Sensing Ambient Light for User Experience-Oriented Color Scheme Adaptation on Smartphone Displays

Jiadi Yu, Jiaming Zhao
Department of Computer Science and Engineering
Shanghai Jiao Tong University
{jiadiyu, jmzhao}@sjtu.edu.cn

Yingying Chen
Department of Electrical and Computer Engineering
Stevens Institute of Technology
yingying.chen@stevens.edu

Jie Yang
Department of Computer Science
Florida State University
jie.yang@cs.fsu.edu

ABSTRACT

With the rapid development of information technology, mobile devices have exhibited increasing popularity in recent years. To support the anytime-anywhere service model of mobile devices, one important problem related to the screen display arises when using these devices (e.g., smartphone and tablet) under various lighting conditions. On one hand, it is hard for users to see the display clearly under strong lighting conditions (e.g., sunlight). On the other hand, the screen appears dazzling under weak lighting conditions. This problem related to the mobile device display can significantly degrade user experience and undermine the successful deployment of the anytime-anywhere mobile service model. Existing solutions mainly focus on the automatic adjustment of brightness level under different light conditions. We show that merely utilizing brightness level to solve the display problem is not enough to maintain the user experience under both strong and weak lighting scenarios through experimenting with over 200 volunteers. In this work, we take a different approach by investigating automatic color scheme adjustment to improve user experience. We find that *Readability*, *Comfort level* and *Similarity* are major factors that contribute to user experience. In recognizing these problems, we propose a system, ColorVert, which utilizes the DKL color space to adaptively transform color schemes by sensing ambient light to improve user experience under various lighting scenarios. Our experimental evaluation with over 200 precipitants and various mobile devices demonstrates that ColorVert is more effective in both maintaining as well as improving user experience compared with the existing automatic brightness adjustment system.

Categories and Subject Descriptors

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General Terms

Design, Experimentation, Human Factors

Keywords

Smartphone display; color scheme; user experience; sensing ambient light

1. INTRODUCTION

Mobile devices such as smartphones and tablets have received increasing popularity over the recent years and blended into our daily lives. In particular, equipped with high resolution screens and various web browsers, modern mobile devices have become one of the major sources for web surfing. According to the survey on the Internet, 250 million smartphones were sold in the 3rd quarter of 2013 alone[1]. Compared with traditional desktops or laptops, one important problem related to the screen display is surfaced when using these devices under different lighting conditions for supporting the anytime-anywhere mobile service model. That is, the user experience of screen reading is strongly associated with ambient environments, among them the most important factor is the lighting conditions. On one hand, under strong lighting conditions (e.g., sunlight), some text colors are washed off by the strong light and become undistinguishable from the background color, rendering unreadability. On the other hand, the dazzling screen often makes our eyes uncomfortable at night. Thus, to ensure the successful deployment of the anytime-anywhere mobile service model, it is highly desirable to develop a scheme that can adaptively adjust the way the screen displays the content based on the dynamic ambient environments.

Existing studies on improving smartphone user experience under different light conditions mostly focus on the adjustment of the brightness level. For example, Android and iOS have automatic brightness adjustment system, which can change the brightness level of the screen according to the light strength. And there are subsequent studies to improve such systems by capturing more precise light strength [2]. However, these solutions are far from satisfactory as users remain suffering under both strong and weak lighting conditions even if the highest brightness level is applied. Thus, merely adjusting the brightness level of the device screen cannot solve the problem completely. In this paper, we take a different viewpoint by developing adaptive color scheme adjustment to maintain and improve user experience under different light conditions. Although there exist some work to improve user experience by adjusting color saturation of images and videos[3] or enhancing image contrast[4, 5] according to ambient light, it is hard for these solutions to achieve the high readability for texts under different light conditions. Most of the studies related to color scheme transformation [6] [7], however, only focus on the energy consumption of different color schemes rather than the user experience.

Since 84% of users utilize their smartphones for web surfing[8], we focus our study on web browsers. Although the user experience of mobile devices has gained much attention, existing work has not concerned the impact of the webpage color scheme to user experience. We first set out to investigate the main factors that contribute to user experience when using smartphones. Through an extensive study of over 200 volunteers and the analysis of webpage color schemes, we find that the user experience is mainly determined by *Readability, Comfort level* and *Similarity between the transformed color scheme and the original one*. We further propose ColorVert, which improves user experience by adaptively adjusting the color scheme of web pages based on sensed ambient light under dynamic environments. Specifically, ColorVert applies a novel color transformation algorithm to calculate the optimal color scheme under both strong (e.g., direct strong sunlight) as well as weak lighting conditions based on ambient light sensing. Our prototype implementation of ColorVert on Android-based smartphones and tablets verifies the feasibility of using ColorVert in real environments. Based on the feedback from over 200 volunteers, our system could effectively improve user experience compared with the existing brightness adjustment system. Although our work only focuses on dealing with web browsers, we believe the proposed color transform adaptation approach could be easily extended to handle other smartphone tasks using screen displays.

We highlight our main contributions as follows:

- We empirically investigate the impact factors on user experience when using mobile device under different lighting conditions with over 200 volunteers. The important finding is that the user experience is mainly determined by the readability, comfort level and similarity between the transformed color scheme and the original one.
- We develop a dynamic color scheme adaptation system for smartphone web browsers, namely ColorVert, which can adaptively transform color scheme of webpages to maintain and improve user experience through sensing ambient environments.
- We implement ColorVert on four types of Android devices including smartphones and tablets with different screen sizes. Our prototype of ColorVert shows that our system is light weight and is feasible to use in real-world scenarios.
- We conduct extensive experiments with over 200 volunteers to evaluate the performance of ColorVert. The results of users' feedback confirm that our ColorVert system is effective in improving user experience under both strong and weak lighting conditions.

The rest of this paper is organized as follows. We give an in-depth motivation study in Section 2. Section 3 and Section 4 presents the design details and color transformation algorithm of the ColorVert system respectively. In Section 5, we evaluate the performance of ColorVert and analyze the results. Related work is reviewed in Section 6. Finally, we give conclusive remarks in Section 7.

2. MOTIVATION STUDY

We first provide the background on readability and comfort level of the smartphone screen. Then through the investigation of the existing automatic brightness adjustment system on smartphones and the color scheme of webpages, we find the reason of user experience degradation under both strong and weak lighting conditions. Finally, from the results of user preference survey, we discover main factors that affect user experience.

2.1 Preliminaries

We first introduce the background of the smartphone screen readability and comfort level.

2.1.1 The measurement of Readability

Photometry is the science about the measurement of visible light in terms of its perceived brightness to human vision. The most important physical quantity given in photometry is luminance[9]. Luminance(cd/m^2) describes the amount of light passes through a particular area with a given angle.

Given the smartphone is equipped with OLED displays, there is an effective way to calculate the luminance of screen. Since OLED consists of three kinds of light emitting diode, the total spectral power distribution is the addition of those light sources, specified by an (R,G,B) tuple in the RGB color space. We can first calculate the relative luminance [9][10] of a color, defined as $Y = 0.2126R + 0.7152G + 0.0722B$, where Y is the relative luminance, with its value normalized to 1 for a given white point (when R=G=B=1). We can observe from the formula that green light contributes the most to the luminance, while blue light contributes the least.

Further, we are not only concerning about the luminance of a certain object, but also its luminance difference compared with another object, i.e. the Luminance Contrast:

$$Contrast\% = \frac{|L_1 - L_2|}{max(L_1, L_2)} \cdot 100\%, \tag{1}$$

where L_1 and L_2 are the respective luminance of the objects.

Based on the above information, Relative Visual Performance (RVP) model is introduced to measure the readability[11][12]. It is measured by the speed and accuracy with which a visual task is performed. Specifically, RVP is measured using Reaction Time (RT) which defines as the interval between the onset of the stimulus and the response by humans. Human can reach different RT values given a set of different characteristics of the stimulus. RVP is formally defined by:

$$RVP\% = \frac{RT_0}{RT} \cdot 100\%, \tag{2}$$

where RT_0 is the smallest reaction time a person can achieve, given the best lighting condition and stimulus characteristics. RT is the reaction time of a certain condition. A bigger RVP value indicates we spend less time to get the information of the stimulus and results in a better readability condition, whereas a smaller RVP value means less readability. Usually, a RVP value greater than 80% implies good readability [13][14][11].

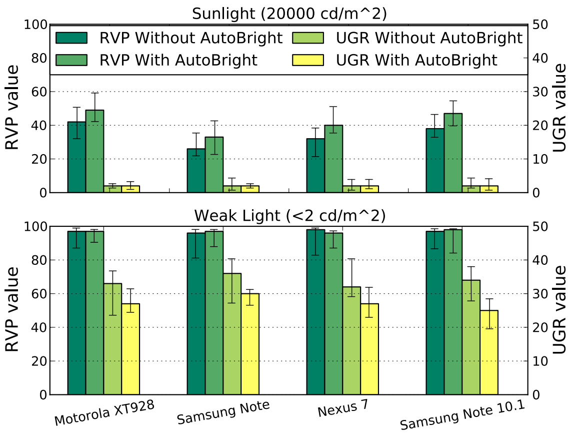


Figure 1: Influence of automatic brightness control on RVP and UGR.

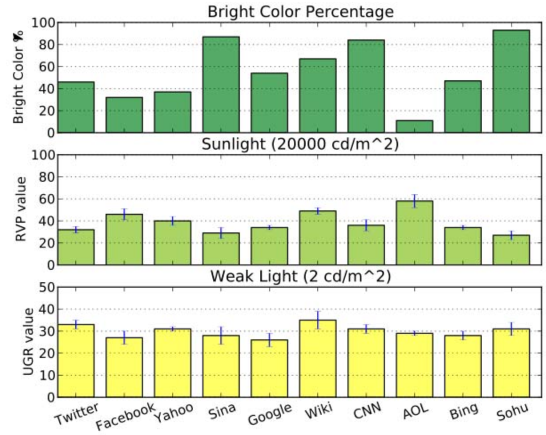


Figure 2: Bright color ratio, RVP and UGR value of different webpages.

2.1.2 The measurement of Comfort Level

When the difference of luminance level between the target and the environment becomes too large, our eyes feel uncomfortable when looking at a target. To evaluate the comfort level, we use the standard metric provided by International Commission on Illumination, the Unified Glare Rating (UGR)[15][16].

$$UGR = 8log\frac{0.25}{L_b}\sum_n(\frac{L_n^2\omega_n}{p_n^2}), \quad (3)$$

where L_b is the ambient luminance, L_n is the luminance of each light source n, ω_n is the solid angle of the light source seen from the observer and p_n is the Guth position index, which depends on the distance from the line of sight of the viewer. By using the UGR, we could analyze the impact of the light emitted by the screen of the smartphone on our eyes. Normally, the standard office lighting has $UGR \leq 19$. A UGR value larger than 25 may make our eyes uncomfortable[15].

2.2 Investigating Existing Automatic Brightness Adjustment System

Since we cannot see the screen clearly under strong lighting conditions and feel the screen is too dazzling at night, many smartphone operating systems (Android and iOS for example) perform automatic brightness control, which dynamically adjusts the smartphone brightness level based on the ambient light strength. In this section, we show that the automatic brightness adjustment system has limited improvement on user experience under strong and weak lighting conditions.

Table 1: The details about the volunteers.

Sex	Age	Under Sunlight	Under Night	Total
Male	20-30	32	21	99
	30-50	25	12	
	over 50	6	3	
Female	20-30	40	21	107
	30-50	18	17	
	over 50	7	4	
Total		128	78	206

2.2.1 User Experience under Strong Lighting Condition

Since the strong light reflected by the smartphone screen can decrease the luminance contrast and wash off the color of texts, it is often hard for us to see the words clearly. As existing work employs automatic brightness adjustment system to improve user experience, we investigate its effectiveness under direct strong light (sunlight) of $20000cd/m^2$ with four kinds of mobile devices: Motorola XT928 with a 4.5' screen, Samsung Galaxy Note with a 5.3' screen, Nexus7 with a 7' screen and Galaxy Note with a 10.1' screen. We implement the tool Psychopy[17] on smartphones to set up experiments to measure the RVP and UGR value of webpages. For Samsung Galaxy Note smartphones, besides automatic brightness adjustment system, we also apply the adapt display mode [3] on our experiments, which is able to automatically adjust color saturation according to ambient light.

To measure RVP value via the Equation 2, the smallest reaction time (RT_0) can be calculated from the formula in [11][12]. For Reaction Time (RT), we do experiments the similar as [11][12]. We recruit 206 volunteers of different ages randomly on college campus. For 128 of them, smartphones are placed under direct sunlight with ambient luminance around $20000cd/m^2$ measured by light sensor. For the other people, smartphones are placed at night where ambient luminance is less than $2cd/m^2$. The details about the volunteers is shown on Table.1. During each trial in the experiment, a webpage is displayed on the screen of smartphones, after a brief, random time delay, and each volunteer is asked to touch the screen as soon as they detect the newly displayed webpage. The time between webpage onset and response is recorded as the RT for that trial. The webpages are selected from the sites most frequently visited by users. After the experiment, each volunteer has a block of RTs for all displayed webpages, and then we are able to calculate their RVP values for the webpages. Moreover, the UGR value of each displayed webpage can be calculated from the Equation 3 according to [15][16].

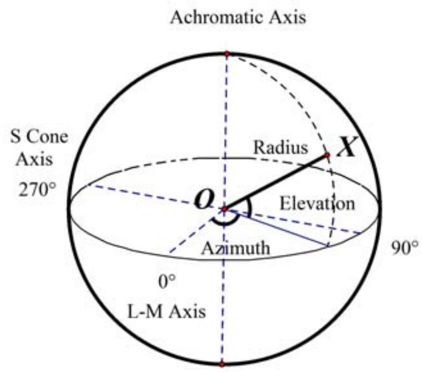


Figure 3: DKL Color Space.

The results are shown in the upper half of Fig.1. From the figure, we can see that, under strong lighting condition, although the UGR value is low enough to keep a good comfort level, the automatic brightness adjustment system only slightly improve the RVP value, which is still too low to achieve a satisfactory readability level (i.e., the RVP value is much less than 80%). The adapt display mode of Samsung Galaxy Note do not much contribute to improve readability level for webpages.

2.2.2 *User Experience under Weak Lighting Condition*

When ambient light strength is weak, as the ambient luminance L_b in Equation 3 decreases, the UGR value increases sharply. A large UGR value would degrade the comfort level for reading. Although the automatic brightness adjustment system could reduce the luminance level of the screen, the results are still far from satisfactory. We perform similar experiments when the ambient light strength is low. From the experiment results shown in the bottom half of Fig.1, the UGR value is still very large (i.e., UGR >19), which results in low comfort level. Moreover, under weak lighting condition, the RVP value is high enough for good readability.

The reason of the large UGR value is that most of the webpages use white or other bright colors as background. Even though the overall luminance level of the screen is reduced, a bright background color still keeps L_n at a high level, which results in low comfort level.

2.3 Studying the Relationship between Color Schemes and User Experience

Since existing brightness adjustment system is not good enough to satisfy user, we study another aspect, *color scheme*, which has significant impact on user experience. In order to understand the relationship between color schemes and user experience, we conduct a survey on the color schemes of some popular webpages. We randomly select 1000 webpages from popular websites such as Google, CNN, etc. It is noticed that most webpages use bright colors in many places in order to attract the attention of user. According to our survey results in Fig.2, 84% of the words on the CNN are light grey and blue, 54% of the words on Google search results page are sky blue and red. Because a lot of webpages utilize bright color scheme, their readability or comfort level are seriously undermined under both strong or weak lighting conditions.

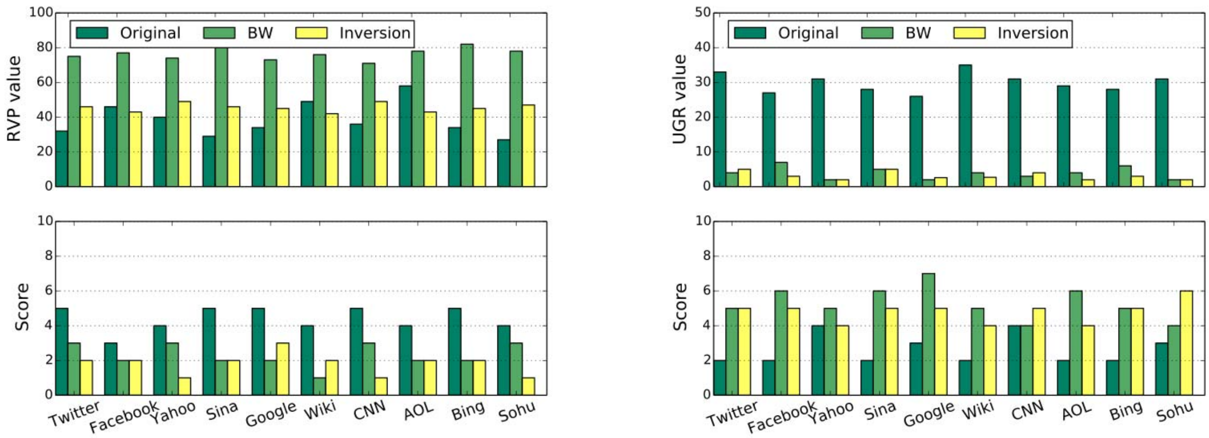
On one hand, under strong lighting conditions, the bright color on the webpages results in the low RVP value. As is shown in the middle part of Fig.2, for most webpages under study, RVP values are under 40%, whereas good readability has RVP value larger than 80%. To fully understand the impact of color on user experience, we introduce the DKL (Derrington, Krauskopf and Lennie) color space[18], which is based on the Macleod and Boynton chromaticity diagram. The DKL color space is shown in Fig.3. DKL uses three axis to describe the color space: S-cone axis, L-M axis, and achromatic axis. For any given plane that is perpendicular to the achromatic axis, all colors on the plane have the same luminance value, i.e., luminance contrast is zero. The biggest plane which intersect the achromatic axis at center is called Isoluminant Plane. Every color is represented in the 3-dimensional space, i.e., (α,h,r), using spherical coordinates that specify the elevation(α) from the isoluminant plane, the azimuth(h) that stands for the hue, and the radius(r) that is the fraction of the maximal modulations along the cardinal axes of the space. By using the DKL color space, we can easily distinguish the luminance effect from the color effect. It is thus convenient for us to analyze the effect of colors on user experience. For a bright color scheme, both foreground and background colors are located in the upper half of the DKL sphere, whose contrast is low, resulting in a low RVP value (i.e., poor readability).

On the other hand, under weak lighting conditions, the bright colors on the webpages cause the high value of UGR, which degrade the comfort level when reading. Our experiment about the bright colors' influence on comfort level is shown in the bottom part of Fig.2. The UGR value is measured when the ambient luminance is less than $2cd/m^2$. It can be seen that for most of the bright colors, UGR value is around 30, which is larger than level of comfortable reading. The reason of the large UGR value is that bright colors keep L_n in Equation 3 at a high level.

2.4 User Preference Investigation

From our above analysis, the existing automatic brightness adjustment system is far from satisfaction of user experience under both strong and weak lighting conditions. Meanwhile, we find user experience has a strong relationship with color schemes. We thus can transform the color scheme of webpages to achieve a better user experience. In the study, the 206 volunteers mentioned in Section 2.2 are shown the same static webpages on smartphones with a series of color schemes. For 128 of them, smartphones are placed under direct sunlight with ambient luminance around $20000cd/m^2$ measured by light sensor. For the other people, smartphones are placed at night where ambient luminance is less than $2cd/m^2$. The volunteers are asked to score each web page by 1 to 10 with our grading system, in which the level one indicates that the color scheme results in the lowest user experience and the level increases as the user experience improves. We select webpages from the sites most frequently viewed by user, and for each webpage we present 3 color schemes:

- **Original**, remain the original color scheme of webpages with existing automatic brightness adjustment system.
- **Inversion**, replace all colors with their inversion color. Since most of the webpages use bright colors for back-



(a) strong light (b) weak light

Figure 4: User preference of different color schemes.

ground and foregrounds, use inversion can increase RVP value and decrease UGR value.

- **Black-White**, for Black-White color scheme. Under strong lighting condition, the RVP value can reach the maximum when we use white for background and black for foreground. Under weak lighting condition, the UGR value can be significantly decreased when we use black for background and white for words.

All transformations are applied to foregrounds and background. The average scoring results and the RVP value under strong ambient light are shown in Fig.4(a), whereas the average scoring results and UGR value under weak ambient light are shown in Fig.4(b). From the scores given by users, we obtain important user feedbacks. Under strong lighting conditions, the Original and Inversion color schemes cannot meet users' requirement on readability, i.e., RVP values are low. Although the Black-White scheme can achieve the highest RVP value among those transformation methods, the scores given by users are very low. This is because a Black-White scheme is dull to users. Therefore, a high RVP value alone can not satisfy users. Moreover, although RVP values are low for the original color scheme, users give a relative high preference score for it. The reason is that users are used to the original color scheme of a webpage and if the color scheme is not similar to the original one, users may feel the webpage is strange and unsatisfactory. Thus, users prefer the webpage to be similar to the original one. Under weak lighting conditions, users prefer the color scheme with a lower UGR value, like Black-White or Inversion color scheme. This is because a lower UGR value means a better comfort level, which contributes to user experience improvement.

According to the analysis above, we find that the automatic brightness adjustment system is not satisfactory and color schemes have significant impact on user experience. User experience thus can be improved by transforming color schemes. In particular, we notice that user prefer color schemes with a high RVP value under strong lighting condition and a low UGR value under weak lighting condition. In addition, users prefer color schemes which are similar to the original one.

3. COLORVERT DESIGN

In order to build an efficient color scheme adaptation system, we devise a new system, ColorVert, that improves user experience by dynamically adjusting the color scheme of webpages based on the light strength sensed at the light sensor on smartphones. The workflow of ColorVert is shown in Fig.5. There are three major units in our system: *Dynamic Sensing Unit*, *Transforming Unit*, *Execution Unit*. Firstly, a Sensing Unit senses the changes of ambient light strength. When ColorVert captures the change of light strength, it will trigger the Transforming Unit where the optimal color scheme for the present webpage will be calculated. Secondly, Transforming Unit gathers useful information about the webpage such as font size and colors from the web browser engine. Based on ambient light strength and the webpage information, the Color Transformation Algorithm is employed to generate the best substitute color for both the background and foregrounds of the webpage. Finally, the Executing Unit receives the output of the algorithm and applies the new color scheme to display on the smartphone screen.

Dynamic Sensing: ColorVert can sense ambient environments and calculate the optimal color transformation scheme accordingly. Light sensor in smartphones can sense light events, which happens when ambient light strength has significant change. When ColorVert captures the change of light strength, it will trigger the Transforming Unit where the optimal color scheme for the present webpage will be calculated. Since the light strength change leads to the change of RVP and UGR value, it is possible that readability and comfort level are degraded. ColorVert thus needs to calculate the optimal color scheme once the change of light strength happens.

Transforming: After ColorVert senses ambient environments, the Transforming Unit first collects information from both the light sensor and the web browser, such as the ambient light strength, original color scheme and font size of the webpage. Based on the collected information, ColorVert

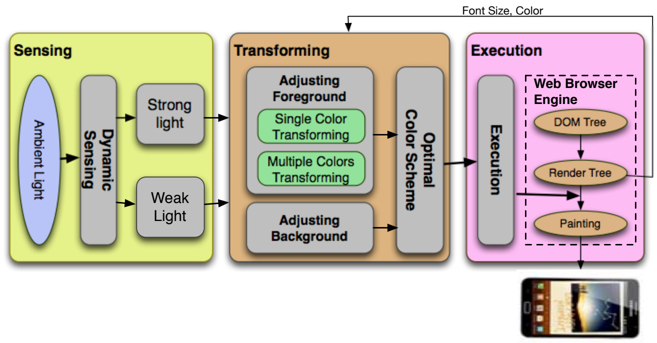


Figure 5: ColorVert design model.

employs Color Transforming Algorithm to calculate the optimal color scheme for foreground and background respectively. Considering the contrast between foreground and background color of webpages, the algorithm calculates the optimal color scheme of foreground and background respectively. Specifically, the color scheme transforming algorithm considers user readability, the comfort level and the similarity between transformed color scheme and original color scheme. The calculated optimal color scheme thus can significantly improve user experience. The detailed algorithm is introduced in Section 4.

Execution: The final step is to apply the optimal color scheme to Web Browser. Considering the working flow of the Web Browser Engine, after a webpage is successfully downloaded, the Web Browser Engine first begin to parse the file and construct a DOM tree. DOM tree contains the styling information together with visual instructions in the HTML and CSS. Then, the DOM tree is used to construct a Render Tree. Finally, a Painting stage traverses the Render Tree and paints each node by calling a series of Library functions.

ColorVert is executed at the painting stage of the Web Browser, after the Render Tree of a webpage is constructed. During the painting stage, ColorVert changes the interface between Web Browser Engine and Library functions to substitute the original color scheme with our optimal color scheme. Thus the painting functions paint the render tree nodes with the specified colors.

4. COLOR SCHEME TRANSFORMING ALGORITHM

In this section, we present the color transformation algorithms, which are used to calculate the optimal color scheme in Transforming Unit. The optimal color scheme can significantly improve user experience.

4.1 Criteria Construction

According to our analysis in Section 2, user experience is mainly determined by the following factors: RVP value (i.e., readability) for strong lighting conditions, UGR value (i.e., comfort level) for weak lighting conditions and Similarity between the original and transformed webpage.

1)RVP value: The mechanism of deciding RVP value is complex. In our experiment, we find that there are mainly three factors affect RVP value: *Luminance Contrast*, *Color Hue Difference* and *Font Size*.

Luminance Contrast: In Section 2, we illustrate how to calculate the actual luminance contrast and RVP value. All colors on a plane of the DKL color space have the same luminance value. The luminance contrast is the distance of two planes. In order to exclude the effect of color hue, we select a pair of foreground and background color from the achromatic axis in Fig.3 (i.e., $(90^0, 0, r)$) to study the relationship between the luminance contrast and RVP value. The font size of words is fixed at 13px. We observe the words and record RVP values under different luminance contrast levels between the foreground and background color (i.e., different the r value). The results are shown in Fig.6 that RVP is up to 80% when luminance contrast is equal to θ. It can be seen that when luminance contrast is bigger than θ, there is no significant change in RVP value as luminance contrast increases, while when the luminance contrast is less than θ, the RVP value decreases dramatically as luminance contrast decreases. Therefore, when luminance contrast is bigger than a certain value θ, the RVP value can satisfy the requirement of readability.

Color Hue Difference: Besides luminance contrast, the color hue can also affect RVP value. In order to exclude the effect of the luminance contrast, we select a pair of foreground and background colors from the isoluminant plane (i.e., $(0, h, r)$ in the DKL color space, where h is the color hue and r specifies the radius). The color hue difference of a color pair is defined as $|h_1 - h_2|$, where h_1 is the color hue of the foreground color and h_2 is the background color hue. First we discuss the impact of r on RVP value. In this experiment, we fix h_1 at 0 degree and h_2 varies from 0^o to 360^o. As the experiment results shown on the upper half of Fig.7, RVP value is the highest when the color hue difference is equal to 180^o, i.e. $|h_1 - h_2| = 180^o$. The results also show that the bigger the r value, the higher the RVP value, where $r = 1$ indicates that the color is on the surface of the DKL color sphere. Next, we discuss the impact of h_1 on RVP value. We set h_1 as a series of values $(0^o, 60^o, \ldots, 300^o)$. $|h_1 - h_2|$ varies from 0^o to 360^o and r is fixed at 1. The results are presented on the bottom half of Fig.7. The results show that as long as the color hue difference of the color pair remains the same, RVP value is similar among different color hue h_1. This indicates the color hue itself does not affect RVP value, what matters is only the color hue difference between the foreground and background.

Font Size: A bigger font size can make the words more clear and improve user experience in reading. Font size is usually specified in CSS, with the unit px. Most words in the ordinary webpages are within the range of 10-25px. We fix the color hue difference at 180^0 to discuss the relationship between the font size and RVP value. The experiment results are shown in Fig.8. We can see that the change in font size results in the change of θ, i.e., the bigger the font size, the smaller the luminance contrast constraint θ.

2) UGR value: Under weak lighting conditions, we can improve user experience by decreasing UGR value. From the Equation 3, UGR value can be decreased by reducing the total luminance of the screen L_n.

3) Similarity: Similarity is another important factor that contributes to user experience. In order to evaluate the Similarity of a transformed color with the original one, we define the distance of two colors, color a and b, as the spherical distance of two points in the DKL space, repre-

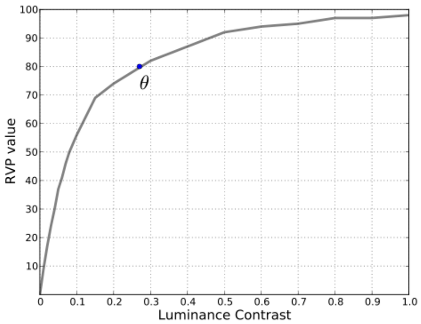


Figure 6: Relationship between the luminance contrast and RVP value.

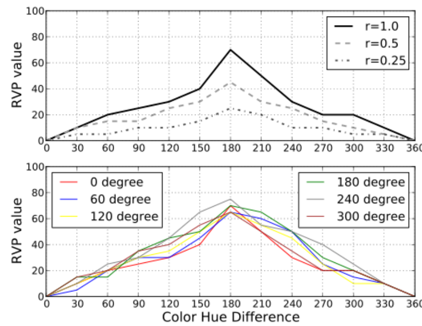


Figure 7: Relationship between the color hue and RVP value.

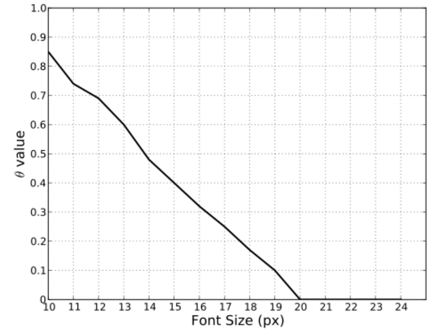


Figure 8: Relationship between the font size and RVP value.

sented as $distance(a, b)$. The smaller $distance(a, b)$ implies a higher similarity.

4.2 Color Transformation under Strong Lighting Condition

In this section, we discuss the color transformation algorithm under strong lighting conditions based on the criteria above. Given a webpage include foreground colors $(x_1, x_2, \ldots, x_n)$ and a background color y, we aim to find an optimal color scheme that consists of foreground color $(x'_1, x'_2, \ldots, x'_n)$ and an uniform background color y'.

4.2.1 Foreground Color Transformation

The foreground of a webpage is its various words that contain different information. Firstly, we design an optimal substitution for a single color words. Since a webpage is normally composed of words with different colors, we need to further deal with the problem of multiple foreground colors. With the criterion constructed, we determine the available color pairs for foreground and background. Based on the criteria discussed in Section 4.1, when performing color transformation, we need to consider the following constraints:

- We should keep the luminance contrast of the foreground and background above θ.
- Color pairs of foreground and background should be located on the surface of the sphere ($r = 1$), and their color hue difference should be 180^o.

Since the bright color texts are easier to be washed off by the strong light, we select the foreground colors from the bottom half of the sphere (i.e., dark colors) in the DKL color space. In order to meet the the luminance contrast and color hue constraints of the foreground and background, the upper half of the sphere is selected for background. We then can calculate the *Available Area*, i.e., the colors in those areas can meet the constraints of the foreground and background. It is shown in shaded areas (surface spherical crowns) in Fig.9. Also, the font size results in the change of the shading area. When the font size becomes bigger, the available area also becomes bigger, and vice versa.

Single Color: Considering the available area, our transformation method for a single color x is quite straightforward. We just need to find out a color x'_1 in the available area which has the highest similarity with the original color. Fig.9 shows our transformation method. In order to keep the similarity, the h value of the original color x_1 is fixed. Firstly, we increase the r value of the x_1 to x_1^*. Then, we decrease the α value of x_1^* until it goes into the available area. Finally, x'_1 is selected as new word color, and the other half of the color pair y_1 as background color. So for a single color, we could effectively find a color pair that is optimal.

Multiple Colors: Most of popular webpages usually have multiple bright colors on a single webpage. If each color is transformed using the method above, it is possible that color collision could occur. Color collision means two or more different colors in the original webpage are transformed to the same color. To illustrate this, we refer to Fig.9, which shows a bright color x_1 is transformed to x'_1 on a webpage. Suppose that the original color scheme of the webpage also include the color x'_1, or there is another color x_2 which is also transformed to x'_1 by the method above, a color collision occurs. Usually, in webpages, different word colors are used to represent different kinds of information. If the color collision occurs, it is hard for users to distinguish them and understand what kind of information they are representing. Therefore, it is necessary to eliminate the color collision.

To avoid color collision, we first extend our definition of Similarity: similarity is not only associated with the distance between two colors, but also associated with their relative weight that is the percentage of a given foreground color. The color with a higher percentage, i.e., bigger weight, has a larger impact on the similarity. So we use the weighted distance to evaluate the similarity of two color schemes. We assume that the original color scheme includes color $(x_1, x_2, \ldots, x_n)$, and the new color scheme includes color $(x'_1, x'_2, \ldots, x'_n)$ after transformation. w_i in $(w_1, w_2, \ldots, w_n)$ represents the weight of the corresponding color. If x_i is already located in the available area before transformation, then we do not change x_i and let $x'_i = x_i$. The similarity can be defined as:

$$\frac{1}{WeightedDistance} = \frac{1}{\sum_{i=1}^{n} w_i \times distance(x_i, x'_i)}. \quad (4)$$

A smaller weighted distance indicates the color scheme is more similar to the original one.

Further, we introduce a constrain to our transformation method, that is

$$\{\forall x'_i, x'_j | distance(x'_i, x'_j) > \beta, i \neq j\}, \quad (5)$$

where β is a parameter that describes the color distance that can distinguish two kinds of colors. This constraint guaran-

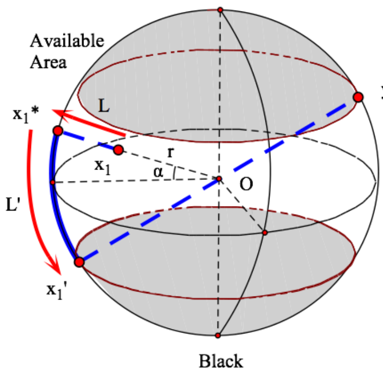


Figure 9: Transformation method for single foreground color under strong lighting conditions.

tees that any two colors in the new color scheme must be separated for a certain distance, so that any two word colors could be easily distinguished. In order to guarantee the constraint, we set collision areas, which represent the sets of points that have distances less than β with any already selected color. We select a color from *remaining available area* (that is, *available area* $-$ *collision area*) with the largest similarity (i.e., $min(WeightedDistance)$). Apparently, in order to maintain the largest similarity, the color selected should be on the boundary of the remaining available area.

With the two equations above, we could calculate the optimal color scheme for multiple foreground colors. The algorithm is described in Algorithm 1. Since a color with a bigger weight should have a higher transformation priority according to the Equation 4, we first sort all the colors according to their weights. Then the first *for* loop can find out all the colors that do not need to transform and then update the remaining available area accordingly. In the second *for* loop, we deal with colors that need to change, i.e., select a color with the largest similarity from the remaining available area. Suppose that we totally maintain k points on the boundary of the remaining available area, the complexity of the loop is $O(nk)$. However, considering that there are usually only a few kinds of colors in a webpage, k is much larger than n, so the total complexity of the algorithm is $O(k)$.

4.2.2 Background Color Transformation

Above work allows us to find an optimal color scheme for a given webpage with many foreground colors. We can always find an optimal background color for a foreground color, e.g., if x'_1 in Fig.9 is selected as foreground color, the other half of the color pair y_1 is selected as background color. This is because it can guarantee Color Hue constraints, i.e.,

$$|h_{foreground} - h_{background}| = 180^o. \quad (6)$$

Thus, many background colors will be selected for multiple foreground colors. However, users are used to a uniform background in a webpage for all foreground colors. So we present a background calculation algorithm to find an optimal uniform background color as follows.

We assume that $(y'_1, y'_2, \ldots, y'_n)$ are the background colors for multiple foreground colors. (x'_i, y'_i) is a color pair that meet our all constraints. Assume the color y' is the optimal background color for the whole webpage, we should select a

Algorithm 1 Foreground Color Transformation

Require: A set of foreground colors $(x_1, x_2, \ldots, x_n)$ in a webpage and their respective weight $(w_1, w_2, \ldots, w_n)$ and font size $(f_1, f_2, \ldots, f_n)$.

Ensure: The approximate optimal foreground colors $(x'_1, x'_2, \ldots, x'_n)$ which can meet our constraint in Equation 5 and maximize the similarity in Equation 4.

Sort $(x_1, x_2, \ldots, x_n)$ according to their weight so that their weight is in a decreasing order.
Initialize the similarity sum of the colors as $\mathcal{S}$
Initialize the collision area as $\mathcal{C}$
for $i = 1 \to n$ **do**
  Calculate the Available Area $\mathcal{A}_i$ to the font size f_i
  if Color x_i is already in its available area **then**
    Let $x'_i = x_i$
    Let x'_i as centre, β as radius, draw sphere SP_i
    Update the collision area as $\mathcal{C} = \mathcal{C} \cup SP_i$
  end if
end for
for $i = 1 \to n$ **do**
  if Color x_i is not in its available area $\mathcal{A}_i$ **then**
    $\mathcal{A}_i = \mathcal{A}_i - \mathcal{C}$
    From the boundary of $\mathcal{A}_i$ select the color x'_i which can minimize $distance(x_i, x'_i)$
    Let x'_i as centre, β as radius, draw sphere SP_i
    Update collision area as $\mathcal{C} = \mathcal{C} \cup SP_i$
    Update $\mathcal{S} = \mathcal{S} + w_i \times distance(x_i, x'_i)$
  end if
end for

color that is the closest to all color $(y'_1, y'_2, \ldots, y'_n)$ as y', i.e., minimal weighted distance:

$$min(\sum_{i=1}^{n} w_i \times distance(y', y'_i)). \quad (7)$$

Thus, from Equation 7, we can calculate a color y' as the optimal uniform background color.

4.3 Color Transformation under Weak Lighting Conditions

In this section, we discuss the color transformation algorithm under weak lighting conditions. When we use our smartphones at night, the luminance of ambient light L_b is very low. A slightly increasing of L_n in Equation 3 thus could rise the UGR value sharply, which makes our eye uncomfortable. In order to reduce the value of UGR, we should try to reduce the luminance of our smartphone screen, i.e., L_n.

4.3.1 Background Color Transformation

Since the background color occupies most of the screen and contributes to most of the luminance, it is important to first find a background color with a low luminance level. Taking this fact into consideration, black is the best color to use as background at night, because its luminance is zero, which is in accordance with the luminance level of the ambient environment. Black color can significantly reduce the UGR value and makes our eyes quickly adapt to the display screen, so user experience is improved.

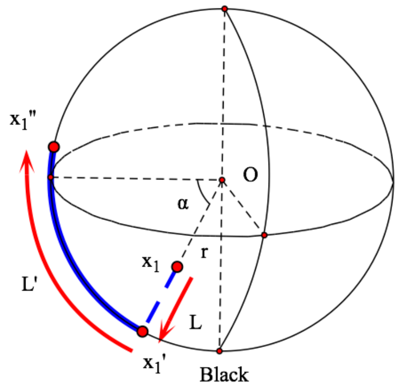


Figure 10: Transformation method for single foreground color under weak lighting conditions.

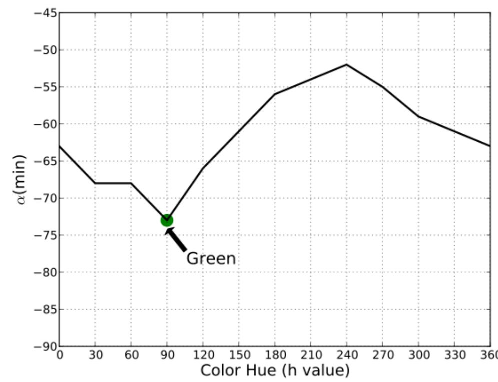


Figure 11: Color hue difference and their minimum α value.

4.3.2 Foreground Color Transformation

For foreground, we need to consider color transform algorithm for single color and multiple colors. There are some constraints that we need to take into consideration for the foreground color transformation under weak lighting conditions.

- Readability of a webpage: we should make sure that the RVP value is above a certain value χ.
- Similarity between the original color and transformed color: the new color should be selected from the same hue axis of the DKL color space, i.e., $h = h'$.

Single Color: Given the criteria above, we first focus on RVP requirement. RVP can be improved by increasing the luminance contrast. Fig.10 shows our transformation method. If there is a foreground color x_1 with $RVP_{x_1} < \chi$, we first move the color x_1 along the line L. If RVP value requirement cannot be satisfied when it reach x'_1, we continue moving the color alone the arc L' by increasing the α value of the color till we find a color x''_1 with $RVP_{x''_1} \geq \chi$. For any foreground color x_i with $RVP_{x_i} \geq \chi$, we do not transform the color.

We further discuss the transformation method for an achromatic color. Achromatic colors, especially black, usually occupy a large percent of total words in a webpage. Since achromatic colors do not belong to a certain color hue, it could be moved in any directions. Thus, we need to find out a certain direction, i.e., a certain color hue that could meet the requirement of RVP value as well as maintaining the lowest luminance. An experiment is performed in order to find the optimal color hue. In our experiment, we select black as background of the webpage and $x(\alpha, h, r)$ for foreground. According to the results presented in Fig.7, we fix $r = 1$ and let h equals to a series of values. For each value of h, color set $(\alpha, h, 1)$ is a longitude on the surface of the sphere. Then from $\alpha = -90^o$, we gradually increase the value of α, until the RVP value of the word exceeds the requirement χ. The results are shown in Fig.11. Firstly, the color we select meets the RVP requirement. So according to our experiment above, for each color hue h_i, we guarantee that $\alpha \geq \alpha_{i_{min}}$ (α is the minimum that can meet our RVP value requirement). Secondly, we should keep UGR value as low as possible. Since α represents the luminance of a certain color, the bigger the α is, the higher luminance the color has. To keep the lowest possible UGR, we should select the color hue with a smallest $\alpha_{i_{min}}$, which is green (h= 90^o) according to the experiment results. Therefore, under weak lighting conditions, green can meet RVP value requirement with the lowest α and is the best substitution for achromatic colors.

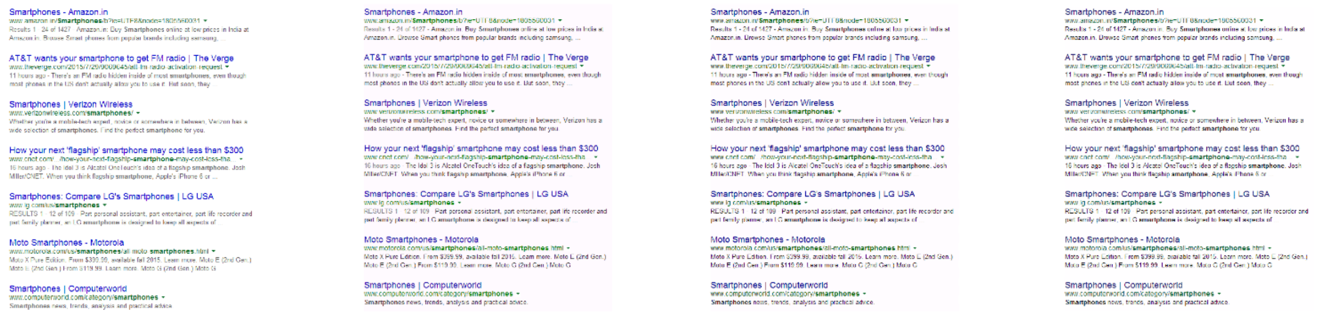
Multiple Colors: For multiple colors, it is possible that conflict can occur when performing color transformation. We already discuss the solution to color conflict under strong lighting conditions on Section 4.2. Similarly methods are applied under weak lighting conditions.

5. EVALUATION

In this section, we first present the prototype implementation of ColorVert and then we evaluate ColorVert under both strong and weak lighting conditions respectively. After that, we discuss the transformation time and overhead of ColorVert.

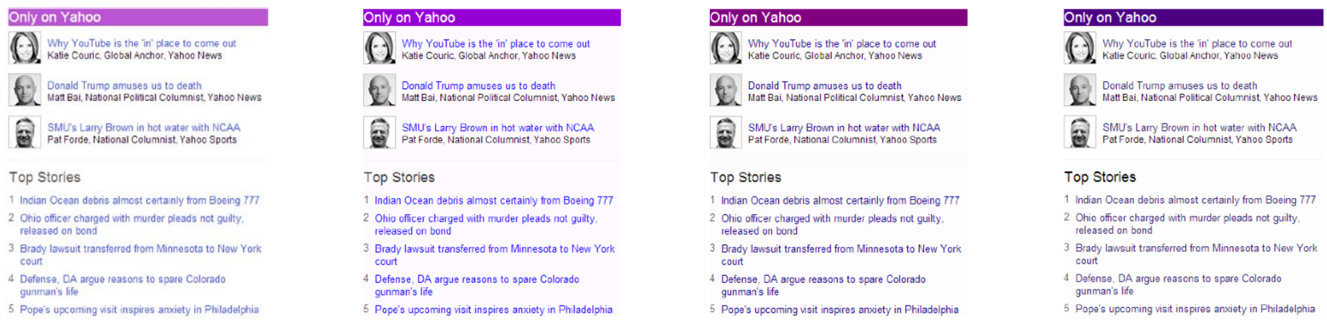
5.1 Prototype Implementation

We implement ColorVert as an Android App and install it on four mobile devices with different CPU frequency and screen size, i.e., Motorola XT928 with a 4.5' screen and a 1.2GHz dual core CPU, Samsung Galaxy Note with 5.3' screen and a 1.4GHz dual core CPU, Nexus 7 with a 7' screen and a 1.3GHz quad core CPU, Galaxy Note 10.1 tablet with a 10.1' screen and a 1.4GHz quad core. ColorVert senses the light strength condition by using the light sensor embedded on the mobile devices. According to the light sensor's reading, ColorVert calculates the optimal color scheme and executes it on the mobile devices. Fig.12 and Fig.13 show two examples of the original and transformed webpages performed by ColorVert under strong lighting conditions with various lighting strengths. We observe that in the transformed webpages bright colors become darker as the strength of the sunlight increases, while the similarity of the two webpages is preserved before and after applying ColorVert. We then present two examples of transformed webpages performed by the inversion color scheme and ColorVert respectively in Fig.14 and Fig.15 under weak lighting conditions. We find that although the background color of both schemes is adapted to black so that UGR value is reduced, the foreground colors from ColorVert are more comfortable to users than those from the inversion scheme.



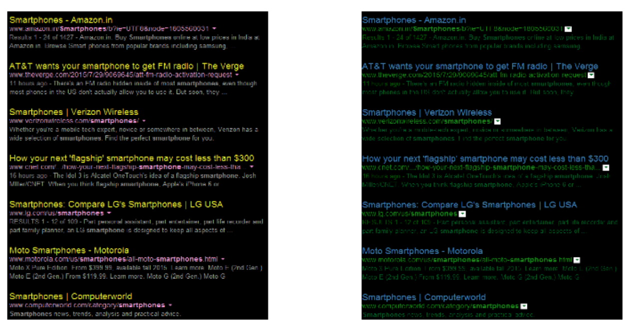
(a) original (b) $20000cd/m^2$ (c) $30000cd/m^2$ (d) $40000cd/m^2$

Figure 12: Example 1 of applying the ColorVert prototype under strong lighting conditions.



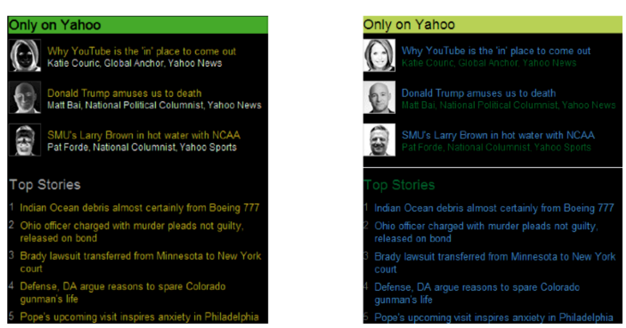
(a) original (b) $20000cd/m^2$ (c) $30000cd/m^2$ (d) $40000cd/m^2$

Figure 13: Example 2 of applying the ColorVert prototype under strong lighting conditions.



(a) inversion (b) colorvert

Figure 14: Example 1 of applying Inversion and ColorVert schemes under weak lighting conditions.



(a) inversion (b) colorvert

Figure 15: Example 2 of applying Inversion and ColorVert schemes under weak lighting conditions.

5.2 Impact on User Experience of ColorVert

In order to evaluate the effectiveness of ColorVert, we first request those 206 volunteers mentioned in Section 2 to grade the user experience for some popular webpages which are transformed by ColorVert on Motorola XT928, with an ambient light strength of around $20000cd/m^2$ for strong lighting conditions (sunlight) and around $2cd/m^2$ for weak lighting conditions (at night). With each webpage, users are shown with both the original with auto-brightness adjustment(**Original**) and the transformed webpage(**ColorVert**) simultaneously on two Motorola XT928 phones and they are not aware of which one is the transformed one. The results of the survey are shown in Fig.16. For each webpage, two bars on the left show the RVP value and user experience score of the strong sunlight respectively while the two bars on the right show the UGR value and user experience score of the weak light respectively. From Fig.16 we can observe that with ColorVert, RVP values are improved to around 70% under strong lighting conditions, which is sufficient for satisfying reading experience. User experience scores are also significantly improved under strong lighting conditions. Moreover, under weak lighting conditions, although UGR values are decreased with a small decline compared with the inversion color scheme, the better comfort level and similarity help ColorVert a lot to achieve a higher score of users' feedback. From our study, we observe that the preserved similarity and the improved readability and comfort level contribute to the user experience improvement.

Next, we evaluate the performance of our system under different light strengths by using different smartphones. We randomly select 100 webpages and use four different mobile devices to display these webpages. Fig.17(a) shows our

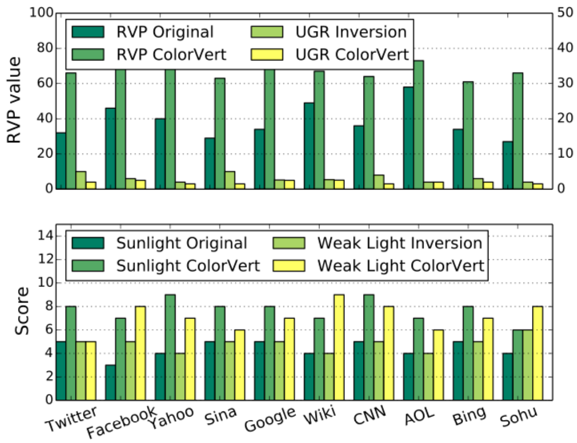


Figure 16: RVP, UGR and user experience score of ColorVert.

results under strong lighting conditions, in which sunlight strength varies between $15000 - 30000cd/m^2$. *RVP Ratio* is the ratio between RVP value of the optimal color scheme and original one, i.e.,

$$RVP\ Ratio = \frac{ColorVert\ RVP}{Original\ RVP}. \tag{8}$$

It can be seen from the figure that as sunlight strength increases, the RVP Ratio rises, which indicates that ColorVert effectively prevents RVP value from sharp decreasing under strong lighting conditions. Also, we set up another experiment to evaluate the impact of different screen sizes on ColorVert. ColorVert is applied to the four devices stated above and we require volunteers to score the color scheme. We present the average user experience score in the bottom half of Fig.17(a). From the figure, ColorVert improves user experience on all four kinds of devices. And there are little difference of the user feedback for different screen sizes.

For weak lighting conditions, we perform similar experiments which restrict the ambient light luminance in the range of $0 - 100cd/m^2$ and calculate the UGR Ratio, which is defined as

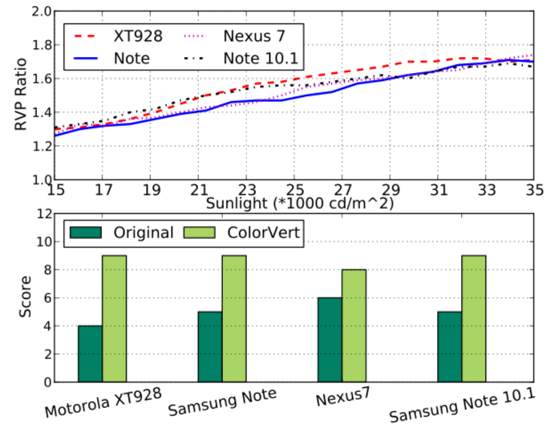
$$UGR\ Ratio = \frac{ColorVert\ UGR}{Inversion\ UGR}. \tag{9}$$

Fig.17(b) shows the results. It can be seen that the UGR Ratio decreases as lighting strength goes down, which indicates that ColorVert can reduce the UGR value under weak lighting conditions. User experience survey under weak lighting conditions shows similar results as those of strong lighting conditions.

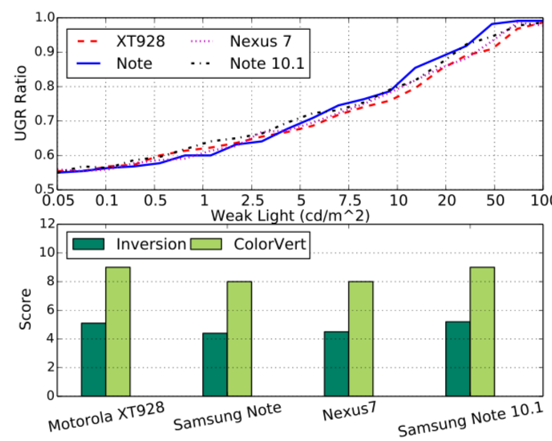
Therefore, our color transformation model can achieve a good user experience across different webpages and mobile devices for both sunlight and weak lighting conditions.

5.3 Transformation Time

Transformation time is another critical issue that concerns our system. User experience would be severely degraded if the transformation time cannot keep up with the occurrence of different kinds of events. We set up our system on four mobile devices, and further set their CPU frequency to certain levels. Then we randomly select 100 webpages and open them on four devices with different CPU frequencies under



(a) strong light



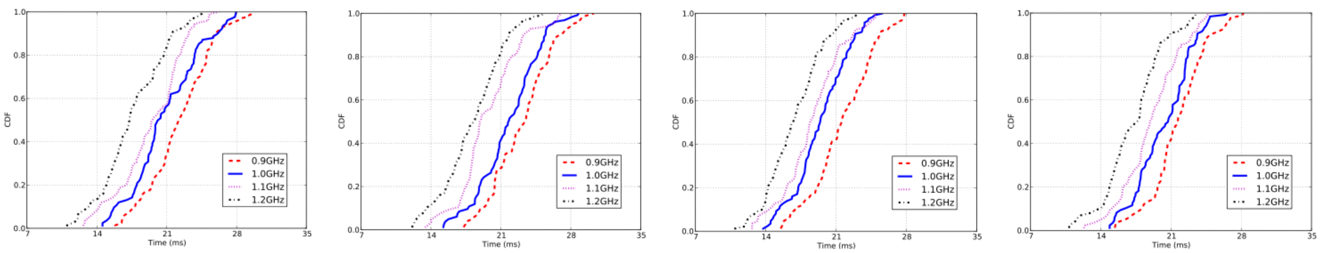
(b) weak light

Figure 17: UGR, RVP ratio and user experience score of different devices.

both strong and weak lighting conditions. In order to extract the time of color transformation, webpages are first saved on our mobile devices to avoid the interference from network connection. We record both the time consumed to load a webpage with and without our system and calculate their average time difference. Based on the trace collected, Fig.18 plots CDF of the color transformation time of ColorVert. It can be seen from the Fig.18 that for Motorola XT928 which uses 1GHz CPU frequency, about 90% of the ColorVert transformation time are within 25ms. Other devices show similar results. These results are very encouraging as they demonstrate the transformation time is very short, which is not noticeable by users. Also, we could see from the Fig.18 that CPU frequency almost has little effect on the performance of our system. Therefore, the delay caused by our system is acceptable in daily use and will not cause user experience degradation.

5.4 Overhead Analysis

Although Sensing Unit monitors the user and light event in real time and recalculate the optimal color scheme according to the events, the overhead of our system is negligible. Firstly, when there is no event occurs, our system does not perform any calculation. Secondly, we have taken various of



(a) Motorola XT928 (b) Samsung Galaxy Note (c) Nexus 7 (d) Samsung Galaxy Tab

Figure 18: CDF of average transform speed of ColorVert on different devices.

methods to decrease the occurrence frequency of both sensing light and human-screen interactions to further lessen the overhead. Also, total recalculation has a complexity of $O(k)$ and Fast Transformation only performs a linear transformation. So that only a few computation is need to calculate our optimal color scheme. As a result, our system is lightweight and the overhead could be negligible.

6. RELATED WORK

In this section, we review the existing work that related to our research. Modern mobile devices have introduced the automatic brightness adjustment system[19], which could change screen brightness level with ambient light. There are subsequent studies aimed at improving the performance of automatic brightness adjustment system[2] to improve user experience. However, they only focus on the luminance level of the screen without taking the color scheme into consideration, which is insufficient under very strong and weak lightning conditions.

With the explosive growth of smartphone usage, there are some researches about color scheme for smartphone displays to improve user experience under strong and weak lightning conditions. [20] present a theoretical basis to adjust use-preferred color temperature for smart-phone displays under various illuminant condition, but [20] do not consider readability and similarity that contribute to user experience, and do not propose any adaptive color scheme solution. Although there exist some work to improve user experience by adjusting color saturation[3] or contrast[4, 5] according to ambient light, they focus on images and videos display which is hard to achieve higher readability for texts. Moreover, [21] shows long-wavelength light affects visual performance under weak lightning conditions, but they do not discuss relationship between foreground and background color.

Moreover, researchers are interested in smartphone screen color scheme adaptation. Focused on saving the energy, [6] can adjust the color scheme of webpages to reduce the power consumption of smartphones. [7] constructs a predictive model for mobile systems and [22] uses a multi-objective optimization to find the most energy efficient color scheme. However, the purpose of these work is to improve energy efficiency while sacrifices user experience. The work[23] proposes a frame rate adaptation system, which considers both energy efficiency and user experience. However, it does not refer to the adaptive color adjustment for improving user experience. Also, there are some existing studies that try to adjust webpages for smartphone screens[24][25]. However, they aim at fitting the webpage into the small smartphone screen without considering the effect of ambient light on user experience.

Although the user experience of mobile devices has gained much attention, existing work has not concerned the impact of the webpage color scheme to user experience. Our work is different from the previous studies in that we explore the relationship between color and user experience, then design ColorVert, which can adaptively adjust the color scheme to improve user experience.

7. CONCLUSION

In this paper, we address the problem on the readability of mobile device screen display under dynamic lighting conditions. Through analyzing the color schemes on mobile device displays, we find that merely applying bright colors results in user experience degradation under both strong and weak lighting conditions. Furthermore, after running experiments with over 200 volunteers, we find that readability, comfort level and similarity are major factors that contribute to user experience when reading mobile device screens. We develop an adaptive color scheme transformation system, ColorVert, which senses the ambient light conditions and utilizes our proposed color transformation algorithm to adaptively calculate the optimal color scheme under both strong and weak lighting conditions. We prototype ColorVert on several types of smartphones and tablets. Extensive experiment results with over 200 participants demonstrate the effectiveness of the ColorVert design compared with the existing automatic brightness adjustment system. The prototype implementation shows that ColorVert is feasible to be applied in real-world scenarios for maintaining and improving user experience under various lighting conditions.

Although our work only focuses on dealing with plain text of web browsers, we believe the proposed color transform adaptation approach could be easily extended to handle other smartphone tasks with plain text using screen displays. In the future, we will extend our user experience-oriented color scheme on display of images, video and embedded text.

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