spectrum lighting (such as an overcast sky), we expect our method to be most useful under highly directional and narrow-band lighting (such as sunsets and many indoor lighting environments). We first sought to establish whether a particular scene was an appropriate use case for our application by asking subjects to rate the degree to which the original captured image matched their perception. The distribution of ratings is shown in Figure 6a. The overall average rating for the original images was $2.78 \pm 0.622$ (out of 5), indicating that – at least for the 12 scenes tested – most of the colors in the captured image were at least somewhat wrong most of the time. Several subjects also reported great surprise at the degree to which the original captured image did not match their perception of the scene. These results demonstrate that current automatic methods leave something to be desired with regards to matching human perception.

Second, we sought to determine how accurately subjects were able to capture their perception of the scene with our interface. Each subject was provided a brief (5 second) tour of the controls and encouraged to explore the adjustment space as needed. Subjects were then asked to adjust the captured image to best match their impression of the scene under the current lighting environment. On the first trial subjects typically spent between 10 and 30 seconds obtaining an image. On subsequent trials the adjustment time ranged between 2 and 15 seconds depending on the complexity of the scene and the experience of the user. Once the subject had obtained a satisfactory image, he or she was asked to rate the degree to which their new image matched the scene using the same scale as for the original image. Across scenes we found a significant difference for "self" ratings compared to the corresponding original image ratings; repeated measures t-test, $t = 5.738, p < 0.0001$. On average, self ratings increased by 1.02 (on a 5-point scale) for the edited images. The overall distribution of rating changes (edited minus original) is shown in Figure 6c.

Next we asked subjects to complete a forced choice task and a cross-subject rating task to ascertain the level of agreement between subjects. Each of the other non-editing observers were presented with a set of three images in random order and asked to select the image which best matched their perception of the scene. The three choices included grey world, white-point/original, and user adjusted images, as illustrated in Figure 5. After selecting the best match, each subject was then asked to rate the user-edited image on the same 5-point scale (a "cross" subject rating). We found a significant difference for cross subject ratings across scenes as compared to their corresponding original image ratings; repeated measures t-test, $t = 5.656, p < 0.0001$. On average, cross ratings increased by 0.79 (on a 5-point scale) for the edited images. The overall distribution of rating changes (edited minus original) is shown in Figure 6d.

Finally, the original editor was also asked to choose the best match amongst the three choices (including their edited image), which enabled us to further gauge whether the user was happy with their edits. Subjects then reversed roles, each taking turns editing the original to match their perception of the scene and judging their fellow observer's edits. The overall average rating for all user-adjusted images was $3.69 \pm 0.873$ (out of 5). (Note that there are two user-adjusted images per original.) The distribution of ratings for user-adjusted images is shown in Figure 6b. No significant difference was found between the overall distributions of self ratings versus the overall distribution of cross ratings, $t = 1.157, p = 0.25$, suggesting that users generally agreed on the appearance of the scene and did not rate their own images preferentially.

However, sometimes users were unable to obtain a better match than the original image. In the forced choice task $15\%$ of editors selected the original image as the best match and $31\%$ percent of non-editors selected the original image as the best match (none of the subjects selected the "grey world" image). In trials where editors did not select their own image, the average rating for the original scene was 2.9. Since the mean rating for the original in these cases is within a standard deviation of the overall average, we conclude that the adjustment parameters that we provided were insufficient to produce the correct image. Additionally, although a majority of non-editors selected the edited image as the best match, the discrepancy between editor and non-editor satisfaction may indicate some disagreement regarding scene appearance.

## 7 Limitations

There are two perceptual caveats regarding the usefulness of our *in situ* technique. First, user-directed adjustments are only as good as the observations of the user, and we therefore expect variability in the quality of the perceptual matches obtained. However, we also expect that the pickiest users will be the best observers and provide the most useful input to the perceptual matching process. Second, we are only able to determine whether the adjusted image is a good match under the capture-time illumination; subsequently viewing the image under a different lighting environment may not evoke the same perceptual response. It is possible that the emissive properties of the display and color constancy may help provide continuity under various lighting conditions (we performed several *ad hoc* experiments which indicated this seems to be at least partially the case). However, since slow adaptation effects prohibit rapidly switching between multiple lighting environments, it is difficult to determine to what degree the image still resembles the user's perception of the original scene without relying on memory.

Our ability to achieve an accurate perceptual match is also limited by the dynamic range and color gamut of the display device. The variety of colors and luminances that one might encounter in the world is far greater than the number we are currently able to display. Even so, there is also evidence to suggest that clipped LDR images are able to provide a good approximation of our perception of HDR scenes [Čadík et al. 2008].

## 8 Conclusion and Future Work

In this paper we presented a new method for photo capture and editing that allows the user greater control in achieving perceptually accurate photographs. By interactively adjusting color temperature and tint, overall lightness, and shadows/highlights lightness, users are able to quickly edit the captured image to match their perception of the scene in situ at the time of capture. This method produced more perceptually valid images in a large majority of the cases we tested, as demonstrated by our user study. Additionally, we believe the interface and validation procedure we presented provides a useful framework for further research into the perceptual matching of real world scenes.

We anticipate a wide variety of potential use cases for our application, including amateur and professional photography on both mobile and digital cameras, as well as product and real estate photography. Additionally, by collecting and analyzing a large volume of data regarding the edits that users make in a wide variety of scenes, we hope to produce better automatic white balance and lightness correction in the future.

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