Contributing Factor for Color Constancy Is Influenced

by Illumination Color and Observer's Color Vision Type

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ABSTRACT

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Color constancy is a common phenomenon where the perceptual color of a surface does not change as the spectral composition and intensity of illuminant changes. The cone adaptation of the photoreceptors at the retina and cognitive mechanism occurring at a higher level are considered as two main factors contributing to color constancy. However, it is not clear whether the utilization of color constancy mechanisms depends on illuminant conditions and color vision types.

In this study, 5 color normal observers and 7 color deficient observers (3 deutans, 2 protans and 2 protanomalous observers) participated in the experiments. They were asked to make an asymmetric simultaneous surface match on a monitor screen.

For color normal observers, results data showed that the mechanisms of von Kries type of cone adaptation/gain control or estimation of theoretically calculated color mechanisms were selectively used to mediate the color constancy. Under green illuminant, stimulating mainly M cones, color normal observers used cone adaptation /gain control mechanism to achieve the color constancy; instead, under red illuminant, stimulating mainly L cones, observers used the estimation mechanism. Under purplish blue illuminant and greenish yellow illuminant, stimulating mainly S cones, because the color predicted by the von Kries model and the theoretically calculated color are very close, the application of two models in the color constancy could not be separated.

Experimental data showed that the degree of color constancy of one protanomalous observer is almost as good as that of color normal observers, but he tried to obtain the color constancy by estimating the theoretically calculated color under both green illuminant and red illuminant. Dichromatic observers, however, selectively used this estimation model or the model of von Kries type of cone adaptation/gain control, explored from the aspects of LMS cone responses. L cone responses of matched colors on deutans followed the von Kries model under green-, red- and purplish blue-illuminants; L cone adaptation/gain control contributed to the compliance of luminance with the von Kries model. Only under purplish blue illuminant, S cone responses of deutans showed partial cone adaptation/gain control. Protans showed M cone adaptation/gain control only under green illuminant. M cone adaptation/gain control also contributed to luminance adjustment. Under both green- and purplish blue-illuminants, S cone responses of protans followed cone adaptation/gain control. It seems that deutans used mainly cognitive estimation for the color changes caused by S cone stimulation changes to obtain the color constancy; protans tend to use S cone adaptation/gain control and luminance-related estimation mechanism to achieve the color constancy.

Keywords: Color constancy, Color deficiency, Illumination color, von Kries model, Theoretically calculated color model

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Chapter 1

General Introduction

1.1 Color constancy of observers with normal color vision

Color constancy refers to the phenomenon where the perceived color of object remains constant despite changes of spectral composition and intensity of illuminant. To complete color constancy, human adopt some mechanisms to discount the influence of illuminant color on the surface of object. Under nearly natural viewing conditions, besides three classic hypotheses: adaptation of local surround, adaptation of the spatial average of the image and adaptation of the most intense image region, it is suggested that there are some other mechanisms to mediate the color constancy (Kraft and Brainard 1999). The color constancy based on three-dimensional scenes or objects is better than that based on flat surfaces. It was found that color constancy was better when the target color was learned in a cue-rich 3D scene than in a 2D palette (Hedrich et al. 2009). Compared to computer simulations of flat surfaces, three-dimensional scenes contain many additional cues for illuminant estimation, such as shadow, light reflection from atmosphere, light reflection from surfaces (Delahunt and Brainard 2004a), peripheral illumination (Hansen et al. 2007), specular highlight (Yang and Maloney 2001; Yang and Shevell 2003) and visual identity of an object

(Olkkonen et al. 2008). It was reported that the color constancy under reflected light changes is similar to that under light source changes; the color constancy under two physically different types of illuminant changes might be mediated by a common mechanism (Delahunt and Brainard 2004a). Under the condition where the central patch was surrounded by only peripheral illumination, a certain amount of color constancy exists, which indicates that the presence of spatial contrast between test patch and peripheral illumination plays a role in the color constancy (Hansen et al. 2007). The visual identity of an object has a measurable effect on color perception, and that this effect is robust under illuminant changes (Olkkonen et al. 2008). Now, consider the following situation. Two walls with different reflectance properties are illuminated respectively by two light sources which have different spectral composition. The reflected light from two walls is made equal. We still can perceive that these two scenes have different illuminants. However, when these two illuminated walls are presented on monitor, they will look exactly the same. Computer simulations of flat surfaces have no spatial cues and all of information observers need comes from background.

Computer simulation of flat surfaces is often used to investigate the color constancy by a simultaneous color matching task. In simulated scenes, observers have to estimate illuminant from illuminated surfaces. A "simple" background consisting of one or two colors, such as uniform gray background, cannot provide enough illuminant information for observers. Adaptation to background illuminant, or adaptation to background chromaticity, is considered as a main factor contributing to color constancy based on a uniform background. It was found that the shift in chromaticity of the achromatic point was in the direction of the chromaticity of the background, while the magnitude of the shift increased as an increasing function of background luminance and as a decreasing function of contrast (Werner and Walraven 1982). Chromatic adaptation is spatially localized with a time-course on the order of 10 sec (Fairchild and Lennie 1992). Photoreceptor sensitivity changes explained the effect of numerous large uniform backgrounds on the color appearance of many targets with high precision (Chichilnisky and Wandell 1995). High values of constancy index correspond to almost complete von Kries adaptation in all three cone types (Murray et al. 2006). The above researches showed that the cone adaptation to the uniform background has a considerable effect on the appearance of target color. Chromatic contrast between test patch and background also influences the appearance of test patch. As response to the hypothesis proposed by Golz and MacLeod (Golz and MacLeod 2002), Granzier et al. found that only within 1 degree visual field, the luminance-redness correlation has an effect on the color appearance of central patch and therefore suggested that contrast at borders, not illuminant estimation from scene statistic information took effect (Granzier et al. 2005).

Chromatic backgrounds with more illuminant information can contribute to better color constancy than simple gray backgrounds (Kuriki and Uchikawa 1996). With brief adaptation, the chromatic surround, such as Mondrian, can contribute to better color constancy than black or gray surround; complete adaptation to the illuminant helps to achieve almost perfect color constancy in surface-color matches (Kuriki and Uchikawa 1996). The context has a large effect on the recalled colors; the color recalled from memory after a 10-min delay is least affected by the illuminant during training when complex background was presented (Jin and Shevell 1996). Color constancy based on the variegated backgrounds with many differently colored surfaces is mediated by two commonly accepted mechanisms: cone adaptation to illuminant and illuminant estimation from image surfaces. Contrast adaptation induced by illuminant changes may influence color constancy (Webster and Mollon 1995). However, the effect of chromatic contrast can be reduced by using high-spatial frequency chromatic variation (Golz 2008; Smithson and Zaidi 2004) or almost three-dimensional image with rich cues (Zaidi et al. 1997). The illuminant adaptation has a large effect on appearance-based color constancy, while the chromatic bias of the background has a small effect (Smithson and Zaidi 2004). Bäuml found that in complex visual field, image surfaces play a minor role in color constancy and illuminant adaptation takes main effect (Bäuml 1999a). Photoreceptor and opponent-color signals from a large sample of natural and man-made objects were systematically correlated under different phase of daylight, which indicates that human may utilize simple cone adaptation to complete the partial color constancy and even do not use cognitive strategy (Zaidi et al. 1997). The achromatic loci were mainly affected by the illumination, not the background surface; the absence of local contrast effect was ascribed to the richness of the stimulus condition (Brainard 1998). This conclusion coincides with the theory that cue-richness of scenes can help to reduce the effect of chromatic contrast. The result that von Kries model, which is formulated by considering only influence of illuminant, ignoring the effect of image surfaces, provided a good description of the data under different surface collections (Bäuml 1999a) demonstrated that chromatic background has less effect on the color constancy. At receptor level, the L and M cones tend to adapt so as to support color constancy, whereas S cones are strongly influenced by the illuminant changes (Nieves et al. 2000). No difference was found in color constancy between the condition where color renders are complete simulation and the condition where the cone excitation ratios of image surfaces are broken for two illuminant conditions, which indicates the achievement of color constancy is not related with the detailed relationship between image surfaces, but relevant to the general illuminant which illuminated the scene (Rinner and Gegenfurtner 2002).

According to von Kries model which is a prominent cone adaptation model, the spectral sensitivities of the three kinds of photoreceptor can be varied independently by a constant. It was reported in literatures (Bäuml 1999a;b; Brainard and Wandell 1992; Brainard et al. 1997) that the matches data can be described well by von Kries model. The mapping between the cone coordinates of standard objects and matched objects was well approximated by a diagonal linear transformation (Brainard and Wandell 1992). The above results consistent with von Kries model (Bäuml 1999a;b; Brainard and Wandell 1992; Brainard et al. 1997) were obtained under illuminant changes along daylight locus (Brainard and Wandell 1992). It seems that under illuminant changes along daylight locus, von Kries cone adaptation plays an important role in the color constancy. Observers' matches can be described by either of two simple models, diagonal model and equivalent illuminant model (Brainard et al. 1997). For both surface match and appearance match, von Kries model provides a substantially better description of the adjustment than perfectly color constant theoretical matches (Bäuml 1999b). However, recently, the systematic violation of von Kries rule was found and von Kries rule was limited for explaining color and lightness constancy, suggesting that cortical mechanisms must underlie color constancy (Kulikowski et al. 2012). Lightness constancy was found, irrespective of the change of chromatic adaptation (Sobagaki et al. 1974).

Many scientists begin to argue that von Kries cone adaptation is not the only factor contributing to color constancy. The cognitive mechanism occurring at a higher level also plays a very important role (Goddard et al. 2010). Information from image surfaces may help the color constancy. Color constancy is also related with working memory (Allen et al. 2012). The effects of image surfaces on color constancy were investigated from two aspects. One hypothesis is that the constancy of spatial cone-excitation ratios of images surfaces contributes to the color constancy (Foster et al. 2006; Foster and Nascimento 1994; Nascimento et al. 2002). The other hypothesis is that observers estimate illuminant by exploiting luminance-redness statistic information from scenes (Golz 2008; Golz and MacLeod 2002) or by referring to bright colors in scene (Uchikawa et al. 2012). In the second hypothesis, it seems that luminance information in scenes has a strong effect on color constancy (Kuriki 2006; Martinovic et al. 2011). By exploiting both mean redness and luminance-redness correlation statistics, an observer discriminates the redness of objects making up the scene and the redness of the light source that illuminates the scene (Golz and MacLeod 2002). In the region of 4.3 degree, the illuminant estimation based on luminance-redness correlation, not chromatic contrast at borders, mainly contributed to color constancy (Golz 2008). The luminance balance of surfaces with no chromaticity shift had clear effects on the observers' matches (Uchikawa et al. 2012).

Now, the question is whether these mechanisms work together or selectively participate in the color constancy under different illuminant conditions. Some scientists expect that the color constancy under illuminant changes on daylight locus should be better than that off daylight locus, because we frequently experience daylight illumination. Surprisingly, it was found that the color constancy under illuminant changes on daylight locus is not better than that under illuminant changes off daylight locus (Delahunt and Brainard 2004b; Hedrich et al. 2009), on the contrary, the color constancy under blue and green illuminants is better than that under red and yellow illuminants (Delahunt and Brainard 2004b). It seems that observers do not select mechanisms according to experience frequency of illuminant. Is it possible that under different illuminant conditions, observers select mechanisms according to other rules, such as if the illuminated scene can provide enough cues for illuminant estimation? In this study, computer simulations of flat surfaces with variegated backgrounds were used in an asymmetric simultaneous color matching task. There were eight test illuminants: green (Highly-saturated and Desaturated), red (Highly-saturated and Desaturated) illuminants along confusion lines; purplish blue (Highly-saturated and Desaturated), greenish yellow illuminants (Highly-saturated and Desaturated) near daylight locus. By comparing the chromatic shift from standard colors to matched colors, von Kries model predicted colors and theoretically calculated colors, color constancy mechanisms adopted by observers under different illuminant conditions were investigated.

1.2 Color constancy of color deficient observers

About 5% of males are color deficient observers, most of whom confuse red and green colors. There has been the important question how is the color constancy of color deficient observers who have poor color discrimination abilities. Because of the variation or loss of L cone or M cone, the cone adaptation of red-green color deficient observers must be different from that of color normal observers. Their ability on judgment about color of illuminant is also expected to be weakened compared to that of color normal observers. Furthermore, their corresponding cognitive mechanisms mediating color constancy can be special and different from those of normal trichromatic observers.

Baraas and Nascimento investigated the color constancy of color deficient observers by asking observers to discriminate reflectance changes from illuminant changes. Under illuminant changes along daylight locus, protans and deutans performed more poorly than color normal observers (Baraas et al. 2010); protans show nearly normal color constancy under natural reflectance spectra (Baraas et al. 2004); protanomalous and deutaronomalous trichromats performed as well as color normal observers (Baraas et al. 2006); tritans have poorer color constancy performance than color normal observers. Protanopes performed less well than color normal observers in both natural reflectance spectra and Munsell spectra, but their discriminations of illuminant and reflectance changes were indeed more accurate with natural spectra (Baraas et al. 2004). Under illuminant changes along orthogonal axis to daylight locus, it seems that the color constancy performance of red-green color blind is poorer than that of normal observers (Amano et al. 2003). In the above studies, the contribution of deviations in spatial cone-excitation ratios in the remaining cone class was mainly investigated and it was suggested that color constancy depends on preserving spatial ratios of cone-specific excitations and information about deviations in spatial cone-excitation ratios in the remaining medium-to-long-wavelength-sensitive cone class was indeed not used effectively.

Rüttiger investigated the color constancy of red-green dichromats under red-green and blue-yellow illuminant in cardinal directions and daylight illuminant (Rüttiger et al. 2001). The color constancy performance of color deficient observers is similar to that of normal observers along all three axes. However, their variability is greater along the red-green cardinal axis. He concluded that the performance of dichromats may be mainly determined by their relatively intact blue-yellow subsystem of color vision. Color constancy of color deficient observers appears to be a partial compensation, similar in magnitude and variability to that of color normals, rather than a full correction of illuminant changes.

Morland studied the color constancy performance of color deficient observers under red, green, blue and dark blue illuminant conditions (Morland et al. 1997). The color constancy of color deficient observers decreases systematically with loss in discrimination. Adaptation of the retinal photoreceptor is considered as a presumably significant factor in color constancy for color deficient observers.

In the above researches, color deficient observers did not show desirably poor color constancy under conditions in which they can discriminate the color difference of illuminant. However, it has not been investigated about the color constancy under undetectable illuminant change for color deficient observers. It is still not clear whether the color deficient observers have cone adaptation/gain control and whether cone adaptation/gain control contributes to the color constancy. The second purpose of the dissertation is to investigate how is the color constancy on the color deficient observers under illuminant changes along their individual confusion lines. It is necessary to investigate how L, M and S cone of color deficient observers respond in the color constancy task under the condition where the illuminant color changes are completely undetectable for them.

1.3 Research motivations

In technical aspect, to measure the degree of color constancy of color normal observers, the distance between standard color, theoretical color and matched color plotted in a uniform chromaticity diagram was used as Arend and Reeves did (Arend and Reeves 1986; Arend et al. 1991), and its variation form (Troost and Weert 1991) have also been most commonly used. However, this method is inappropriate for the measurement of the degree of color deficient observers' color constancy. It is necessary to adopt a common analysis method by which the color constancy principles of color normal and color deficient observers are presented clearly.

Thus, the objectives of this research are set as follows:

(1) Investigation of color constancy mechanisms of color normal observers, including possible differences between color constancy mechanisms of color deficient and color normal observers with possible influence of illuminant condition;

(2) Investigation of whether color deficient observers have color constancy when they cannot discriminate the color differences between standard illuminant and test illuminants, including the mechanism of it;

(3) Investigation of the color constancy performance of color deficient observers when they can discriminate the color difference between two illuminants, including the comparison with the color constancy performance of color normal observers under the same illuminant condition;

(4) Proposition for a new way of color constancy analysis that is appropriate for analyzing the result data of both color normal and color deficient observers.

1.4 Survey of previous literature

Survey of previous literature on color constancy of color normal observers is summarized as follows according to publishing date.

1. Title: Systematic violations of von Kries rule reveal its limitations for explaining color and lightness constancy (Kulikowski et al. 2012)

Author: J.J. Kulikowski, A. Daugirdiene, A. Panorgias, R. Stanikunas, H. Vaitkevicius and I.J. Murray

Journal: J. Opt. Soc. Am. A (February 2012) 29(2), A275-A289

Points of this research: The asymmetric color matching was done. The illuminant changes were along daylight locus, from reference illuminant C to test illuminant A (2856K) or S (sky blue). It was found whether or not the observer utilizes luminance information in their match strongly influences the degree to which the con contrast rule holds (von Kries rule). When lightness constancy (the luminance was adjusted toward the theoretically calculated luminance under test illuminant) is attempted, the cone contrast of L cone or M cone was weakened. When the L and M cones hold the contrast rule, the lightness constancy is zero. von Kries cone adaptation is incompatible with lightness constancy, suggesting that cortical mechanisms must underlie color constancy.

2. Title: Estimating illuminant color based on luminance balance of surfaces (Uchikawa et al. 2012)

Author: K. Uchikawa, K. Fukuda, Y. Kitazawa and Donald I.A. MacLeod

Journal: J. Opt. Soc. Am. A (February 2012) 29(2), A133-A143

Points of this research: This study was to investigate whether color constancy exploits the potential cue that was provided by the luminance balance of differently colored surfaces. Simulated black body radiations of 3000 (or 4000), 6500, and 20000K were used as test illuminants. The results showed that the luminance balance of surfaces with no chromaticity shift had clear effects on the observer's achromatic setting, which was consistent with the hypothesis on estimating the scene illuminant based on optimal colors.

3. Title: Individual differences in simultaneous color constancy are related to working memory (Allen et al. 2012)

Author: E.C. Allen, S.L. Beilock and S.K. Shevell

Journal: J. Opt. Soc. Am. A (February 2012) 29(2), A52-A59

Points of this research: This study examined the relation between simultaneous color constancy and working memory-the ability to maintain a desired representation while suppressing irrelevant information. It was found that higher working memory was related with poorer simultaneous color constancy in the complex-background condition. It was reported that this finding supports a role for higher-level cognitive mechanisms in color constancy.

4. Title: Color constancy improves for real 3D objects (Hedrich et al. 2009)

Author: M. Hedrich, M. Bloj and A.I. Ruppertsberg

Journal: Journal of Vision (2009) 9(4):16, 1-16

Points of this research: It was found that color constancy was better when the target color was learned in a cue-rich 3D scene than in a 2D palette. It was not found that illuminant changes on daylight locus are better compensated for than those off daylight locus.

5. Title: Can illumination estimates provide the basis for color constancy? (Granzier et al. 2009)

Author: J.J.M. Granzier, E. Brenner and J.B.J. Smeets

Journal: Journal of Vision (2009) 9(3):18, 1-11

Points of this research: Results showed that subjects were very poor at judging the color of a lamp from the light reflected by the scene it illuminated, but much better at judging the color of a surface within the scene. It was concluded that color constancy must be achieved by relying on relationships that are insensitive to the illumination rather than by consciously judging the color of the illumination.

6. Title: The role of chromatic scene statistics in color constancy: spatial integration (Golz 2008)

Author: J. Golz

Journal: Journal of Vision (2008) 8(13):6, 1-16

Points of this research: Granzier (2005) found that only within 1 degree visual field, the luminance-redness correlation has an effect on the color appearance of central patch and therefore thought that contrast at borders, not illuminant estimation from scene statistic information took effect. In this study, it was found that in the region of 4.3 degree, the maximum effect of luminance-redness correlation will reach 75%. The spatial extent measured by Granzier is likely to be caused by the difference in the size of the surround elements and the salience of the border that separates the inner region of the surround from the outer region.

7. Title: Color appearance of familiar objects: effects of object shape, texture, and illumination changes (Olkkonen et al. 2008)

Author: M. Olkkonen, T. Hansen and K.R. Gegenfurtner

Journal: Journal of Vision (2008) 8(5):13, 1-16

Points of this research: The effect of memory colors on color appearance was studied by presenting photographs of fruit on a monitor under various simulated illuminations. It was concluded that the visual identity of an object has a measurable effect on color perception, and that this effect is robust under illuminant changes.

8. Title: Effects of spatial and temporal context on color categories and color constancy (Hansen et al. 2007)

Author: T. Hansen, S. Walter and K.R. Gegenfurtner

Journal: Journal of Vision (2007) 7(4):2, 1-15

Points of this research: In this study, color constancy was investigated in a color-naming categorical task under different conditions of surround illumination and patch size. Nearly perfect color constancy occurred when both spatial contrast and temporal contrast between test patch and the illumination were available in the center of the visual field. It was also found that the presence of spatial contrast between test patch and peripheral illumination plays a role in the color constancy.

9. Title: Color constancy in natural scenes explained by global image statistics (Foster et al. 2006)

Author: D.H. Foster, K. Amano and S.M.C. Nascimento

Journal: Europe PMC Funders Author Manuscripts, June 2007

Points of this research: It was found that the variance in color constancy index was more likely to be explained by receptor-based rather than colorimetric properties of the images. 43% of variance in color constancy index was explained by the log of the mean relative deviation in spatial cone-excitation ratios across the two images of a scene. Other factors, the mean chroma and the mean hue of the image also took effect.

10. Title: Almost complete color constancy achieved with full-field adaptation (Murray et al. 2006)

Author: I.J. Murray, A. Daugirdiene, H. Vaitkevicius, J.J. Kulikowski and R. Stanikunas

Journal: Vision Research (2006) 46, 3067-3078

Points of this research: A successive asymmetric color matching task was used to study the changes in color appearance of simulated Munsell samples under two Planckian illuminants, standard illuminant A and illuminant S. A modified Brunswik ratio (BR) was used to measure the degree of color constancy. Higher values of BR were obtained when longer adaptation periods and larger background were used at the same time. It was found that high values of BR correspond to almost complete von Kries adaptation in all three cone types.

11. Title: The loci of achromatic points in a real environment under various illuminant chromaticities (Kuriki 2006)

Author: I. Kuriki

Journal: Vision Research (2006) 46, 3055-3066

Points of this research: The data shows that the shifts in achromatic points in real illuminated environments depend strongly upon both of the stimulus intensity and the illuminant chromaticity. von Kries chromatic adaptation which is independent of test surface intensity level cannot be used to model the achromatic point shifts. It is supposed that the log of the relative cone weight implicit in the achromatic setting depends almost linearly on (1) the log of the relative cone excitation by the illuminant and (2) the log of the test field intensity.

12. Title: Color constancy in natural scenes with and without an explicit illuminant cue (Amano et al. 2006)

Author: K. Amano, D.H. Foster and S.M.C. Nascimento

Journal: Visual Neuroscience (2006) 23, 351-356

Points of this research: High-resolution hyperspectral images of natural scenes were used. In the first experiment, the sky illuminating the scene was directly visible to the observer; in the second experiment, a large gray sphere was introduced into the scene so that its illumination by the sun and sky was also directly visible to the observer. It was found that color constancy did not worsen when the sky was eliminated from view. Judging surface color in natural scenes seems to be independent of an explicit illuminant cue.

13. Title: Luminance-color correlation is not used to estimate the color of the illumination (response to "influence of scene statistics on color constancy") (Granzier et al. 2005)

Author: J.J.M. Granzier, E. Brenner, F.W. Cornelissen and J.B.J. Smeets

Journal: Journal of Vision (2005) 5, 20-27

Points of this research: It has been suggested by Golz et al. that the correlation between luminance and color within a scene helps to separate the influences of illumination and reflectance. The results in this study, consistent with those of Golz and Macleod, confirm that the perceive color has a tendency toward the chromaticity of bright surfaces. However, the results here show that only the correlation within about 1 degree of the target is relevant. Therefore, it is suggested that the bias of perceived color away from the chromaticity of bright surfaces is the result of an interaction between color and luminance when the border contrast is determined, not the result of illuminant estimation from the correlation between luminance and color within the whole scene.

14. Title: Does human color constancy incorporate the statistical regularity of natural daylight? (Delahunt and Brainard 2004b)

Author: P.B. Delahunt and D.H. Brainard

Journal: Journal of vision (2004) 4, 57-81

Points of this research: The primary purpose of this experiment was to assess whether the degree of color constancy under illuminant changes along daylight locus was higher than that along red-green color direction. Significance differences in constancy under illuminant changes along different color direction were found for the invalid-cue conditions, but not for the valid-cue conditions. The degree of color constancy under blue and green test illuminants was higher than that under red and yellow illuminants.

Comment: According to our model, under blue and green illuminant, cone adaptation mechanism was used to mediate the color constancy; the presence of cue plays a very important role in color constancy under red and yellow illuminant, because the color constancy is mediated by reflectance model. Under valid-cue condition, observer can get many cues to help color constancy, so the color constancy performance under four illuminants does not make much difference. Under invalid-cue condition, observer cannot get cues from surround environment, which will reduce the degree of color constancy under red and yellow illuminant, but has no apparent effect on the color constancy performance under blue and green illuminant. Another reason is that the index calculation method led to the difference.

15. Title: Color constancy under changes in reflected illumination (Delahunt and Brainard 2004a)

Author: P.B. Delahunt and D.H. Brainard

Journal: Journal of Vision (2004) 4, 764-778

Points of this research: The color constancy under reflected light illumination changes was investigated in this study. It was found that the constancy with respect to reflected light changes is similar to results across light source changes. The color constancy under two physically distinct types of illuminant changes might be mediated by a common mechanism. Results also showed that the presence of local surround cue of the test patch played a critical role in the constancy across reflected light changes.

16. Title: Color constancy in context: roles for local adaptation and levels of reference

(Smithson and Zaidi 2004)

Author: H. Smithson and Q. Zaidi

Journal: Journal of Vision (2004) 4, 693-710

Points of this research: The background with high spatial-frequency chromatic variation was used to reduce the effect of chromatic contrast on the color appearance. Results clearly showed that the illuminant adaptation has a large effect on appearance-based color constancy, while the chromatic bias of the background has a small effect. When the test surface and its background were respectively illuminated by different illuminants, observers continued to show reasonable color constancy.

17. Title: Cone contributions to color constancy (Rinner and Gegenfurtner 2002)

Author: O. Rinner and K.R. Gegenfurtner

Journal: Perception (2002) 31, 733-746

Points of this research: It has been suggested by Foster (Foster et al. 2001b) that local cone excitation ratios play a prominent role in relational color constancy which refers to the ability of the observer to discriminate the reflectance changes from illuminant changes. In this paper, no difference was found in color constancy between the condition where color changes were induced by illuminant changes and the condition where local cone ratios of background surfaces were broke between the two illuminant conditions. The results show that constant cone ratios are not necessary for color constancy. In addition, it was shown that perceptual color constancy measured by achromatic adjustments is to a large part complete after 25ms.

18. Title: Influence of scene statistics on color constancy (Golz and MacLeod 2002)

Author: J. Golz and Donald I.A. Macleod

Journal: Nature (February 2002) 415(7), 637-640

Points of this research: The average chromaticity of the retinal image of an illuminated scene was used by the visual system to estimate the illumination. But this measure is not sufficient: a reddish scene under white light can produce the same mean stimulation as a neutral scene under red light. However, scene redness and illuminant redness affect the luminance-redness correlation within the image differently. It is reported that by exploiting both mean redness and luminance-redness correlation statistics, an observer discriminates the redness of objects making up the scene and the redness of the light source that illuminates the scene.

19. Title: Color constancy from temporal cues: better matches with less variability under fast illuminant changes (Foster et al. 2001b)

Author: D.H. Foster, K. Amano and S.M.C. Nascimento

Journal: Vision Research (2001) 41, 285-293

Points of this research: The degree of color constancy was significantly higher with sequential stimulus presentation than with simultaneous presentation. The variance between observers was also markedly reduced with sequential stimulus presentation. The visual system seems to have mechanisms in which temporal transient cues are utilized to mediate color constancy and adaptation is not required.

20. Title: How temporal cues can aid color constancy (Foster et al. 2001a)

Author: D.H. Foster, K. Amano and S.M.C. Nascimento

Journal: Color Research and Application (2001) supplement 26, S180-S185

Points of this research: Observers made surface-color matches between patterns presented successively or simultaneously. It was found that the degree of constancy was significantly higher for successive presentation. Transient cues may offer a useful source of information for making color constancy judgments.

21. Title: Response of the human visual system to variable illuminant conditions: an analysis of opponent-color mechanisms in color constancy (Nieves et al. 2000)

Author: J.L. Nieves, A. García-Beltrán and J. Romero

Journal: Ophthal. Physiol. Opt. (2000) 20(1), 44-58

Points of this research: A classical successive color matching experiment was done under illuminant changes along daylight locus. Arend's index calculation method was used to measure the degree of color constancy. Color vision mechanisms respond differently to iluminant changes when color constancy is considered at both receptoral and post-receptoral levels. At receptor level, the L and M cones tend to adapt so as to support color constancy, whereas S cones are strongly influenced by the illuminant changes. Good approaches to color constancy linked particularly to the yellow-blue mechanism.

22. Title: Mechanisms of color constancy under nearly natural viewing (Kraft and Brainard 1999)

Author: J.M. Kraft and D.H. Brainard

Journal: Proc. Natl. Acad. Sci. USA. (January 1999) 96, 307-312

Points of this research: Three classic hypotheses are that constancy is mediated by local adaptation, by adaptation to the spatial mean of the image, or by adaptation to the most intense image region. In this study, color constancy was measured under nearly natural viewing conditions by controlling the presence of these three factors. Three classic hypotheses were ruled out and it was suggested that there is more to constancy than can be easily explained by the action of simple visual mechanisms.

23. Title: Color constancy: the role of image surfaces in illuminant adjustment (Bäuml 1999a)

Author: K. Bäuml

Journal: J. Opt. Soc. Am. A (July 1999) 16(7), 1521-1529

Points of this research: The observers were instructed to adjust the test surface so that it appeared achromatic to them under bluish test illuminant or yellowish test illuminant on the daylight locus. A restrictive von Kries model is formulated by considering only influence of illuminant, ignoring the effect of image surfaces. It was found that the proposed von Kries model provided a good, although not perfect, description of the data under the different surface collections. The results suggest that image surfaces play only a minor role in the illuminant adjustment of human visual system.

24. Title: Simultaneous color constancy: how surface color perception varies with the illuminant (Bäuml 1999b)

Author: K. Bäuml

Journal: Vision Research (1999) 39, 1531-1550

Points of this research: The observers made two kinds of simultaneous asymmetric color matches; surface match and appearance match. Standard illuminant and four test illuminants were drawn from the CIE daylight locus. Both types of matches were well described by von Kries model. For both types of matches, von Kries model provide a substantially better description of the adjustment than perfectly color constant theoretical matches. The two types of matches differed only quantitatively, there was no qualitative difference between them. In the surface matches, L cone and M cone have nearly complete cone adaptation, and the deviations from perfect constancy were mainly due to failures in the adjustment of the S cone signals.

25. Title: Color constancy in the nearly natural image. 2. Achromatic loci (Brainard 1998)

Author: D.H. Brainard

Journal: J. Opt. Soc. Am. A (February 1998) 15(2), 307-325

Points of this research: Observers made achromatic settings under a variety of illuminants and the test surface was viewed against a number of different backgrounds. The results showed that the achromatic loci were mainly affected by the illumination, not the background surface. This indicated that color appearance cannot be predicted solely on the basis of local contrast. The absence of local contrast effect was ascribed to the richness of the stimulus condition in this experiment.

26. Title: Color constancy in the nearly natural image. 1. Asymmetric matches (Brainard et al. 1997)

Author: D.H. Brainard, W.A. Brunt and J.M. Speigle

Journal: J. Opt. Soc. Am. A (September 1997) 14(9), 2091-2110

Points of this research: The color constancy was measured by asymmetric matches under more natural viewing conditions. It was found that observers' matches can be described by either of two simple models, diagonal model and equivalent illuminant model. Diagonal model may be linked to ideas about the cone adaptation at the retinal level. Equivalent illuminant model, proposed in this study, provides a link between human performance and computational models of color constancy.

27. Title: Color constancy in variegated scenes: role of low-level mechanisms in discounting illumination changes (Zaidi et al. 1997)

Author: Q. Zaidi, B. Spehar and J. DeBonet

Journal: J. Opt. Soc. Am. A (October 1997) 14(10), 2608-2620

Points of this research: It was found that photoreceptor and opponent-color signals from a large sample of natural and man-made objects under one kind of natural daylight were systematically correlated with the signals from those objects under other different phase of daylight. In a variegated scene, correlations between spatially local chromatic signals across illuminants and the desensitization caused by eye movements across spatial variations help the visual system to discount illuminant changes.

28. Title: Limitations of surface-color and apparent-color constancy (Kuriki and Uchikawa 1996)

Author: I. Kuriki and K. Uchikawa

Journal: J. Opt. Soc. Am. A (August 1996) 13(8), 1622-1636

Points of this research: Surface-color matching and apparent-color matching experiments were carried out under illuminant changes along daylight locus. With brief adaptation, the chromatic surround, such as Mondrian, can contribute to better color constancy than black or gray surround. Complete adaptation to the illuminant helps to achieve almost perfect color constancy in surface-color matches. In cone specific analysis, it was found that S cone systems were more influenced by the illuminant than were the other cone systems.

29. Title: Color constancy under natural and artificial illumination (Lucassen and Walraven 1996)

Author: M.P. Lucassen and J. Walraven

Journal: Vision Research (1996) 37(17), 2699-2711

Points of this research: An asymmetric haploscopic matching paradigm was used to measure the color constancy. Four test illuminants were used: two broadband phases of daylight and two spectrally impoverished metamers of these lights, each consisting of only two wavelengths. The results show the expected failure of color constancy under two-wavelength illumination, and approximate color constancy under natural illumination. The "response function" model (Lucassen & Walraven, 1993) was found to provide somewhat more accurate predictions, under all illuminant conditions, than "Judd-Cohen" model.

30. Title: Color memory and color constancy (Jin and Shevell 1996)

Author: E.W. Jin and S.K. Shevell

Journal: J. Opt. Soc. Am. A (October 1996) 13(10), 1981-1991

Points of this research: In this experiment, it was found that the complex and the "gray" backgrounds have very different effects on the measurements of color constancy. The color recalled from memory after a 10-min delay is least affected by the illuminant during training when complex background was presented. However, the illuminant during training has a strong effect on the recalled color when only a "gray" background was presented.

31. Title: Time course of chromatic adaptation for color-appearance judgments (Fairchild and Reniff 1995)

Author: M.D. Fairchild and L. Reniff

Journal: J. Opt. Soc. Am. A (May 1995) 12(5), 824-833

Points of this research: The results suggested two stages of adaptation: one extremely rapid (a few seconds) and the other somewhat slower (approximately 1 min). Chromatic adaptation at constant luminance was 90% complete after approximately 60s.

32. Title: Photoreceptor sensitivity changes explain color appearance shifts induced by large uniform backgrounds in dichoptic matching (Chichilnisky and Wandell 1995)

Author: E.J. Chichilnisky and B.A. Wandell

Journal: Vision Research (1995) 35(2), 239-254

Points of this research: This paper was used to test von Kries' hypothesis in uniform background conditions. It was found that photoreceptor sensitivity changes explained the effect of numerous large uniform backgrounds on the color appearance of many targets with high precision. Post-receptoral sensitivity changes provided a poorer account of the data. The apparent sensitivity of each receptor class varied inversely with changes in background light absorbed by that receptor class, but did not depend on background light absorbed by the other two receptor classes.

33. Title: Asymmetric color matching: how color appearance depends on the illuminant (Brainard and Wandell 1992)

Author: D.H. Brainard and B.A. Wandell

Journal: J. Opt. Soc. Am. A (September 1992) 9(9), 1433-1448

Points of this research: Six test illuminants were obtained along daylight locus. For any illuminant change, it was found that the mapping between the cone coordinates of standard objects and matched objects was well approximated by a diagonal linear transformation. The results were consistent with von Kries' hypothesis. In addition, the change in the diagonal elements of the linear transformation was a linear function of the illuminant change.

34. Title: Binocular measurements of chromatic adaptation (Troost et al. 1992)

Author: J.M. Troost, L. Wei and C.M.M. De weert

Journal: Vision Research (1992) 32(10), 1987-1997

Points of this research: The color difference between adapting light and target has an influence on the extent of chromatic adaptation. It was found that the color shift in observers' matches caused by chromatic adaptation has a maximum when the color differences between target and adapting light lie around 0.05 (u', v')-chromaticity units. Except for the simple von Kries model, Retinex Theory and difference contrast, a number of models gave good predictions for the L-wave and M-wave fundamental systems, but that predictions for the S-wave system were less accurate.

35. Title: Chromatic adaptation to natural and incandescent illuminants (Fairchild and Lennie 1992)

Author: M.D. Fairchild and P. Lennie

Journal: Vision Research (1992) 32(11), 2077-2085

Points of this research: The adapting backgrounds were spatially and temporally varied. The effect of spatial configuration and temporal configuration of the adapting background on the chromatic adaptation was investigated. The results show that appearance of the test depends substantially on what was viewed in the preceding 30 sec or so. Chromatic adaptation is spatially localized with a time-course on the order of 10 sec. Since the mechanisms were shown to be spatially localized, the observed temporal integration across eye movements is required to allow these mechanisms to adjust to the spatially integrated scene chromaticity.

36. Title: Simultaneous color constancy: papers with diverse Munsell values (Arend et al. 1991)

Author: L.E. Arend, A. Reeves, J. SchiriIlo and R. Goldstein

Journal: J. Opt. Soc. Am. A (April 1991) 8(4), 661-672

Points of this research: Arend and Reeves (Arend and Reeves 1986) described measurements of color constancy in simulation of arrays of colored papers of equal Munsell value. The experimental design in this study was the same as that in the previous study, except colored papers here spanning a wide range of Munsell values. The data agreed with those of previous equal-value experiment.

37. Title: Corresponding chromaticities for different states of adaptation to complex visual fields (Breneman 1987)

Author: E.J. Breneman

Journal: J. Opt. Soc. Am. A (June 1987) 4(6), 1115-1129

Points of this research: By comparing the results of various experiments under adaptation to chromatically different illuminants and to different levels of the same illuminant of a complex visual field, it was found that; (1) Adaptation to chromatically different illuminants is often incomplete, and the amount of adaptation is less at lower level of illuminance and less for the "blue sensitive" mechanism than for the other two; (2) A linear von Kries model with experimentally determined coefficients gave a good description of data; (3) Adaptation to different levels of the same illuminant produced a chromatic adaptation change even the illuminants have the same chromaticity.

38. Title: Simultaneous color constancy (Arend and Reeves 1986)

Author: L.E. Arend and A. Reeves

Journal: J. Opt. Soc. Am. A (October 1986) 3(10), 1743-1751

Points of this research: The adjusted patch was surrounded by a single color (annulus display) or by many colors (Mondrian display). Observers were instructed to make appearance match or surface match. It was found that the paper matches were approximately color constant; the appearance matches showed little color constancy.

39. Title: Effect of chromatic adaptation on the achromatic locus: the role of contrast, luminance and background color (Werner and Walraven 1982)

Author: J.S. Werner and J. Walraven

Journal: Vision Research (1982) 22, 929-943

Points of this research: The shift in chromaticity of the achromatic point was in the direction of the chromaticity of the background, while the magnitude of the shift increased as an increasing function of background luminance and as a decreasing function of contrast.

40. Title: Chromatic-adaptation study by subjective-estimation method (Sobagaki et al. 1974)

Author: H. Sobagaki, T. Yamanaka, K. Takahama and Y. Nayatani

Journal: J. Opt. Soc. Am. A (June 1974) 64(6), 743-749

Points of this research: The effect of chromatic adaptation on color perception was investigated by use of a subjective-estimation method under a fluorescent lamp and CIE standard source A. The average effects of chromatic adaptation suggested by 13 observers' data were found to fall approximately in the middle of the range of results predicted by several chromatic adaptation models. Lightness constancy was found, irrespective of the change of chromatic adaptation.

41. Title: Prediction of color appearance with different adaptation illuminations (Burnham et al. 1957)

Author: R.W. Burnham, R.M. Evans and S.M. Newhall

Journal: J. Opt. Soc. Am. A (January 1957) 47(1), 35-42

Points of this research: Specifications data of colors which have the same appearance with relatively complete adaptation to daylight, tungsten, and a third greenish illuminant was presented. A method was proposed to predict the color appearance under different illuminants. However, this prediction was limited to pairs of illuminants in this study since the transformation M matrices were developed experimentally.

Chapter 2

General methods

2.1 Equipment

The stimuli were presented on the screen of a 1024×768 resolution, 120 Hz frame rate, 19-in. CRT color monitor (Sony, Trinitron G420), controlled by a computer with a VSG Visage-256MB graphics card (Cambridge Research Systems, Inc.) providing 14-bit resolution for each RGB phosphor. In order to construct linear relationship between input voltage and output phosphor luminance, gamma correction was carried out using light measurement instrument ColorCAL colorimeter controlled by vsgDesktop display calibration software. A 90×60 cm black board was put in front of the screen and separated presentation of screen into two halves, which made left half of the screen viewed from the left side and right half viewed from the right side. The viewing distance was 90 cm.

In order to calculate the error rate between displayed coordinates and real coordinates, each simulated Munsell color chip was displayed on the screen as a form of two separated, rectangular, 5 degree patches and the chromaticity coordinates and luminances of left patch and right patch were measured respectively for two times with an instrument Chroma Meter CS-1000. The averaged errors of left display calculated over all color chips were 2.32% in x, 1.17% in y and 1.92% in Y; the averaged errors of right display were 2.02% in x, 1.59% in y and 3.35% in Y.

Observers adjusted the chromaticity and luminance of test patch with six-button response box of VSG (CB6, CRS) in the CIE 1931 chromaticity diagram. The functions of six buttons on the response box for color normal and anomalous observers were; two buttons were used to control blue-yellow color, two buttons to control red-green colors and two buttons to control luminance (bright-dark). Dichromats reported that they could get any color they want by using only blue-yellow and luminance buttons. Therefore, they only used blue-yellow buttons and luminance buttons to adjust color. The color controlled by blue-yellow button varies along a blue-yellow line which connects the chromaticity point of blue phosphor and chromaticity point of yellow with the maximum luminance of red and green phosphors of the monitor, shown in Figure 2.1.

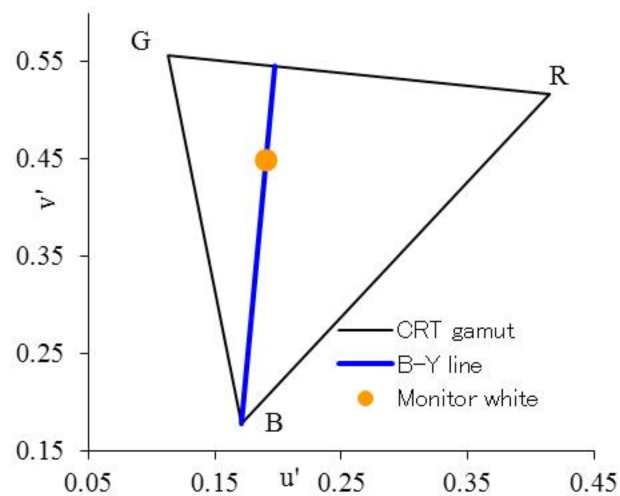


Figure 2.1 B-Y line: Color adjustment locus of dichromats

2.2 Stimuli

All the stimuli were simulations of Munsell matte colored chips in a dark surround. The backgrounds of two stimuli patterns were identical spatial arrangements of ellipses illuminated by different light sources. The standard illuminant was illuminant D65 and invariant in all experiment sessions. Test illuminant was constructed by a linear combination of the daylight spectral basis functions. There were totally four test illuminants which were obtained by increment (labeled green) or decrement (red) of M cone stimulation in 5% (Desaturated) or 10% (Highly-saturated) from D65 along the individual confusion line for dichromats and along standard deuteranopic confusion line (x_d=1.4000, y_d=-0.4000) or by increment or decrement of L cone stimulation in 2.5% (Desaturated) or 5% (Highly-saturated) from D65 along standard protanopic confusion line (x_p=0.7465, y_p=0.2535). Standard deuteranopic and protanopic confusion points here were used by Smith and Pokorny to derive the spectral sensitivity of cone fundamentals for color normal observers. For protanomalous observer, test illuminants were obtained by changing L-cone modulation in 2.5% or 5% from D65 along the pseudo-confusion line, which was defined as the longer axis of the color discrimination ellipsoid of the Cambridge Color Test (CCT). The locations of another four test illuminants were close to daylight locus, but not on daylight locus. The chromaticity coordinates in CIE 1931 chromaticity diagram of four Highly-saturated illuminants are: green(G) (0.2606, 0.3638); red(R) (0.3557, 0.3002), purplish blue(PB) (0.3042, 0.2934) and greenish yellow(YG) (0.3236, 0.3747) shown in Figure 2.2. The corresponding chromaticity coordinates of Desaturated illuminants are located on the half way from D65 illuminant to Highly-saturated illuminants respectively.

Two 5-deg-square patterns were simultaneously presented 8 degrees apart on the color monitor. By referring to the standard pattern, which was virtually illuminated by standard illuminant D65, an observer adjusted the color of a central patch in the test pattern (test patch) virtually illuminated by one of test illuminants. The structure of the standard pattern and the test pattern was the same. In

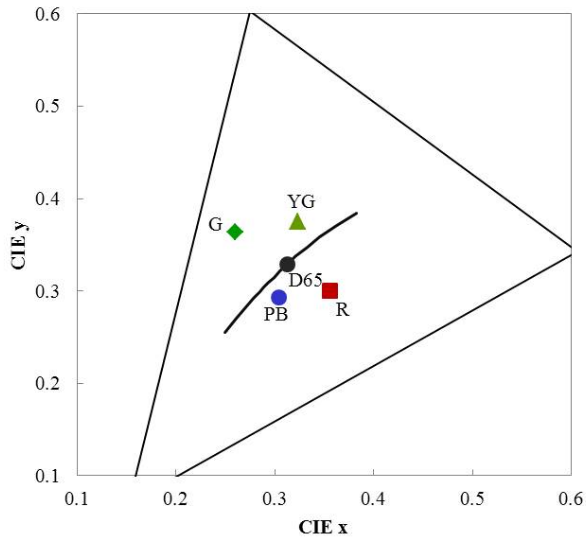


Figure 2.2 Location of the five experimental illuminants in the CIE 1931 xy chromaticity diagram

each pattern, 1-deg-square central patch was surrounded by a background extracted from the whole screen on which 3000 superimposed ellipses were drawn. Each ellipse had a random position and orientation and a random size that changed between 0.4 and 0.6 degrees along the minor axis and between 0.8 and 1 degree along the major axis. These ellipses were simulation of eight surfaces under standard or test illuminants. There were totally six backgrounds with different reflectance surfaces for six sessions. The corresponding 48 Munsell surfaces were taken from Munsell Book of Color in Lightness 5 and Chroma 6, as approximately making 45 degree distance in the hue circle of the Munsell Color System (Chroma was changed to 4 or 8, if the hue was randomly matched to one of 12 surface colors above). The central patch of each stimulus was one of 12 different surfaces: Munsell 5R5/6, 2.5YR5/6, 10YR5/6, 7.5Y5/6, 5GY5/6, 2.5G5/6, 10B5/6, 7.5PB5/6, 5P5/6, 2.5RP5/6, 10RP5/6, and 20% flat-reflectance surface (corresponding to numbers from 1 to 12) which appeared in different trials according to the random sequence. In order to cover as large color range of the Munsell color as possible, each one central patch, except 20% flat-reflectance surface, was taken every 3 hues on 40 Munsell surfaces on the 5/6 hue

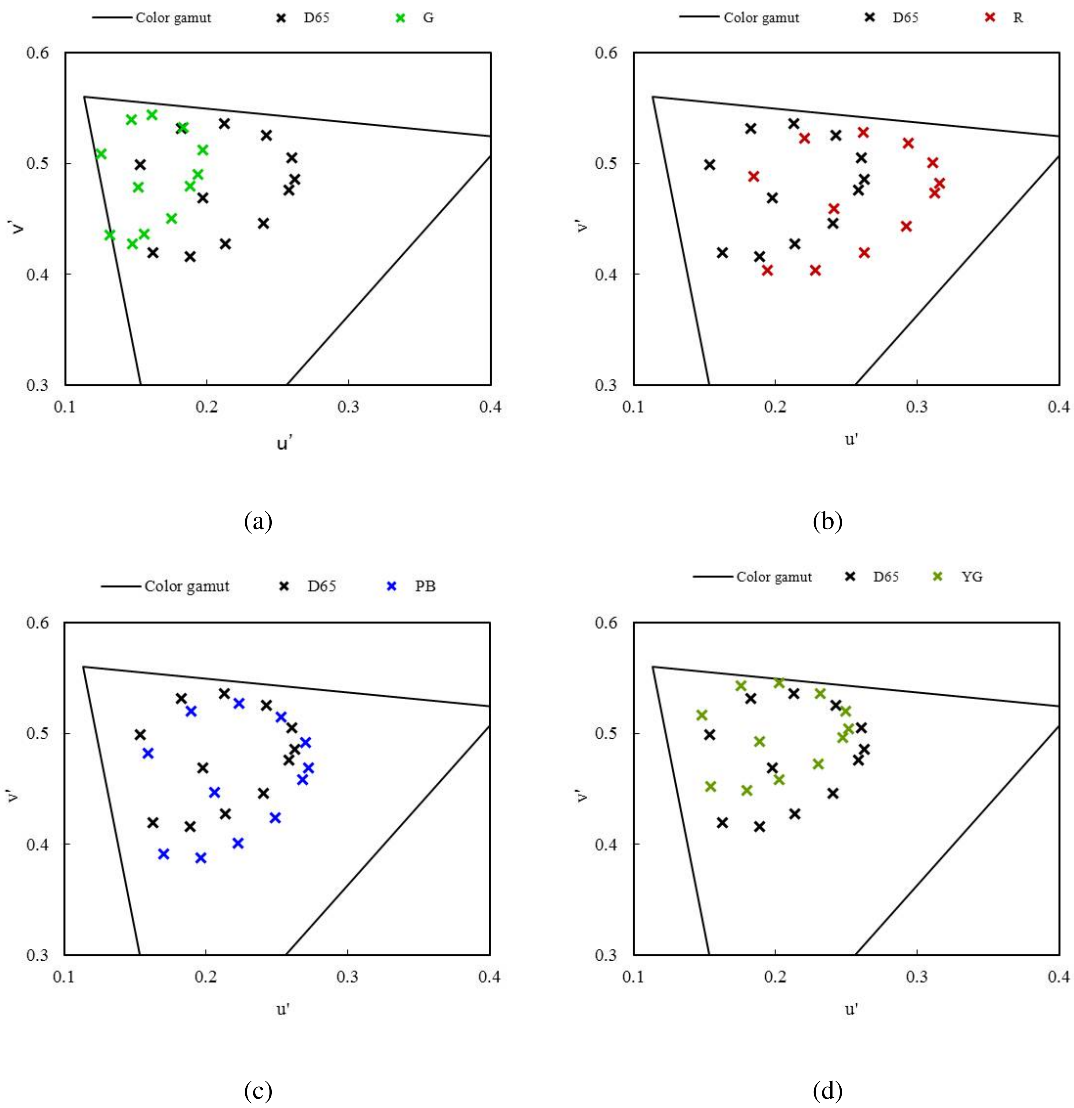


Figure 2.3 The location of twelve central patches under four test illuminants (Highly-saturated R, G, PB and YG) compared to those under D65 illuminant in CIE 1976 (u', v') diagram.

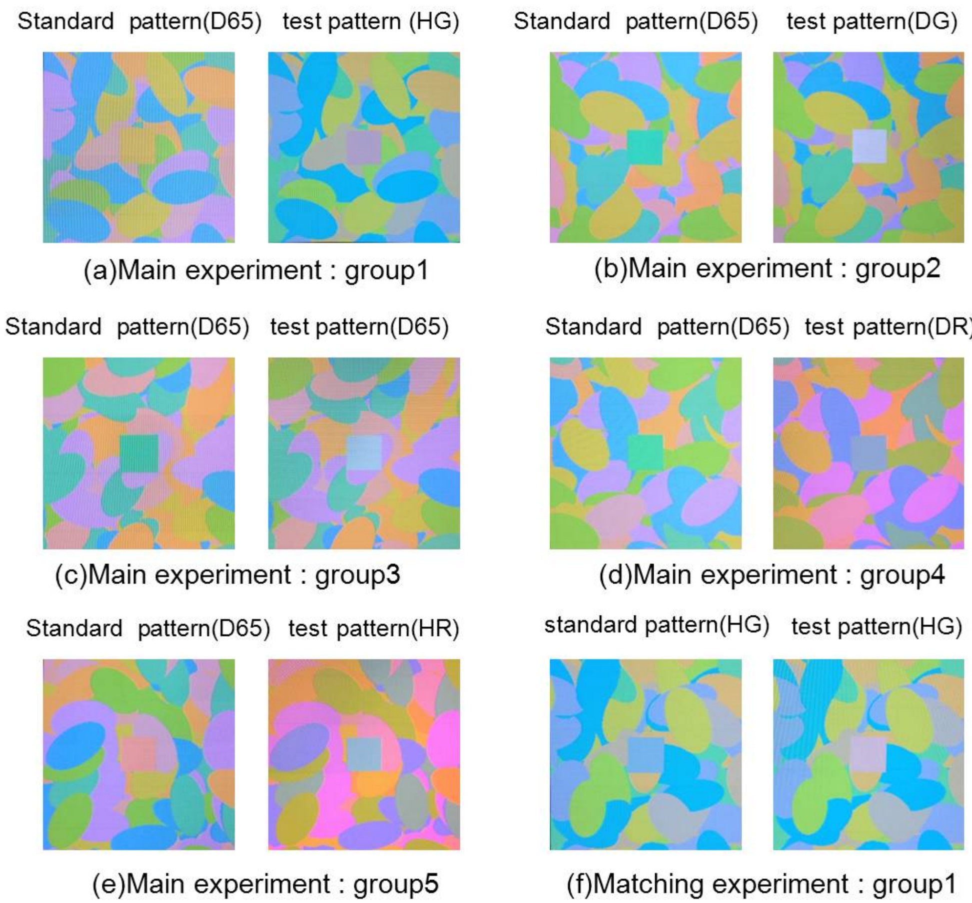


Figure 2.4 5 groups stimuli in one session of main experiment(a, b, c, d, e) and one group stimuli with HG illuminant in matching experiment(f).

circle. Chromaticity coordinates of Munsell color chips under daylight D65 and test illuminants were calculated using CIE 1931 standard color matching functions (for the standard observer). Spectra were sampled at 5-nm intervals, and the integration was performed over 380 to 780nm. The intensity of all illuminants was adjusted to make the same luminance on the 20% flat-reflectance surface illuminated as 25 cd/m^2. Figure 2.3 illustrates the distribution of the twelve central colors under four Highly-saturated illuminants compared to the distribution under D65 illuminant in the approximately uniform color diagram CIE 1976 (u', v'). In Figure 2.3, black symbols indicate the colors under D65 illuminant; Figure 2.3(a, b, c, d) shows the comparison between D65 and Highly-saturated illuminants G, R, PB and YG.

The stimuli simulated under four test illuminants along confusion line in main experiment and the stimuli under Highly-saturated green illuminant in matching experiment were presented in Figure 2.4.

2.3 Procedure

At the beginning of the first session, observers were given 3 min to practice controlling chromaticity and luminance with the six-button response box (CB6, CRS). Observers initially adapted to the D65 white of 25 cd/m^2 for 5 min. Each session was divided into 5 groups according to 5 test illuminant and consisted of totally 5×12=60 trials for 12 colors of the standard patch. Each trial of one group had the same test illuminant. There were totally six sessions for main experiment. Before starting trials on each group, the observer adapted for 5 min to an ellipses background condition, which was the same as formal experimental condition, but without the central patch. After adaptation, they viewed standard pattern from one side of the black board with one eye and test pattern from the other side of the black board with the other eye. In order to match the standard patch in standard pattern, observers used response box to vary the chromaticity and luminance of test patch in test pattern. In each trial, the starting chromaticity of test patch was set at white and starting luminance was set randomly in the 30% range based on average luminance value of twelve central patches under test illuminant. The additional matching experiment for dichromats had three sessions. In matching experiment of dichromats, illuminants of two patterns were the same: both HG illuminant (see Figure 2.4f), HR, DG or DR.

One session approximately took one and half hours, however, there was one color-normal observer who took three hours for each session.

2.4 Instruction

Observers were told that the paper arrays of two patterns were identical and illuminated by different or same light sources and one pattern could not be seen simultaneously by two eyes. Observers were instructed to adjust the color and brightness of rectangular patch in the test pattern and make the test patch look as if "it were cut from the same piece of paper as the corresponding patch in the standard pattern". In the matching experiment, observers were told that the illumination of the two patterns was the same. Time was not limited.

2.5 Observers

The color vision of observers was classified by five clinical methods; Ishihara pseudoisochromatic plates, the Farnsworth D-15 test, Standard Pseudo-Isochromatic Plates and Farnsworth-Munsell 100 hue test and Cambridge Color Test (CCT).

The CCT was used to measure individual confusion lines of dichromats and color discrimination ability of normal observers and the anomalous observer. There were 5 observers with normal color vision (RK, KM, OC, TM and TG) and 7 color deficient observers; 3 deutans (OK, LX and KBY), 2 protans (KMY and OTK) and 2 protanomalous observers (GY and PA). The test results

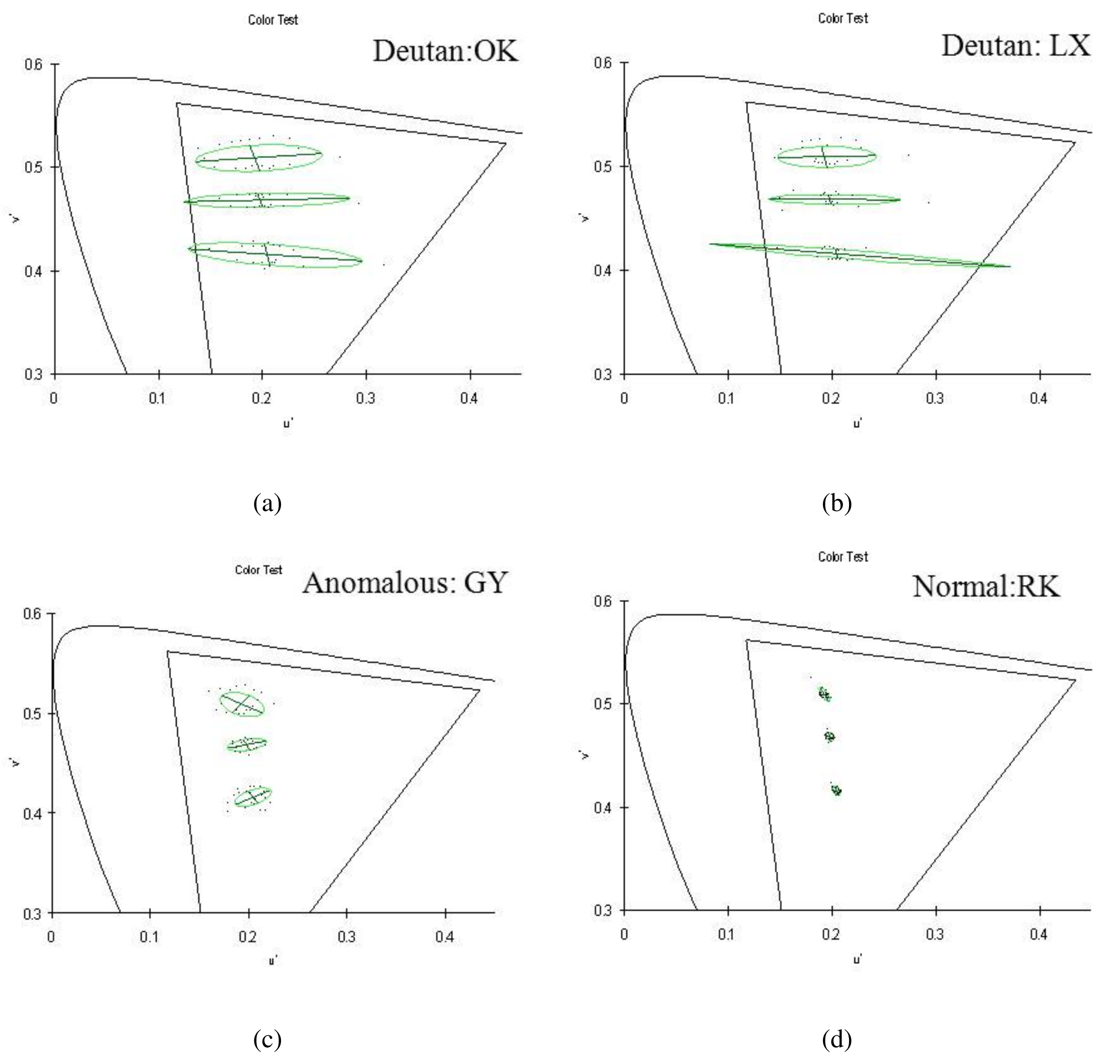


Figure 2.5 CCT resuls of five observers (2 deutan, 1 protanomalous observer and 1 color normal observer

of CCT for four observers are illustrated in Figure 2.5. Figure 2.5 (a and b) show the results of two deutans OK and LX. For observers OK and LX, the ellipses extend to the gamut available from the color monitor and their long axes are directed towards the deutan copuntal point. Figure 2.5c shows the result of one protanomalous observer GY. The length of the ellipse of GY is not so long. His color discrimination ability is not so bad, compared with some extreme protanomalous observers. Figure 2.5d show the result of one color normal observer. 100-Hue test results showed that RK's color discrimination ability is highest in 5 color normal observers. Here, in CCT, the size of discrimination ellipses is very small, which again indicates that the color discrimination ability of RK is higher than averaged value.

2.6 Data analysis in traditional way

Arend's constancy index was used to support the qualitative description of color constancy performance. Perfect color constancy is indicated by index=1; no color constancy is indicated by index=0. For example, when the color chip R5/6 was displayed in the standard pattern, if the observer had perfect color constancy, he would set the chromaticity of test patch to that of R5/6 under test illuminant. On the contrary, if he had no color constancy, he would set the chromaticity of test patch to that of R5/6 under D65 illuminant and make the chromaticity of test patch the same as that of R5/6 under D65.

Arend's index calculation formula is described as: I=1-b/a, wherein I denotes constancy index; b denotes the Euclidean distance from the matched point to the theoretical point, at which color constancy would be perfect; a denotes the Euclidean distance from the standard point, which is the chromaticity of test patch under D65 illuminant, to the theoretical point. The description is illustrated in Figure 2.6.

Because dichromats perceived each color as a mixture of blue and yellow hues, normal chromaticity points could not be used to calculate the color constancy indices. Thus, coordinates of standard and theoretical (perfect constancy) colors were projected onto the blue-yellow line of the color control. Monitor's blue (phosphor) and yellow were used to make color change maximum in the gamut.

In Figure 2.7, filled triangle denotes the matched point; open circle is the standard point; open triangle is the theoretical point. In D65 to D65 illuminant conditions, original standard points were projected onto blue-yellow line (B-Y line). In the matching experiment, original theoretical points were projected onto blue-yellow line under each test illuminant.

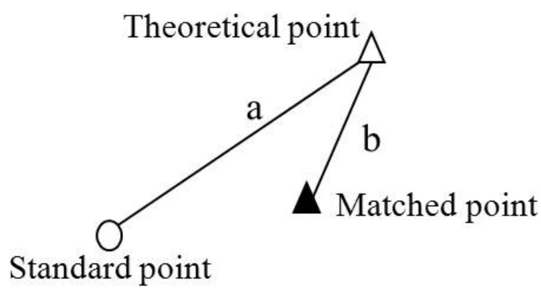


Figure 2.6 Representation of points used in Arend's index calculation

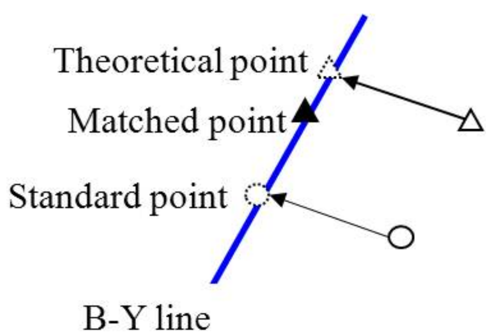


Figure 2.7 Modified version of Arend's index calculation for dichromats

Chapter 3

Color constancy under green illuminant and red illuminant

3.1 Introduction

Asymmetric color matching is one of methods to measure the color constancy performance of observers. Under asymmetric color matching, stimuli were being compared under different viewing conditions (Wyszecki & Stiles 1982), here different illuminants. Stimuli can be viewed successively or simultaneously. For simultaneous color constancy, standard scene and test scene were presented side by side at the same time; for successive color constancy, standard scene and test scene were presented sequentially at the same position. Color constancy of people with normal color vision was investigated by many researchers under simultaneous or successive conditions. Arend and Reeves investigated simultaneous color constancy of normal observers with Munsell color chips with the same lightness (Arend and Reeves 1986) and different lightness (Arend et al. 1991), respectively. Troost and Weert (Troost and Weert 1991) carried out an experiment in which illuminants were presented successively. It was concluded that color constancy must be achieved by relying on relationships that are insensitive to the illumination rather than by consciously judging the color of the illumination (Granzier et al. 2009). Spatial separation of test samples provides cue that allowed observers to maintain two separate perceptual references (Lee and Smithson 2012).

However, there are some people, who account for about 5 percent of the whole population, confuse between red and green from birth. Protan and deutan are two common types of color deficiency. Rüttiger's experiment (Rüttiger et al. 2001) showed that color deficient observers display color constancy similar to that of normal observers along red-green cardinal axis. Amano et al. adopted an experimental method in which observers were required to discriminate surface reflectance changes from illuminant changes. It was reported (Amano et al. 2003) that dichromatic observers' distributions were more elongated than for normal controls in the directions of their confusion line when illuminant was changed along the line perpendicular to daylight locus. Along daylight locus, deuteranopes and protanopes discriminated illuminant changes from reflectance changes more poorly than normal trichromats with Munsell spectral reflectances but less so with natural spectral reflectances (Baraas et al. 2010).

From the above researches, it can be concluded that along daylight locus, or line perpendicular to the daylight locus, color deficient observers still has partial color constancy and their poor color discrimination did not correspond to the equally poor color constancy. This may be because color deficient observers can get cue by detecting the difference of two illuminants' color. In those studies, the chromaticity coordinates of two illuminants are not located on the confusion lines of deutans and protans. Although color deficient observers do not have the good color discrimination ability, they are more sensitive to the color of two illuminants along daylight locus or along the line perpendicular to the daylight locus.

In order to demonstrate if the discrimination of color difference between standard illuminant and test illuminant contributes to the color constancy of color deficient observers, in this research, the chromaticity coordinates of two illuminants were located on the individual confusion lines of dichromatic observers. Four test illuminants were obtained by increasing or decreasing 5% (2.5%) and 10% (5%) M cone (L cone) modulation along individual deuteranopic (protanopic) confusion line. Observers observed standard pattern with one eye and test pattern with the other eye at the same time and made paper match.

3.2 Results

3.2.1 Measurement on color constancy index

Figure 3.1 shows six-session mean chromaticity settings of observers with normal color vision and color deficient observers under test illuminants and D65 illuminant. In Munsell 100 Hue color test, RK's test score is lower than average score of most people and TM's test score is higher than average score of most people, which indicates that RK has higher color discrimination ability and TM has lower color discrimination ability. From Figure 3.1, it can be seen that under illuminant HG (Highly-saturated green), color normal observers and protanomalous observer make adjustment to the illuminant color direction. Protanomalous observer even make more adjustment toward illuminant color direction than color normal observers. The setting of deutan LX seems random. Matched points of LX located at the side of the standard point but far over from the standard point, or the side of the theoretical point but far over from the theoretical point. In Figure 3.2, both of two color normal observers have very good adjustment. Under HR (Highly-saturated red) illuminant, the performance of color normal observers is better than protanomalous observer. LX's data is still random. Figure 3.3 shows the matches of four observers under D65 illuminant to D65 illuminant control illuminant condition. RK's adjustment is the most accurate. Deutan LX's matches have some deviations. Figure 3.4 shows the mean constancy index over 12 central patches under different illuminants for each observer. Color constancy performance of GY under Highly-saturated green and red illuminants is better than that under Desaturated green and red

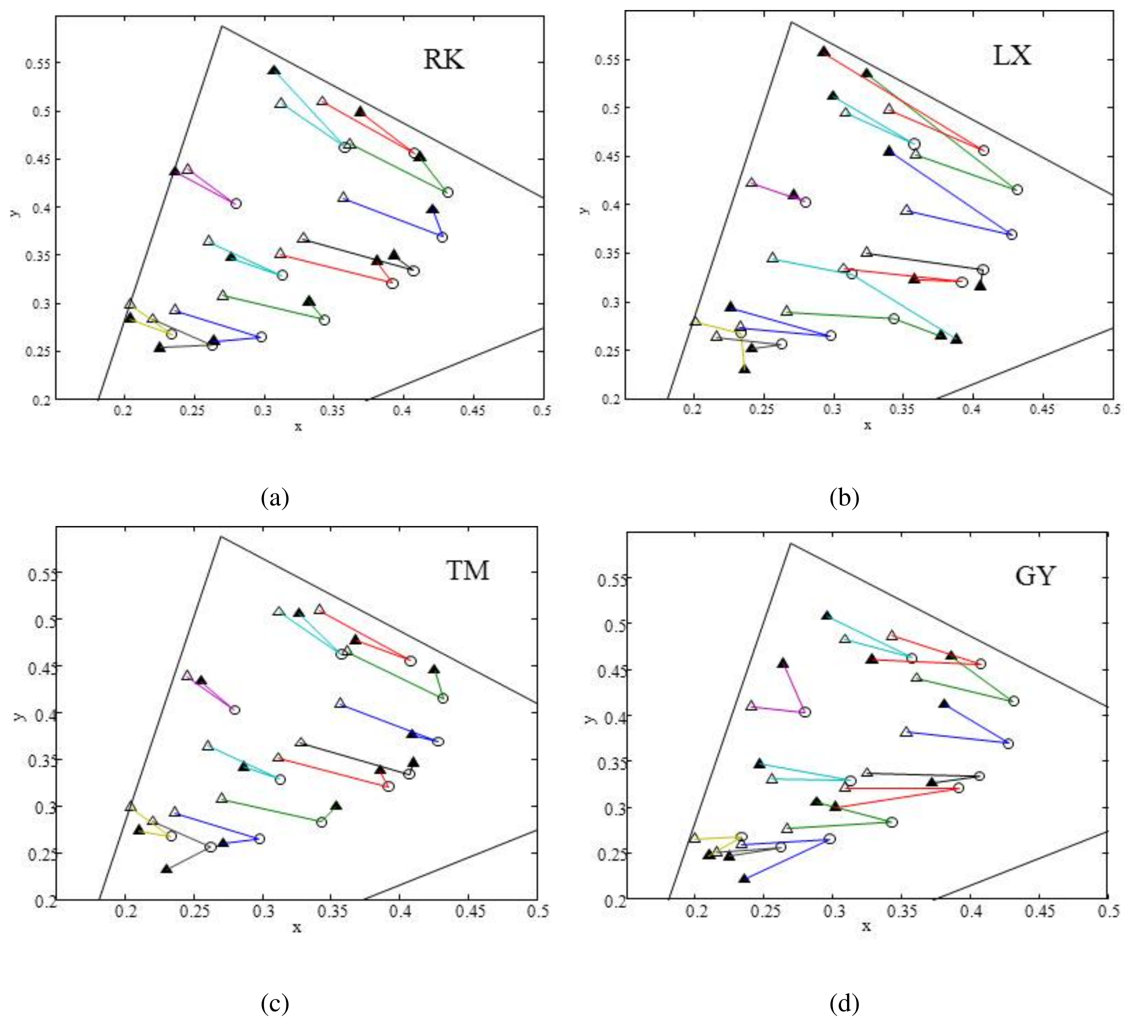


Figure 3.1 Chromaticity settings of four observers (2 color normal observers (RK and TM), 1 protanomalous observer (GY) and 1 deutan (LX)) under green illuminant

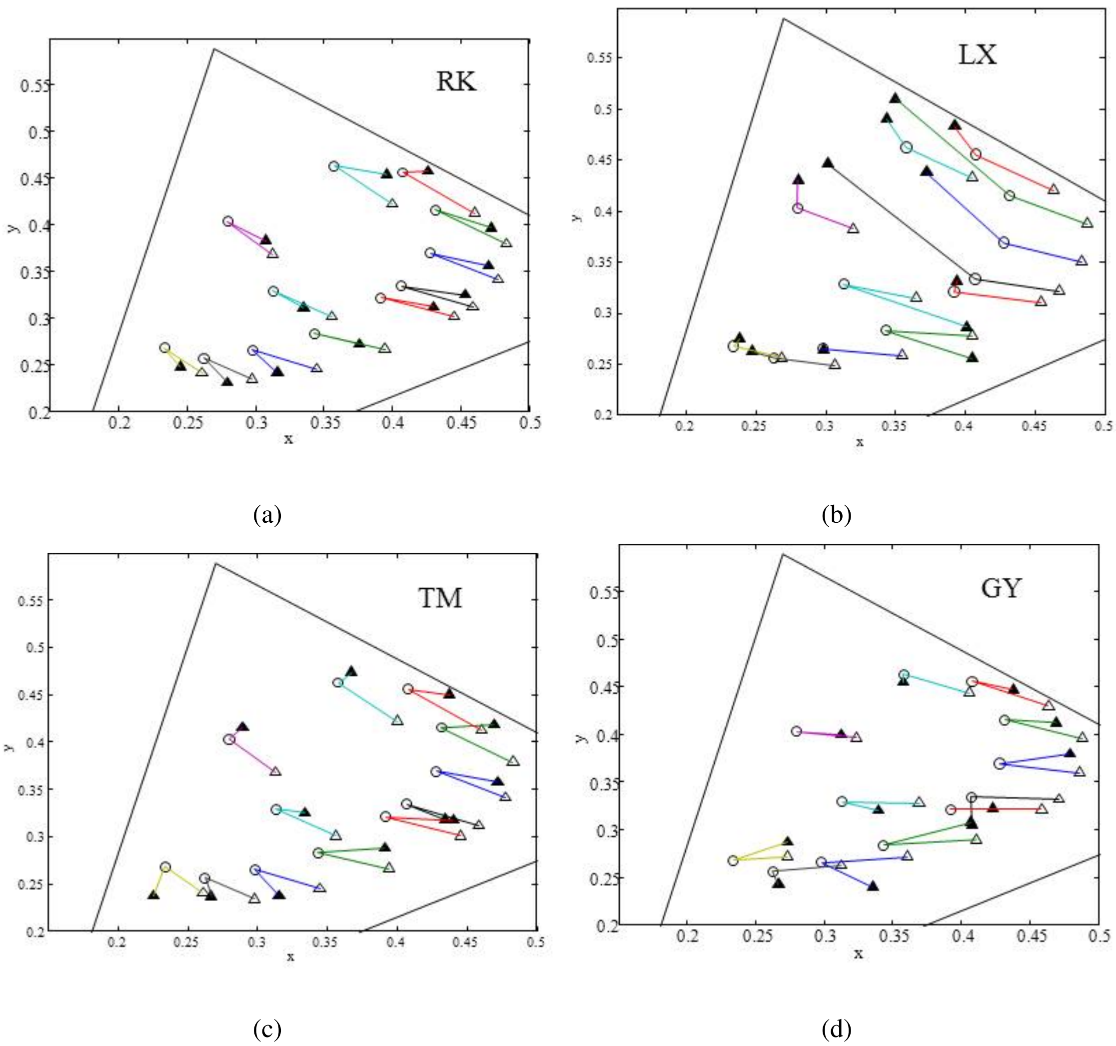
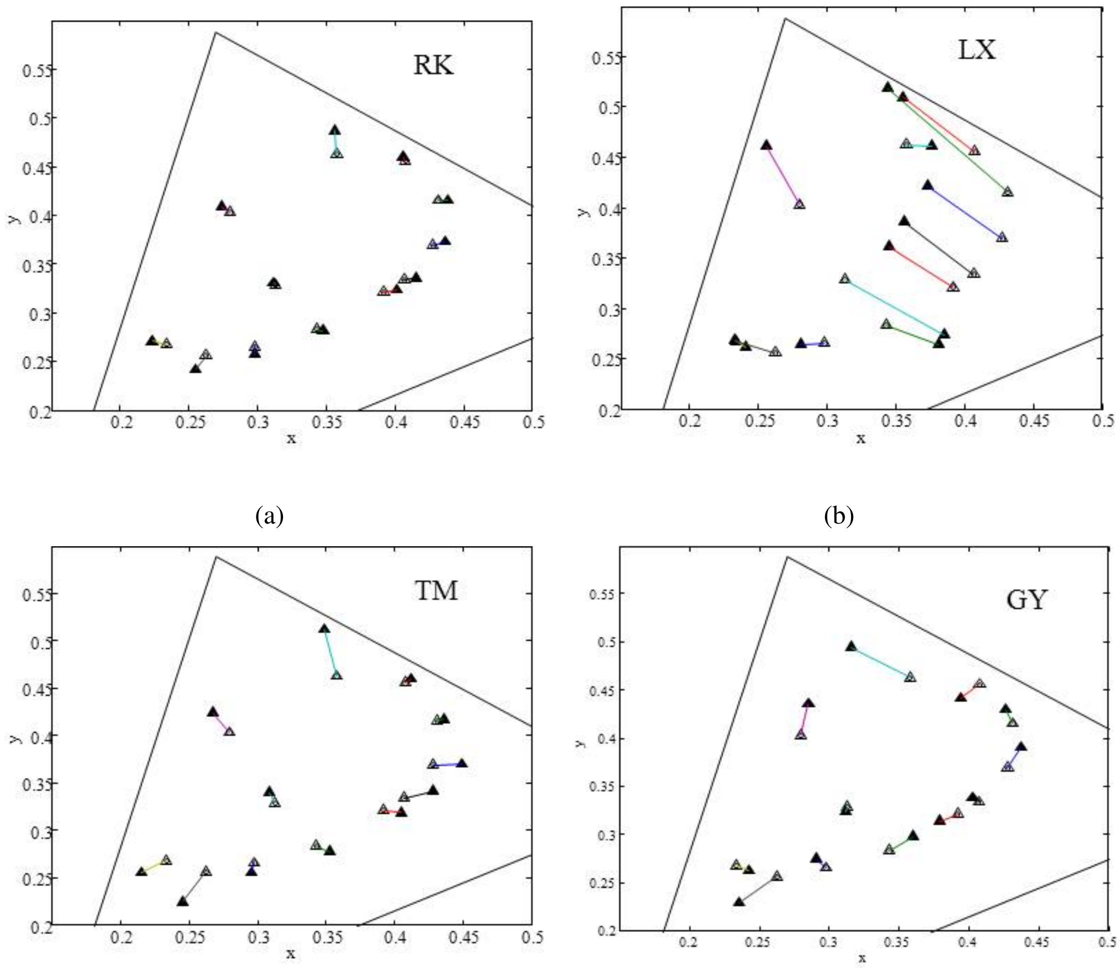


Figure 3.2 (u', v') chromaticity settings of four observers (the same observers with Figure 3.1) under red illuminant



(a) (b)

(c) (d)

Figure 3.3 (u', v') chromaticity settings of four observers over twelve patches under D65 illuminant

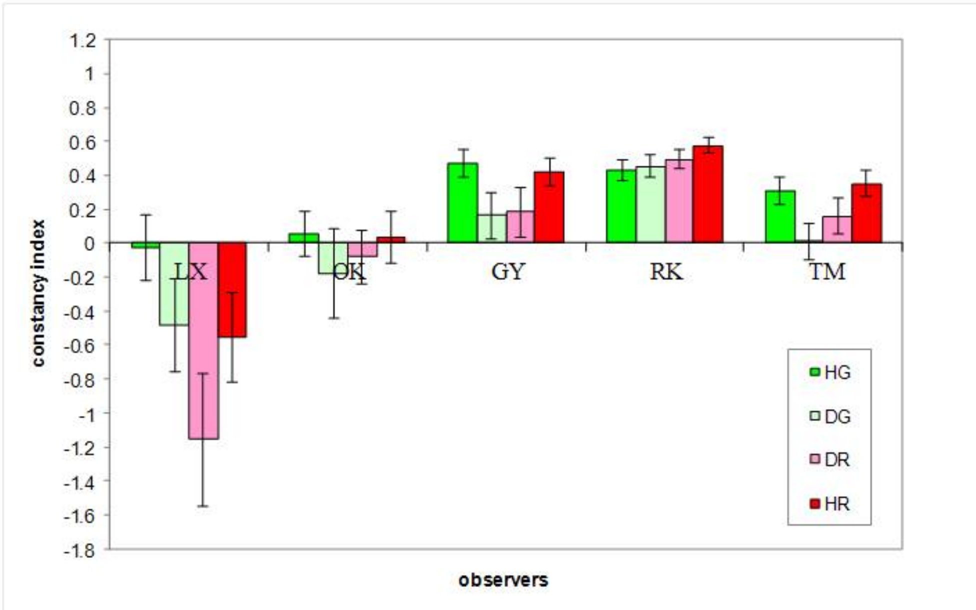


Figure 3.4 Mean constancy index over 12 central patches, 6 sessions for four observers (the same observers with Figure 3.1)

illuminants. For standard error, from largest to smallest, the sequence of observer is LX, GY, TM, RK. Figure 3.4 also shows that for color normal observer TM and color deficient observers LX and GY, color constancy under Highly saturated green and red illuminant is stronger than that under Desaturated green and red illuminant. For the index calculation of dichromats, the standard points and theoretical points have to be projected onto blue-yellow line. The theoretical points were projected onto blue-yellow line by matching experiment. Figure 3.5 shows the data of the deutan OK. In each panel, the data of two central patches under HG illuminant was plotted. Corresponding index value of Figure 3.5 is illustrated in Figure 3.6. The index was calculated according to the method discussed in Chapter 2.

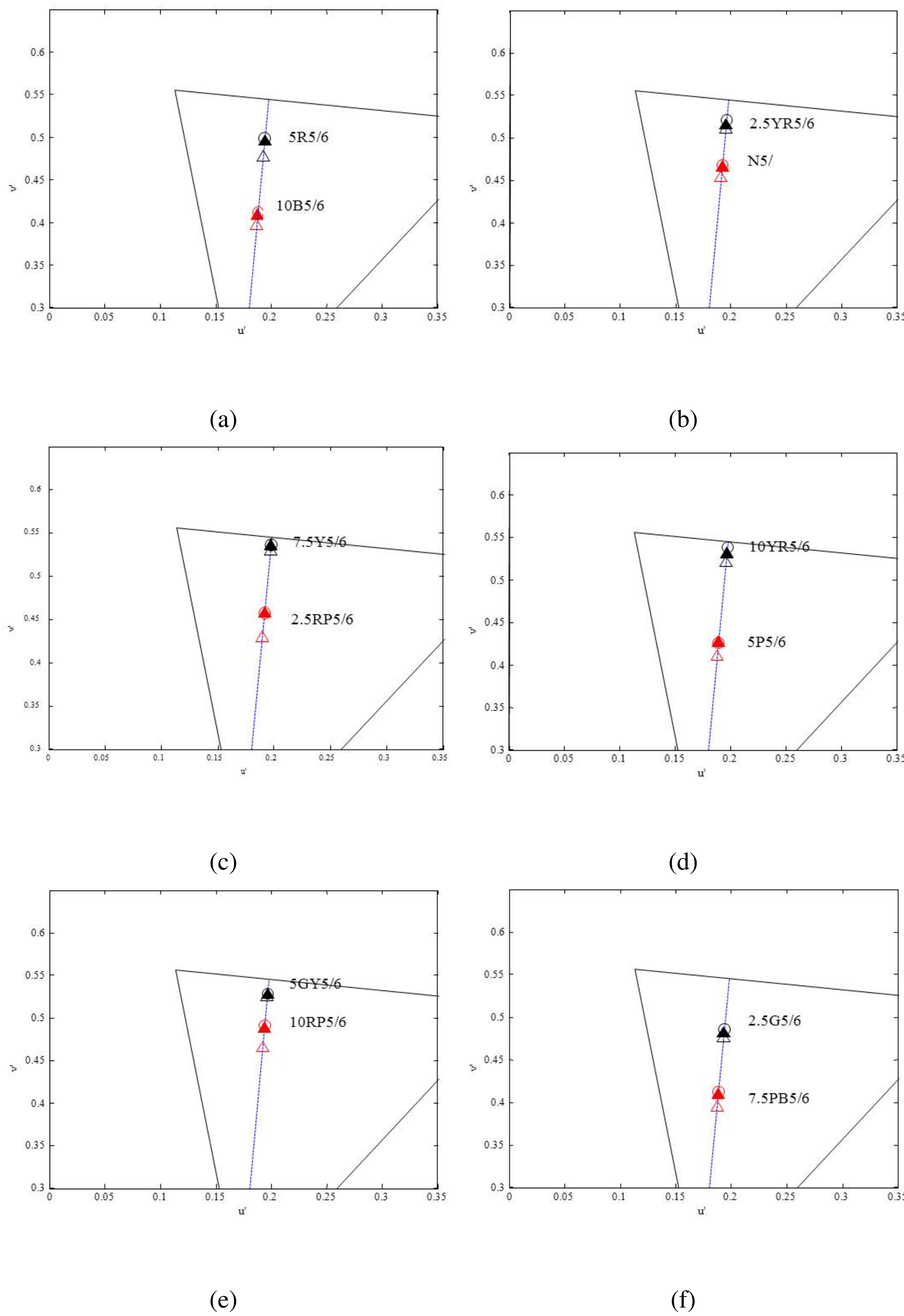
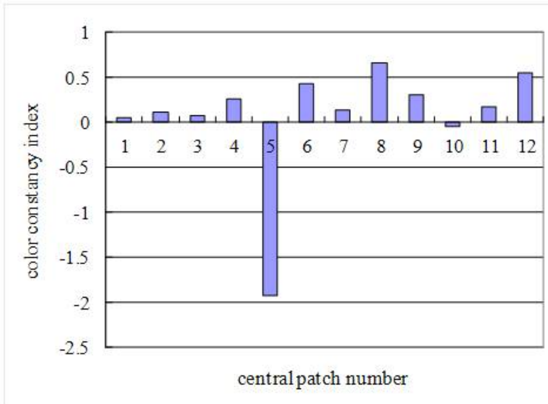
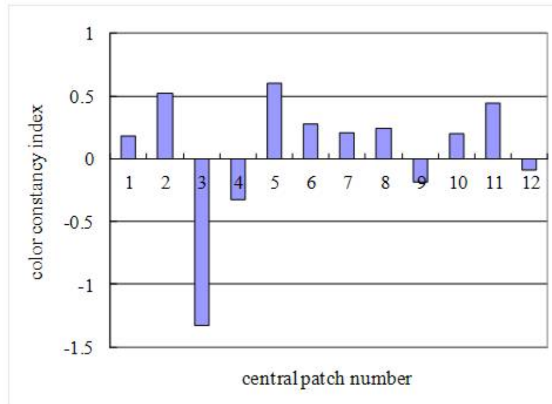


Figure 3.5 The projected (u', v') chromaticity settings on B-Y line under illuminant G for one deutan





(a) (b)

Figure 3.6 Corresponding constancy indices of Figure 3.5, shown in panel (a) and indices under illuminant R (b)

3.2.2 Chromatic shift and cone responses of observers' matching

Arend et al. proposed a color constancy index calculation method to quantitatively measure the degree of color constancy (Arend and Reeves 1986). In this method, theoretical points were calculated under the simple concept in which observers could estimate the reflectance of the test patch surface and the spectral radiance of the illuminant perfectly. The tristimulus values of the theoretical points were obtained by the multiple of the reflectance and spectral radiance of test illuminants. In the new analysis method here, the color constancy performance was estimated in simultaneous comparison with the expected performances calculated by two different models; von Kries cone adaptation/gain control model and reflectance model in which the theoretical point was the same as that used in Arends constancy index calculation.

About the measurement of color constancy performance in CIE 1976 (u', v') diagram, we will pay more attention to the displacement principle of the matched color obtained by observers from the standard color under D65 illuminant. This colorimetric shift was denoted as the Euclidean distance between the chromaticity point of the standard color under D65 and the chromaticity point of the matched color obtained by observers under test illuminant. The displacement of the expected color from the standard color was denoted as the Euclidean distance between the chromaticity point of standard color and the chromaticity point of the expected theoretical color. There are two kinds of expected theoretical points: reflectance theoretical color and von Kries theoretical color. If cone adaptation/gain control to illuminant plays a prominent role in surface match, the (u', v') chromatic shift, luminance or cone responses of twelve matched colors will coincide with those of the von Kries theoretical colors. If theoretically calculated color estimation mechanism plays a key role, the various values of twelve matched colors will overlap with those of reflectance theoretical colors. The coefficients in the von Kries model here were taken to be the inverse of the L, M and S cone responses for a perfect white patch under standard illuminant D65 or test illuminants (R, G, PB, or YG illuminant).

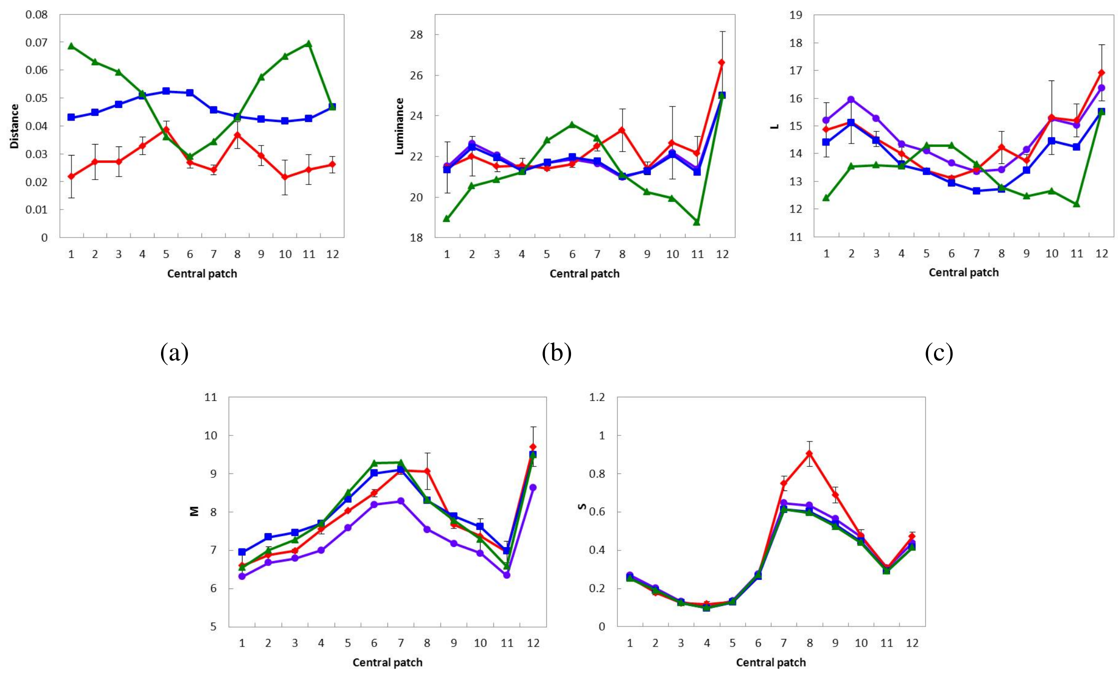
The absolute luminance of the standard colors, matched colors and two kinds of theoretical colors were also measured to explore the relationship between luminance matches and color constancy performance. In order to figure out the visual mechanisms underlying the color constancy performance shown in CIE 1976 color diagram, we also did cone responses analysis of the results. The Smith and Pokorny cone fundamentals (Smith and Pokorny 1975) were used to convert our results into cone responses.

Figure 3.7 for illuminant HG illustrates the color matching result of color normal observers. Figure 3.7a presents the chromatic shift in CIE 1976 (u', v') color diagram. The distances from the chromaticity points of the standard colors to those of the matched colors are denoted by red symbols; to von Kries predicted colors by blue symbols; and to reflectance predicted colors by green symbols. Error bars indicate standard error of the mean. Figure 3.7b shows the luminance matches. Standard colors are denoted by purple symbols; matched colors by red symbols; von Kries predicted color by blue symbols and reflectance predicted color by green symbols. L, M and S cone responses are shown in panels (c, d, e) with the same format as Figure 3.7b. In Figure

3.7a, the overall trend indicates that the shift of the matched colors significantly follows the shift principle of von Kries predicted colors, even it did not lay on the von Kries principle curve. It should be noted that some violations happen to color chips 6 (2.5G5/6) and 7(10B5/6) which seem to comply with reflectance model. It was found that the chromaticity points of matched colors of color chips 6 and 7 were located at the edge of color gamut of monitor. The von Kries predicted points were found to be located out of the color gamut. It is reasonable to believe that these violations were caused by the limited color adjustment of observers. In Figure 3.7c, the von Kries predicted L cone responses are less than those of standard colors under D65 illuminant; the von Kries predicted M cone responses are larger than those of standard colors under D65 illuminant. Because the intensity of D65 and test illuminant is the same, the von Kries predicted luminance is the same as that of standard colors, as seen in Figure 3.7b, which is guaranteed by the decrement of L cone responses and increment of M cone responses in Figure 3.7(c and d). If observer makes luminance adjustment according to von Kries cone adaptation/gain control, the matched luminance will not change under HG illuminant-no lightness constancy and L, M cone responses of matched colors will follow von Kries cone adaptation/gain control model. If the observer wants to keep lightness constancy, they have to use some high-level cognitive strategies which do not depend on the cone responses signals and L, M cone responses of matched colors will not be consistent with von Kries cone adaptation/gain control. From Figure 3.7b, it can be seen that the luminance of matched colors basically fits the luminance of von Kries predicted colors, not the physical luminance induced by HG illuminant. Figure 3.7(c and d) presents the L, M and S cone responses for standard colors, matched colors and two kinds of theoretical colors. Color chip 7 can be viewed as a cut-off point. L cone responses of matched colors with number less than 7 fit von Kries rule; the other parts match with those of standard colors. M cone responses of matched colors basically comply with the von Kries or reflectance model. von Kries model and reflectance model cannot be separated here. However, according to the compliance of matched luminance with von Kries predicted luminance, it can be figured out that M cone responses of matched colors mainly go to the direction of the von Kries model. The S cone responses predicted by von Kries or reflectance model show that the illuminant change from D65 to HG illuminant does not produce noticeable S cone stimulation changes. In general, S cone responses of matched colors appear to correspond well to those of standard colors and theoretical colors, except those of color chips 7 (10B5/6), 8 (7.5PB5/6), 9 (5P5/6) in blue region.

The same representation is also used to illustrate the performance under Highly-saturated red illuminant, shown in Figure 3.8. The main difference between Figure 3.7a and Figure 3.8a is that the (u', v') chromatic shift of matched colors in Figure 3.8a complies with the reflectance model, not von Kries model like Figure 3.7a. In Figure 3.8b, the luminance of matched colors consistently goes beyond the luminance curve of von Kries model predicted colors. Observer seems to try to make use of additional mechanisms to compensate for luminance changes induced by HR illuminant. Figure 3.8c shows L cone responses of matched colors are larger than those of von Kries predicted colors. On the contrary, the M cone responses of matched colors remain the same as those of standard colors. It seems that M cone is not affected much by cone adaptation. Luminance is determined by L and M cone responses. By considering the luminance matches and corresponding L, M cone responses together, it is expected that the luminance of matched colors is not contributed by cone adaptation/gain control, but determined by a high level cognitive strategy. This result reveals that von Kries rule has limitations to explain the lightness constancy (Kulikowski et al. 2012). From Figure 3.8, it can be speculated that observer mainly uses some cognitive strategies to achieve the color constancy and compensate for the luminance changes. The achievement and compensation procedure were accomplished by relying on L cone, more likely without involvement of M cone. The S cone responses here show a similar result with those under green illuminant.

Here only all data of deutan LX and protan KMY, and a part of data for protanomalous observer



(a) (b) (c) (d) (e)

Figure 3.7 The chromatic shift in (u', v') diagram, luminance comparison and LMS cone responses for twelve patches under green illuminant. The data was averaged over 5 color normal observers. The central patch numbers 1 to 12 correspond to color chips: Munsell 5R5/6, 2.5YR5/6, 10YR5/6, 7.5Y5/6, 5GY5/6, 2.5G5/6, 10B5/6, 7.5PB5/6, 5P5/6, 2.5RP5/6, 10RP5/6, and 20% flat-reflectance surface. Error bars indicate standard error of the mean (SEM). (a) The distance from the chromaticity points of standard colors to those of matched colors (red), von Kries predicted colors (blue) and reflectance predicted colors (green). (b) The luminance value of standard colors (purple), matched colors (red), von Kries predicted colors (blue) and reflectance predicted colors (green). Here, the luminance of von Kries predicted colors is matched to that of standard colors. (c) L, M and S cone responses of standard colors (purple), matched colors (red), von Kries predicted colors (blue) and reflectance predicted colors (green).

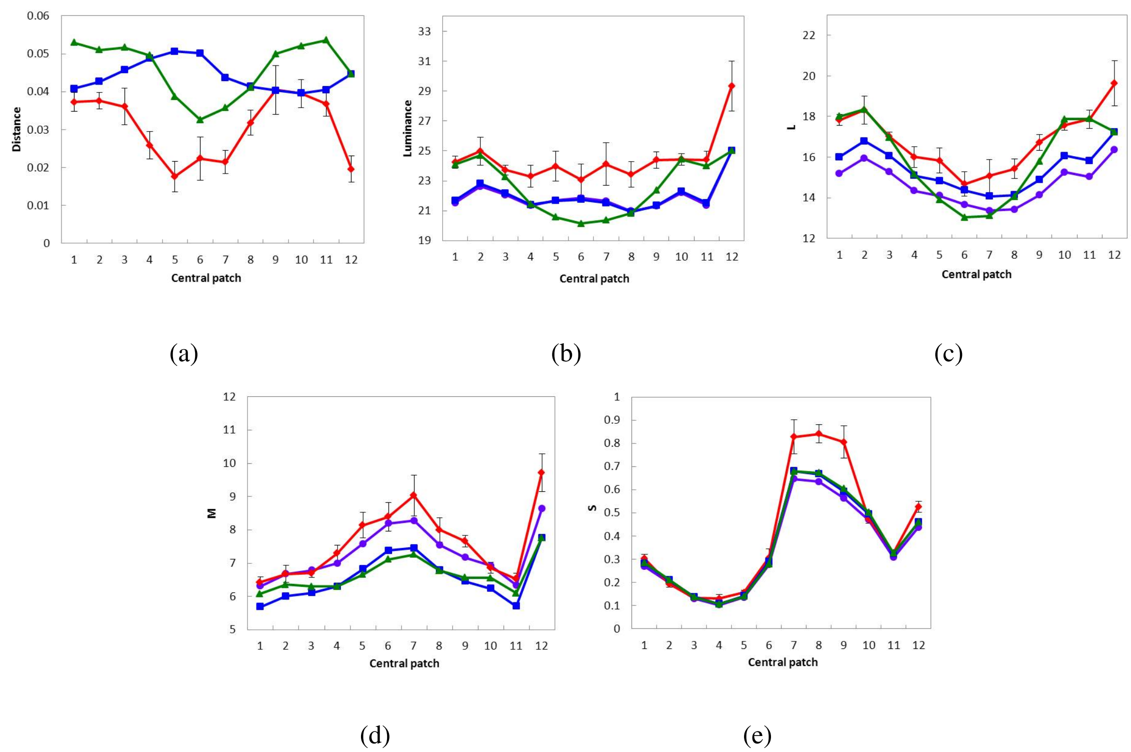
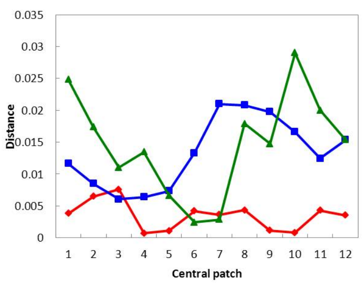
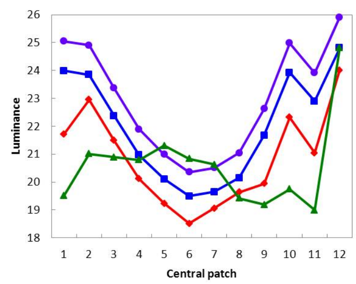


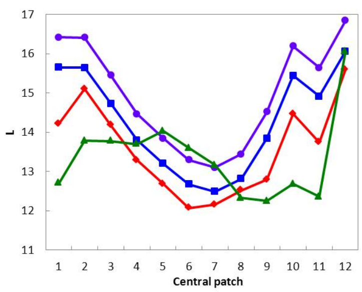
Figure 3.8 The chromatic shift, luminance matches and cone responses data averaged over 5 color normal observers under red illuminant, the same format as Figure 3.7



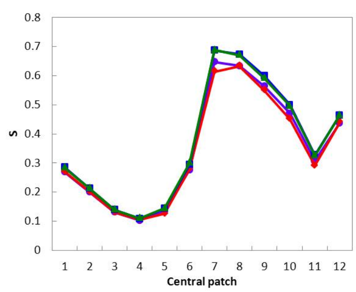
(a)



(b)



(c)



(d)

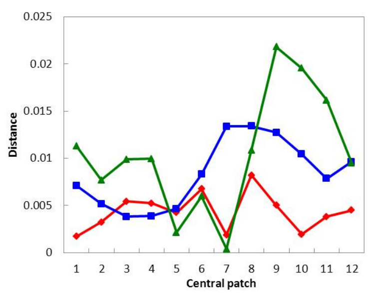
Figure 3.9 The chromatic shift and cone responses data for deutan LX under green illuminant, with the same denotations as Figure 3.7. The M cone responses are not included because deutans lost M cone. (a) chromatic shift in (u', v') diagram; (b) luminance matches; (c) L cone responses; (d) S cone responses

GY was presented. The rest data was attached in Appendix. The projected data under green illuminant for deutan LX was plotted in Figure 3.9. The denotations of Figure 3.9 are the same as those of Figure 3.7.

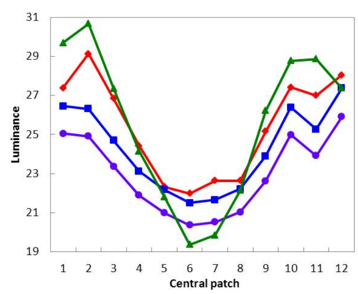
From Figure 3.9a, it can be seen that the chromatic shift value of matched colors from standard colors is very small, which may indicate that LX almost has no color constancy. Figure 3.9(b and c) show that the luminance and L cone responses of matched colors have identical principle. Both of them show a tendency of consistence with the von Kries model, accompanied by a quantitatively systematic deviation from the von Kries model. This systematic deviation may be caused by the LX's adjustment error in illuminant projection from original chromaticity to blue-yellow line. The agreement between luminance matches and L cone responses indicates that for deutan LX, L cone adaptation contributes to luminance adjustment under green illuminant. From Figure 3.9d, it can be found that S cone responses of matched colors fit those of standard colors, not following von Kries rule. This may imply that the deutan LX tends to estimate the surface color changes induced by S cone stimulation changes of illuminant to attempt to mediate the color constancy.

Figure 3.10 presents the matching data for deutan LX under red illuminant. The denotations of Figure 3.10 are the same as those of Figure 3.7. The value of distance between chromaticity points of matched colors and chromaticity points of standard colors in Figure 3.10a seems a little larger than that under green illuminant. In Figure 3.10b, the luminance of matched colors shows a little relevance to reflectance model, but generally follow von Kries model. Observers may have tried estimation mechanism on some color chips. Figure 3.10c shows that again L cone responses serve the luminance process. S cone responses of matched colors stay around of those of standard colors, without large deviations on color chips 7, 8 and 9 compared to those of color normal observers.

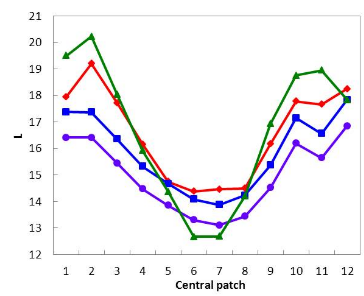
Figure 3.11 shows the protanomalous observer GY's matches under green illuminant. The denotations of Figure 3.11 is the same as those of Figure 3.7. Unexpectedly, in Figure 3.11a, there is approximately agreement between the performance of matched colors and reflectance model,



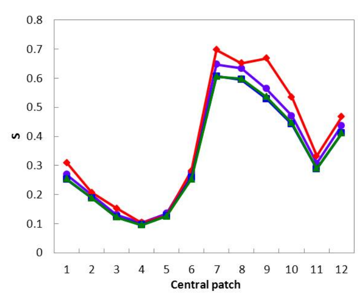
(a)



(b)



(c)



(d)

Figure 3.10 The chromatic shift and cone responses data for deutan LX under red illuminant, with the same format as Figure 3.10.

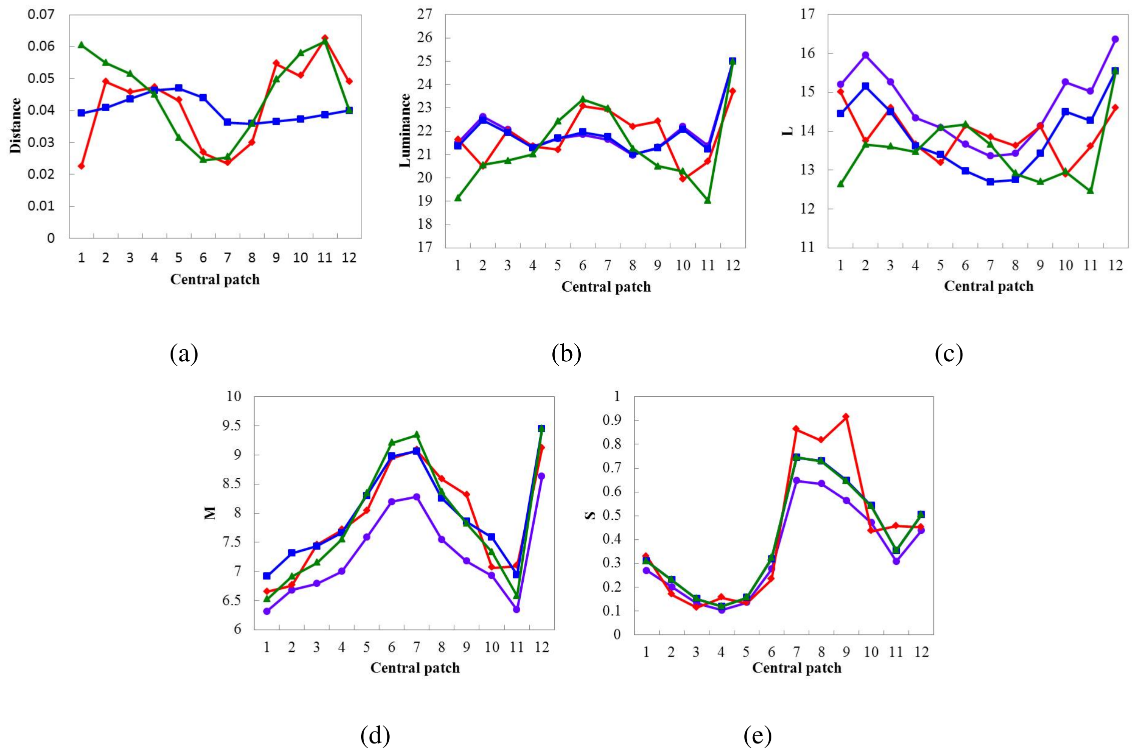


Figure 3.11 The chromatic shift and cone responses data for the protanomalous observer GY under green illuminant, with the same format as Figure 3.7.

which is very different from color normal observers' performance consistent with von Kries model under green illuminant. As seen in Figure 3.11b, GY did not adjust the luminance according to von Kries cone adaptation/gain control rule of color normal observers. The L cone responses of matched colors in Figure 3.11c show as equally weird tendency as luminance matches in Figure 3.11b. The strange L cone responses of matched colors should be caused by the variant spectral sensitivity property of GY's L cone. M cone responses of matched colors are in the good compliance with those predicted by von Kries model, but M cone adaptation is not reflected in luminance adjustment. The similar shapes of matched luminance curve and L cone responses curve of matched colors indicate L cone mainly contributes to the luminance adjustment and M cone does not participate in. S cone responses of matched colors for patch 7, 8, 9 have some deviations from perfect matching with von Kries model.

Figure 3.12 presented the matching data of GY under red illuminant. Figure 3.12a shows that the chromatic shift of matched colors is more likely to follow reflectance model. The luminance matches illustrated in Figure 3.12b appear to have a similar feature with L cone responses of matched colors in Figure 3.12c. M cone responses of matched colors show partial cone adaptation. The same as under green illuminant, the L cone responses mediate the luminance matches under red illuminant. However, the L cone responses characteristic here is different from that under green illuminant. S cone responses illustrated in Figure 12e are similar to those in Figure 3.11d.

Figure 3.13 shows the data of protan KMY under green illuminant. From Figure 3.13a, it can be seen that the chromatic shift curve of von Kries predicted color is similar with that of color normal observers under PB or YG illuminant. This is because protans perceive the color of green illuminant as bluish or yellowish. However, the value of this chromatic shift is very small, which indicates that the green illuminant only produce very small S cone stimulation changes based on D65 illuminant. This is reasonable because green illuminant and D65 are located on the confusion line. Compared to that of deutans, the chromatic shift of KMY's matched colors is not so tiny,

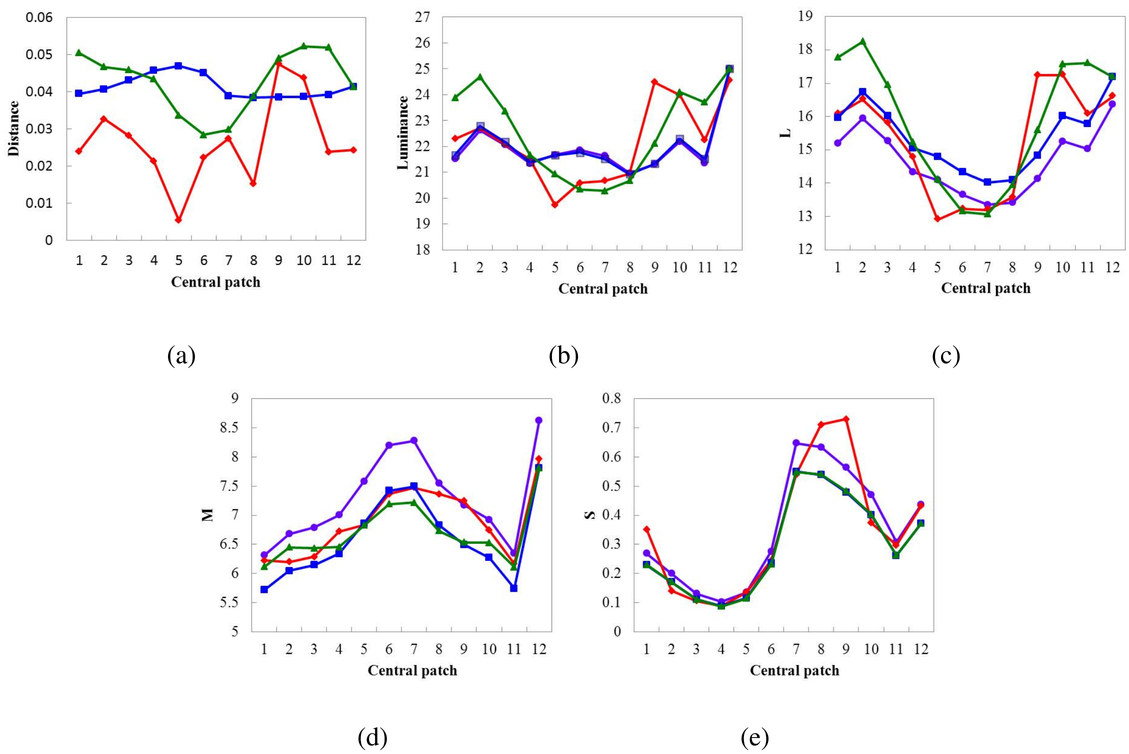


Figure 3.12 The chromatic shift and cone responses data for the protanomalous observer GY under red illuminant, with the same format as Figure 3.7.

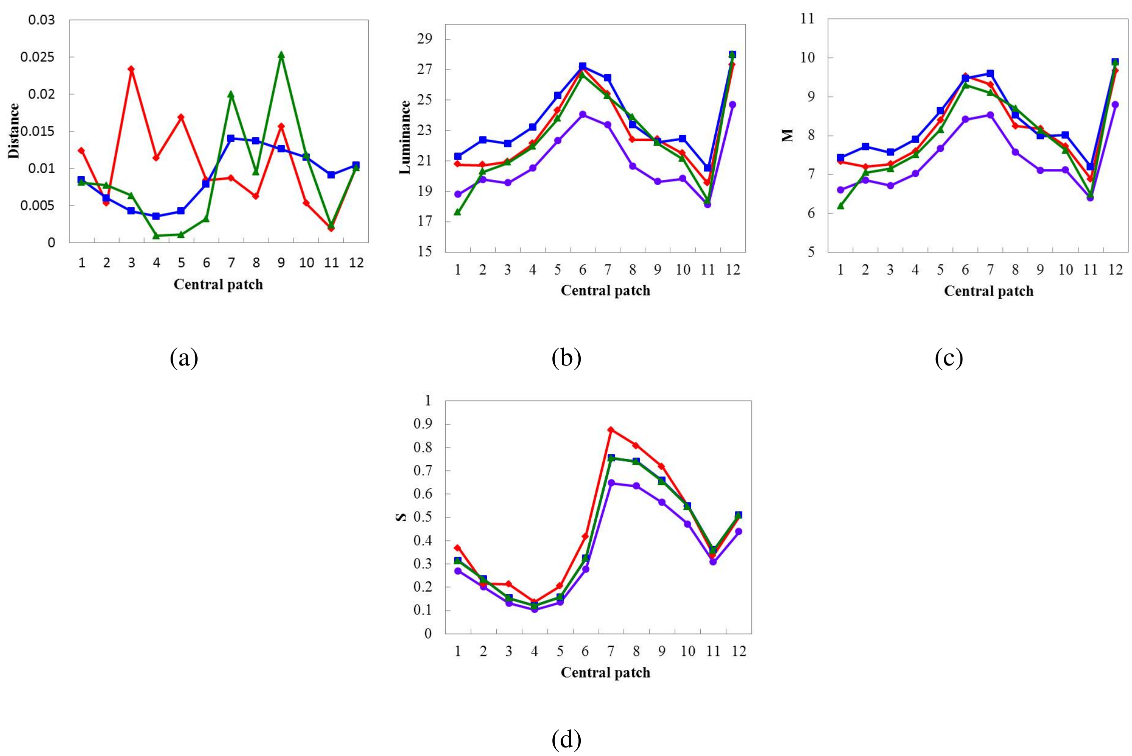


Figure 3.13 The chromatic shift and cone responses data for protan KMY under green illuminant, with the same denotations as Figure 3.7. L cone responses data is not included because protans lost L cone. (a) chromatic shift in (u', v') diagram; (b) luminance matches; (c) L cone responses; (d) S cone responses

but with large deviation. KMY may try to make some adjustment toward test illuminant. Figure 3.13b illustrates the luminance matches. The green illuminant looks brighter than D65 illuminant for protans. In Figure 3.13b, the luminance value predicted by von Kries model is higher than luminance value of standard colors under D65 illuminant. The matched luminance follows von Kries model or reflectance model. Here these two models are not separated. Figure 3.13c shows that the M cone responses curve is similar with that of luminance, which corresponds to the fact that the luminance of protan is contributed by M cone. Protans show S cone adaptation even with some deviation.

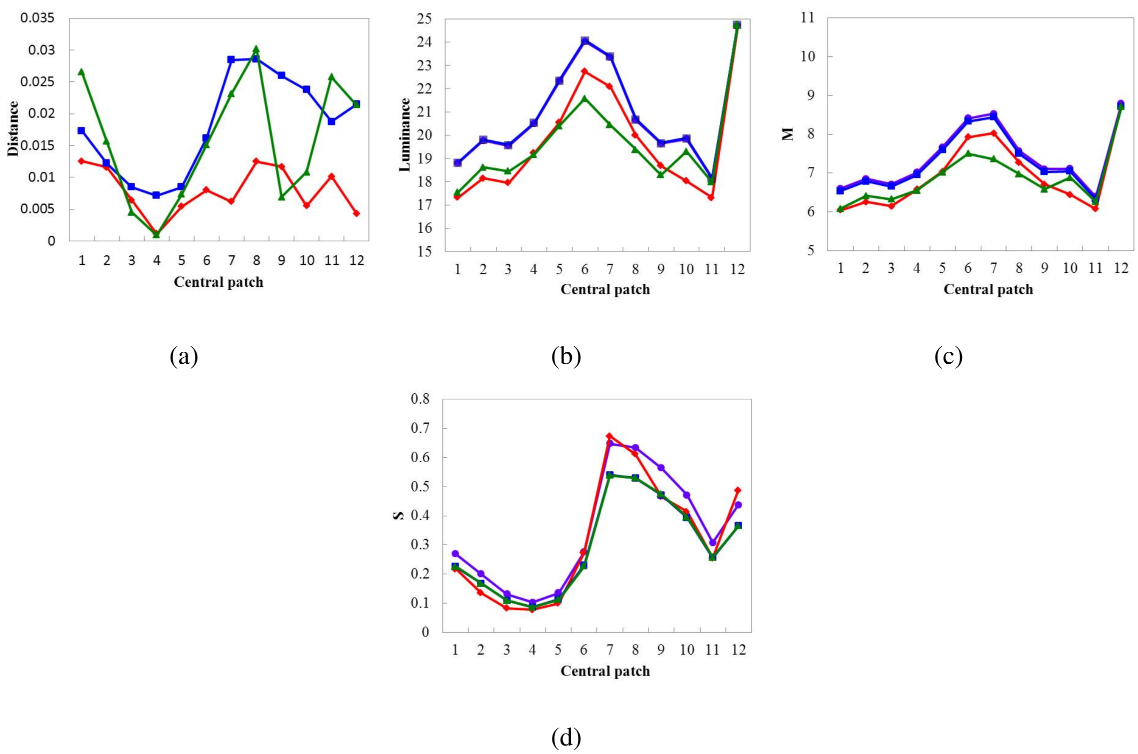


Figure 3.14 The chromatic shift and cone responses data for protan KMY under red illuminant, with the same format as Figure 3.13.

Figure 3.14 shows the matches of KMY under red illuminant. In Figure 3.14a, the chromatic shift magnitude of matched colors from standard colors is less than 0.015 units in CIE 1976 (u', v') diagram. This may mean no color constancy. The matched luminance seems to comply with the reflectance model. The coincidence of von Kries predicted luminance with the luminance of standard colors indicates that the red illuminant looks equally bright as D65 illuminant for protan KMY. This is different from the protans' general case in which the red illuminant looks darker than D65 illuminant, such as protan OTK's case. It is possible that the error of illuminant projection leads to the luminance overlapping of red illuminant with D65 illuminant. According to the usual case in which the luminance of red illuminant is lower than that of D65, the matched luminance which currently stays around reflectance model should originally go to the direction of von Kries model and the matched luminance is correspondingly contributed by the M cone adaptation. Another possibility is that there is indeed no cone adaptation for M cone and the matched luminance of protans was contributed by a cognitive mechanism. From Figure 3.14d, it can be seen that different from green illuminant, KMY does not have the S cone adaptation under red illuminant.

3.2.3 The fitting of matched data with two models predicted value

By multiplying a constant, the ideal von Kries model and reflectance model were vertically shifted to fit matched data, respectively. The constant multiplied by the model was determined optimally in order to make the sum of squares of error between fitting model data and matched data minimum. One fitting condition will be described by four parameters: constant (von Kries), which indicates the shift magnitude of ideal von Kries model to the matched data; constant (reflectance), which indicates the shift magnitude of ideal reflectance model to the matched data; fitting error (von Kries), which is the error between the fitting von Kries model and matched data; fitting error (reflectance), which is the error between the fitting reflectance model and matched data. The value of four parameters in chromatic shift, luminance, L cone responses, M cone responses, and S cone responses is shown in Table 3.1-Table 3.5, respectively. Constant (von Kries) is denoted by K1; constant (reflectance) is denoted by K2; error (von Kries) is denoted by E1; error (reflectance) is denoted by E2.

Table 3.1 Chromatic shift in (u', v') diagram

	K1	K2	E1	E2
Green illuminant (deutan)	0.6106	0.4953	0.000248	0.001326
Green illuminant (protan)	0.5923	0.4821	0.000301	0.001135
Red illuminant (deutan)	0.6753	0.6674	0.001282	0.000345
Red illuminant (protan)	0.595	0.591	0.001018	0.000367
Purplish Blue illuminant	0.6329	0.6389	0.000306	0.000244
Greenish Yellow illuminant	0.4475	0.4393	0.0000648	0.0000711

Table 3.2 Luminance matches

	K1	K2	E1	E2
Green illuminant (deutan)	1.0201	1.0437	7.9842	32.1996
Green illuminant (protan)	1.0043	1.0264	1.3301	24.0036
Red illuminant (deutan)	1.1116	1.0785	5.7661	876.9225
Red illuminant (protan)	1.0977	1.0676	5.5541	409.1832
Purplish Blue illuminant	1.0455	1.0419	1.8064	2.84
Greenish Yellow illuminant	1.028	1.0312	1.4958	8.6887

Figure 3.15a shows the fitting between the matched data and two models; von Kries model and reflectance model, under green illuminant on deutan confusion line. Points on dashed lines denote the ideal von Kries model (blue) and reflectance model (green) expected values. Points on solid lines denote value predicted by fitting von Kries model (blue) and fitting reflectance model (green). Red diamonds denote the matched data. Error bars mean the standard error of mean.

Table 3.3 L cone responses

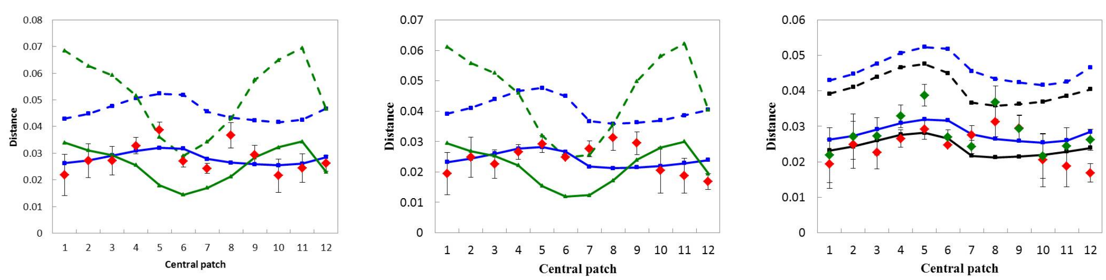
	K1	K2	E1	E2
Green illuminant (deutan)	1.0419	1.0764	2.9561	21.1756
Green illuminant (protan)	1.0291	1.061	0.707	16.6361
Red illuminant (deutan)	1.0905	1.0495	3.1152	11.9675
Red illuminant (protan)	1.0755	1.0387	4.2542	8.7698
Purplish Blue illuminant	1.0433	1.0372	0.798	0.6673
Greenish Yellow illuminant	1.0298	1.0356	0.7054	1.6095

Table 3.4 M cone responses

	K1	K2	E1	E2
Green illuminant (deutan)	0.9828	0.9914	1.4787	1.723
Green illuminant (protan)	0.9614	0.9702	0.1696	0.5545
Red illuminant (deutan)	1.1651	1.1498	1.1683	3.1233
Red illuminant (protan)	1.1527	1.1375	0.4927	1.8947
Purplish Blue illuminant	1.0511	1.0516	0.303	0.256
Greenish Yellow illuminant	1.0248	1.0241	0.1864	0.3218

Table 3.5 S cone responses

	K1	K2	E1	E2
Green illuminant (deutan)	1.2296	1.2358	0.0493	0.0525
Green illuminant (protan)	1.0818	1.0842	0.0188	0.02
Red illuminant (deutan)	1.1793	1.1735	0.0364	0.0348
Red illuminant (protan)	1.2276	1.2239	0.0142	0.0145
Purplish Blue illuminant	0.9572	0.9535	0.0126	0.0119
Greenish Yellow illuminant	1.3869	1.3962	0.0042	0.0041



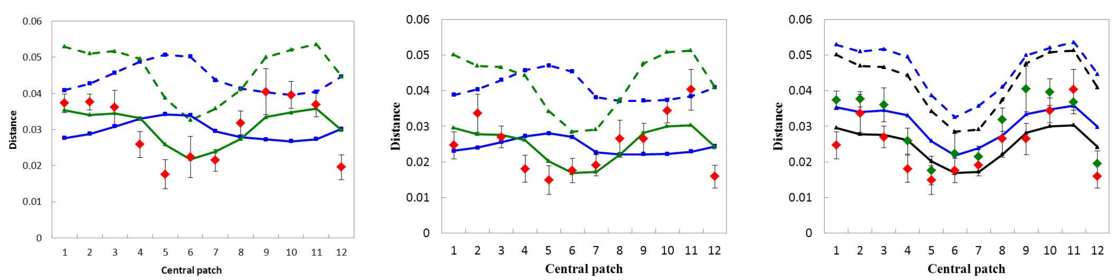
(a) (b) (c)

Figure 3.15 The fitting of matched data with two models under green illuminant along deutan and protan confusion lines. Points on dashed lines denote the ideal von Kries model (blue) and reflectance model (green) expected value. Points on solid lines denote value predicted by fitting von Kries model (blue) and fitting reflectance model (green). Red diamonds denote the matched data. Error bars mean the standard error of mean. (a) fitting of matched data under green illuminant along deutan confusion line; (b) fitting of matched data under green illuminant along protan confusion line; (c) fitting of matched data with von Kries model under both green illuminant on deutan confusion line and green illuminant on protan confusion line.

Figure 3.15b shows the fitting between the matched data and two models under green illuminant on protan confusion line. Figure 3.15b has the same denotations with Figure 3.15a.

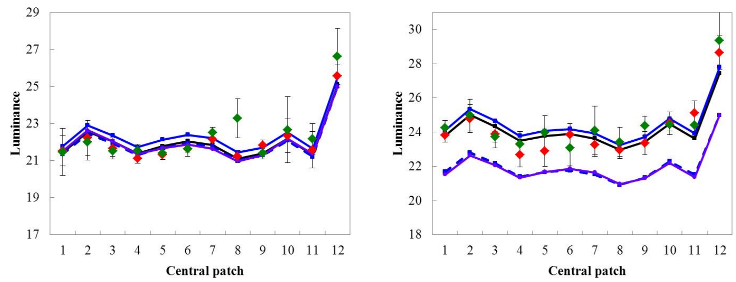
In the previous section, it is shown that the matched data under green illuminant follows the von Kries model; the matched data under red illuminant complies with the reflectance model. There is a small difference between the chromaticity coordinates of green illuminant and red illuminant obtained on deutan confusion line and on protan confusion line. It is expected that the matched data under illuminants on protan confusion line will have a slight shift compared to that on deutan confusion line.

Figure 3.15c shows the fitting of matched points with von Kries model for two kinds of green illuminant. Dashed lines correspond to ideal von Kries model. Solid lines denote fitting von Kries mdoel. Blue lines refer to illuminant condition along deutan confusion line; black lines are along protan confusion line. Green diamonds are matched points along deutan confusion line; red diamonds are matched points along protan confusion line. Figure 3.16 shows the fitting between the matched data and two models under red illuminant. It can be seen that the matched data apparently follows reflectance model. Figure 3.17(a and b) show the luminance fitting under green illuminant and red illuminant.



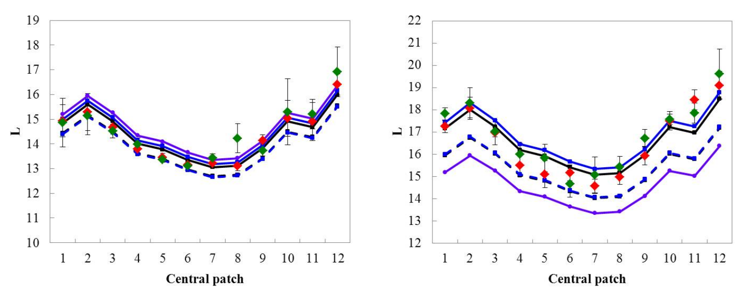
(a) (b) (c)

Figure 3.16 The fitting of matched data with two models under red illuminant along deutan and protan confusion lines, with the same format as Figure 3.15. (c) presents fitting of matched data with reflectance model, which is different from 3.15(c).



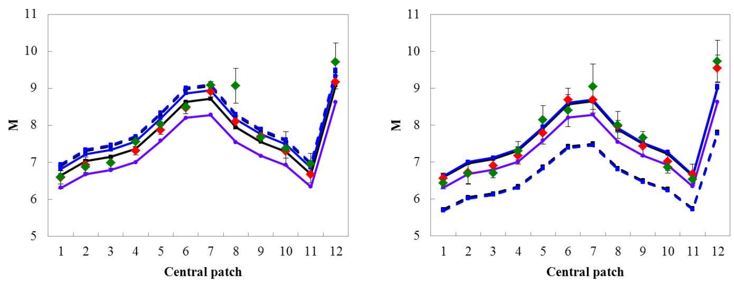
(a) (b)

Figure 3.17 (a) the luminance fitting of matched data with two models under green illuminant along deutan confusion line and green illuminant along protan confusion line; (b) the luminance fitting of matched data with two models under red illuminant along deutan confusion line and red illuminant along protan confusion line. Solid lines denote fitting von Kries mdoel; Blue lines refer to illuminant along deutan confusion line; black lines are along protan confusion line; green diamonds are matched points under illuminants along deutan confusion line; red diamonds are matched points under illuminants along protan confusion line.



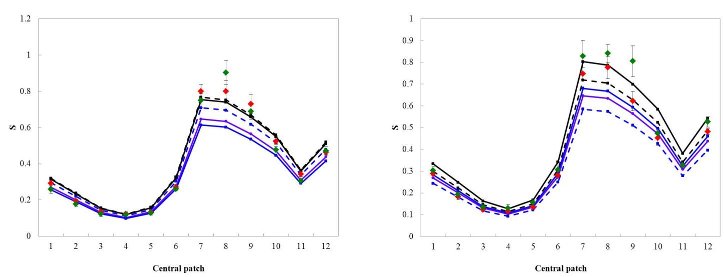
(a) (b)

Figure 3.18 (a) L cone responses fitting of matched data with two models under green illuminant along two kinds of confusion lines; (b) L cone responses fitting of matched data with two models under red illuminant along two kinds of confusion lines. The denotations are the same as those of Figure 3.17



(a) (b)

Figure 3.19 M cone responses fitting of matched data with two models under green illuminant(a) and red illuminant(b), with the same denotations as Figure 3.17.



(a) (b)

Figure 3.20 S cone responses fitting of matched data with two models under green illuminant(a) and red illuminant(b), with the same denotations as Figure 3.17.

Figure 3.18(a and b) show L cone responses fitting under green illuminant and red illuminant. Denotations are the same as Figure 3.17. Figure 3.19(a and b) show M cone responses fitting under illuminant G and illuminant R. Figure 3.20 shows S cone responses fitting under green illuminant (a) and red illuminant (b) along protan confusion line. Figure 3.21 shows S cone responses fitting under green illuminant and red illuminant. Under PB illuminant, von Kries model has a smaller error and therefore is shown. Under YG illuminant, the error of reflectance model is a little smaller than that of von Kries model and the fitting of matched data with reflectance model is presented.

3.3 Discussion

3.3.1 Color constancy degree reflected by index

Dichromats responded that red-green buttons were not necessary for them and on the contrary, made color adjustment procedure complicated. In the second section of experiment, dichromats thought that they could adjust colors accurately. They did not know that their color control way with only blue-yellow buttons was different from color normal observers and they thought color normal observers also did like him.

For deutans, test illuminants were obtained by changing D65 a certain amount of M cone stimulation along their individual confusion line. In deutan's Cambridge Color Test, the long axis of discrimination ellipse is larger than the distance between D65 and four test illuminants, and D65 and four test illuminants all located within discrimination ellipse. So, deutans cannot discriminate the color of D65 and test illuminants. One observer LX (deutan) said:" for two patterns, it must be that one pattern is bright, another pattern is dark. Surfaces in the background should be unchanged. Sometimes, the test illuminant undergoes large changes, sometimes, small changes." LX can discriminate the difference between D65 and test illuminants, but only brightness difference, not color difference.

Dichromats who participated in the present study could not perceive the color difference between standard and test illuminants. Initially, it was expected that dichromats would have no or little color constancy because the perception to the color difference of illuminant changes would provide no cue. However, when the chromaticity coordinates of standard and theoretical points were not located onto the same confusion line, they had the partial color constancy, which is somehow reasonably accurate and is bounded along the blue-yellow chromatic opponent. The color constancy of dichromats may be mediated simultaneously by perception and sensation mechanisms. In dichromats' blue-yellow hues color world, they have their own color constancy based on these two colors, even under the condition that they can not perceive the color difference between standard illuminant and test illuminant.

One protanomalous observer GY reported that for him, it is easier to adjust the color of test patch to ideal color with red-green button than with bight-dark button. Sometimes, he felt that the color of test illuminant might be a little different from that of D65, but he could not perceive clearly. Although GY could not perceive or said clearly what was the color difference of two illuminants, maybe he got this information unconsciously. The color of Highly-saturated red or green illuminant is strong, Desaturated red or green illuminant has little color and nearly the same as that of D65. So, the variability of GY's color constancy under Desaturated green and red illuminants is greater.

3.3.2 Different color constancy mechanisms under green illuminant and red illuminant

As expected, under green illuminant and red illuminant along protan confusion lines, observers show the same mechanisms as under illuminant conditions along deutan confusion lines. This demonstrates that the selective utilization of color constancy mechanisms under different illuminant conditions is a considerably stable phenomenon. The fitting errors of two models with matched points show that under green illuminant, the color constancy performance basically follows the von Kries rule; under red illuminant, the color constancy mainly complies with the reflectance model. It is noted that the stimulation changes of S cone caused by green and red illuminants are much lower than those of L and M cone. The fact that S cone responses of matched colors did not change so much under both green and red illuminants indicates that S cone responses are not closely related with the color constancy under green and red illuminant conditions.

3.3.3 The relationship between cone responses and color constancy

The matched S cone responses have two trends: compliance with von Kries model predicted S cone responses, which indicates that observer has S cone constancy; coincidence with S cone responses of standard colors, which means no constancy. Unlike those of color normal observers, the matched S cone responses of dichromats did not show large deviations on color chips 7, 8 and 9. This fitting characteristic was very stable, which may indicate that dichromats have more accurate and skilled utilization of S cone. For deuteranopic observers, under green and red illuminant conditions, L cone had cone adaptation, which was used to mediate the luminance changes. S cone constancy was nearly nonexistent. Only under green illuminant condition, protans showed the M cone adaptation, which was used to contribute to the luminance adjustment. Under the other three illuminant conditions, M cone responses seemed to follow the theoretically calculated M cone responses. Under green illuminant, S cone showed relatively good constancy. Under red illuminant, S cone had no constancy. The color constancy can be achieved by S cone adaptation or estimating theoretically calculated color changes caused by S cone stimulation changes of illuminants. If dichromatic observers use estimation mechanism on theoretically calculated color to try to obtain the color constancy, they tend to fail under small S cone stimulation changes condition.

The protanomalous observers have variant L cone spectral sensitivities. In trichromatic vision system, it is agreed that the sum of L and M cone responses contributes to the luminance. However, in this study, it was found that under green illuminant and red illuminant, for one protanomalous observer GY, M cone responses did not participate in the luminance; only variant L cone responses contribute to the luminance.

Chapter 4

Color constancy under purplish blue illuminant and greenish yellow illuminant

4.1 Introduction

In Chapter 3, color normal observers selected color constancy mechanisms according to illuminant conditions. Under green illuminant, von Kries cone adaptation/gain control played a main role in color constancy; under red illuminant, the illuminant estimation from image surfaces took effect. Green and red illuminants mainly stimulate L and M cone. The effect on S cone responses is very small. It is necessary to investigate the color constancy mechanisms under purplish blue illuminant and greenish yellow illuminants which mainly stimulate S cone and generate little stimulation to L and M cone.

In Chapter 3, the color constancy of color deficient observers was investigated under illuminant changes along their individual confusion lines (red and green illuminants). In the experiment, dichromatic observers could not perceive the color difference of standard illuminant D65 and test illuminants. Here, their color constancy was investigated under purplish blue and greenish yellow test illuminants. In the present study, all observers could perceive the color difference of illuminants.

4.2 Results

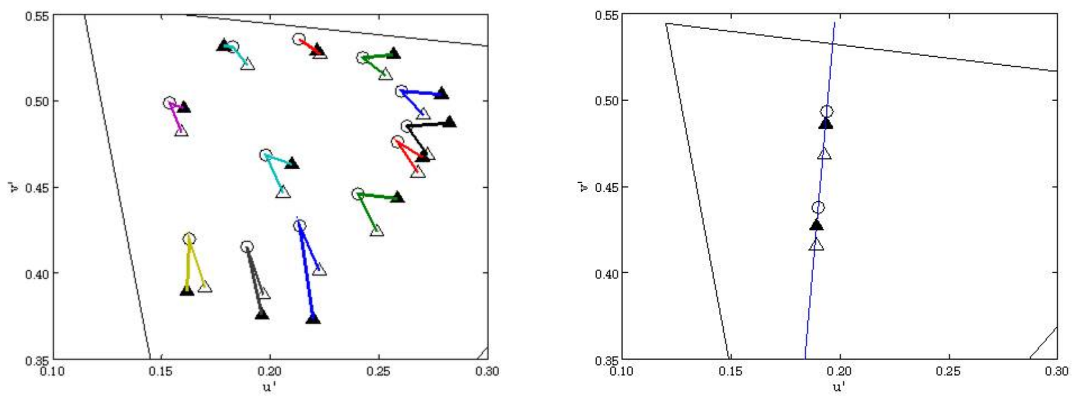
4.2.1 Measurement on color constancy index

Color constancy indices calculation methods were the same as those used in the red-green illuminant condition in Chapter 3. Index value 0 means the color of the central test patch was adjusted to the same as that of the standard patch under D65 illuminant (no constancy); index value 1 means that the color of the central test patch was adjusted to the same as that of the standard patch under purplish blue and greenish yellow illuminants (perfect constancy). The matched points averaged over 6 sessions are indicated by the filled triangles. The open circles indicate the standard points; the open triangles denote the theoretical points.

Figure 4.1a is the color constancy performance of one color normal observer over twelve central patches under purplish blue illuminant; Figure 4.1b is the result of one deuteranopic observer over two central patches under purplish blue illuminant. In D65 to D65 illuminant condition, original standard points were projected onto blue-yellow line. In the matching experiment, the original theoretical points were projected onto blue-yellow line under each test illuminant.

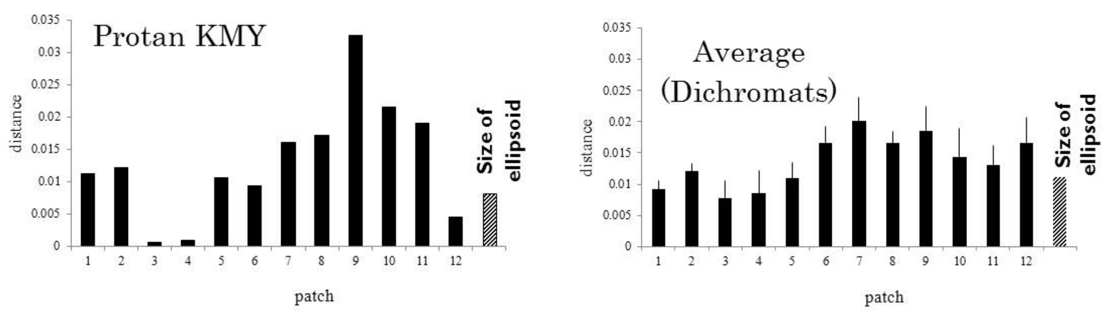
Figure 4.2a shows the distance between standard points and theoretical points on the blue-yellow line for the protanopic observer KMY under purplish blue illuminant. Figure 4.2b shows the averaged distance over five dichromatic observers under purplish blue illuminant. The pattern bars denote the chromatic discrimination range which was the average of three ranges obtained by intersecting the blue-yellow line and the three discrimination ellipses of CCT. When the distance between one standard point and one theoretical point is less than the chromatic discrimination range, dichromats basically cannot discriminate these two colors represented by these two points.

Because of such a case, constancy indices will be unstable. These kinds of data was excluded from the average.



(a) (b)

Figure 4.1 (u', v') chromaticity settings of one color normal observer(a) and projected chromaticity settings of one deutan(b) under PB illuminant



(a) (b)

Figure 4.2 Distance between standard points and theoretical points on the blue-yellow line for dichromats

Figure 4.3(a and b) show the averaged color constancy indices under purplish blue and greenish yellow test illuminants. The indices of color normal observers, indicated by the pattern bars, were the average of those of 5 color normal observers; the dichromatic indices, indicated by the filled bars, were the average of 5 dichromatic observers. In Figure 4.3a, under purplish blue and greenish yellow illuminants, the color constancy of dichromats is stronger than that of color normal observers (0.30 vs 0.19; 0.31 vs -0.07). It can also be seen from Figure 4.3 that for color normal observers, the color constancy under Highly-saturated illuminants is stronger than that under Desaturated illuminants (0.21 vs -0.08). For dichromatic observers, the color constancy under Desaturated illuminants is stronger than that under Highly-saturated illuminants (0.32 vs 0.28). Under Desaturated illuminant conditions, dichromats have stronger color constancy than color normal. Roughly, the color constancy indices of dichromats over all color chips under four illuminant conditions are less than 0.5; color normal observers, too, except the color chip 7. At the same time, it is noted that indices of color normal observers sometimes are minus value with large absolute value, which was not common under the previous red-green illuminant condition.

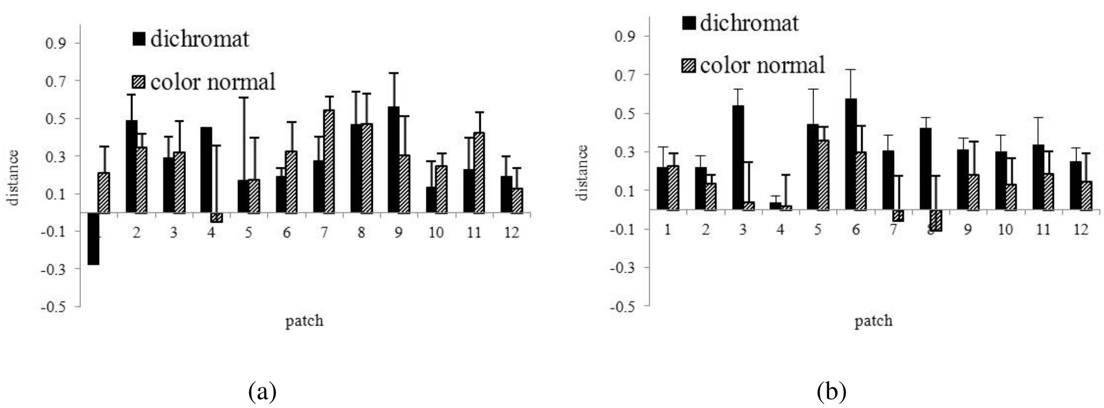


Figure 4.3 The comparison of mean indices between 5 dichromats and 5 color normal observers under PB illuminant (a) and YG illuminant (b)

4.2.2 Chromatic shift and cone responses analysis of observers' matching

The analysis method here is the same as that in section "Chromatic shift and cone responses analysis of observers' matching in color constancy" of Chapter3.

Figure 4.4 presents the data of color normal observers for purplish blue illuminant. In Figure 4.4a, although there is large deviation, the (u', v') chromatic shift of matched colors from standard

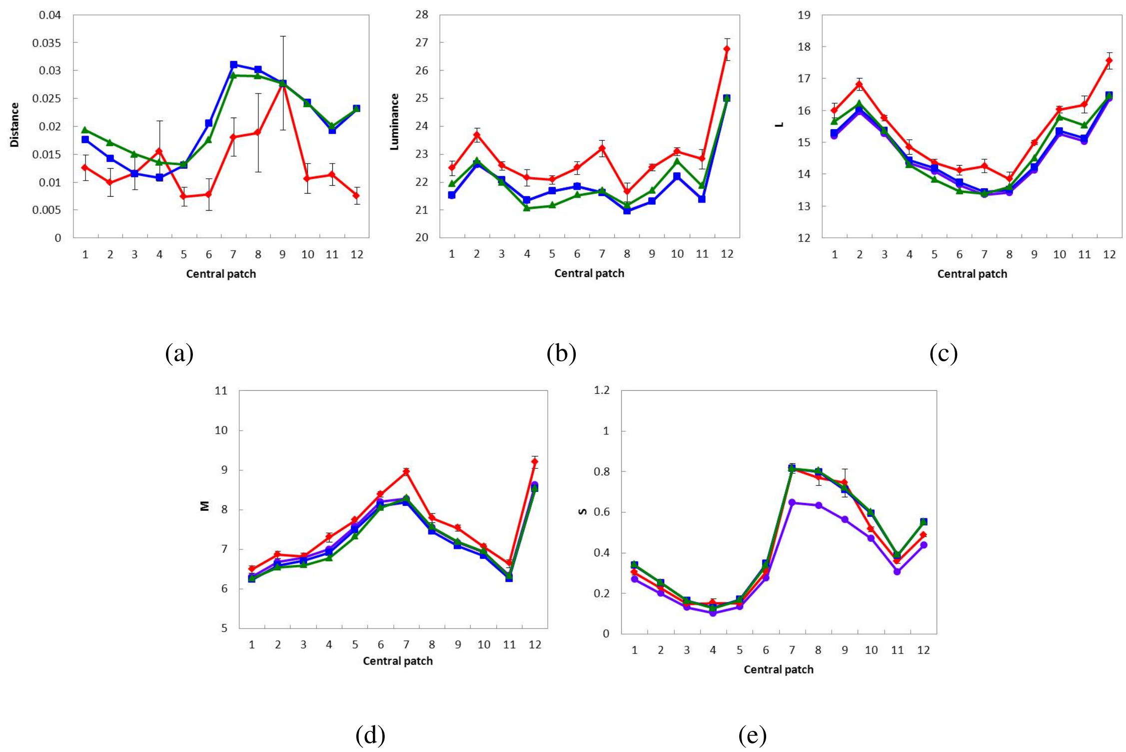


Figure 4.4 The chromatic shift in (u', v') diagram, luminance comparison and LMS cone responses for twelve patches averaged over 5 color normal observers under purplish blue illuminant, with the same format as Figure 3.7.

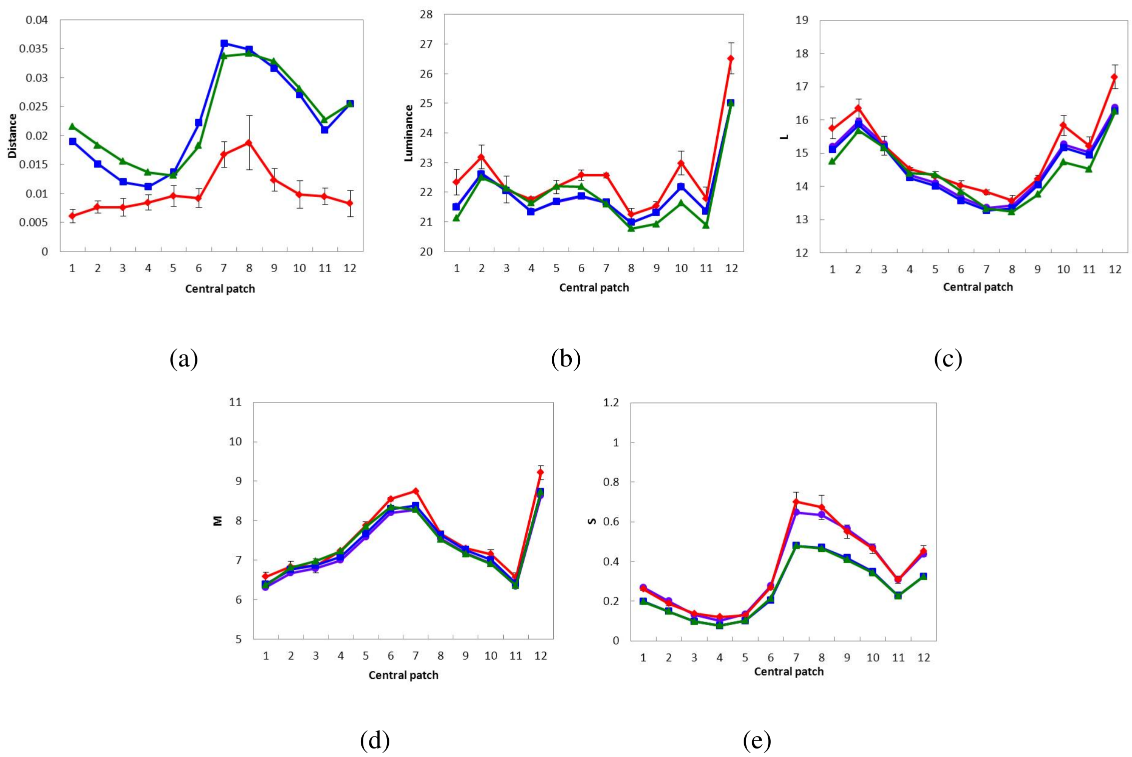


Figure 4.5 The chromatic shift in (u', v') diagram, luminance comparison and LMS cone responses for twelve patches averaged over 5 color normal observers under greenish yellow illuminant, with the same format as Figure 3.7.

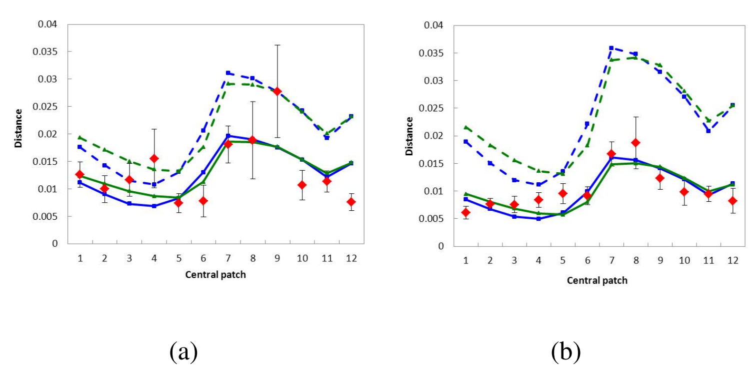
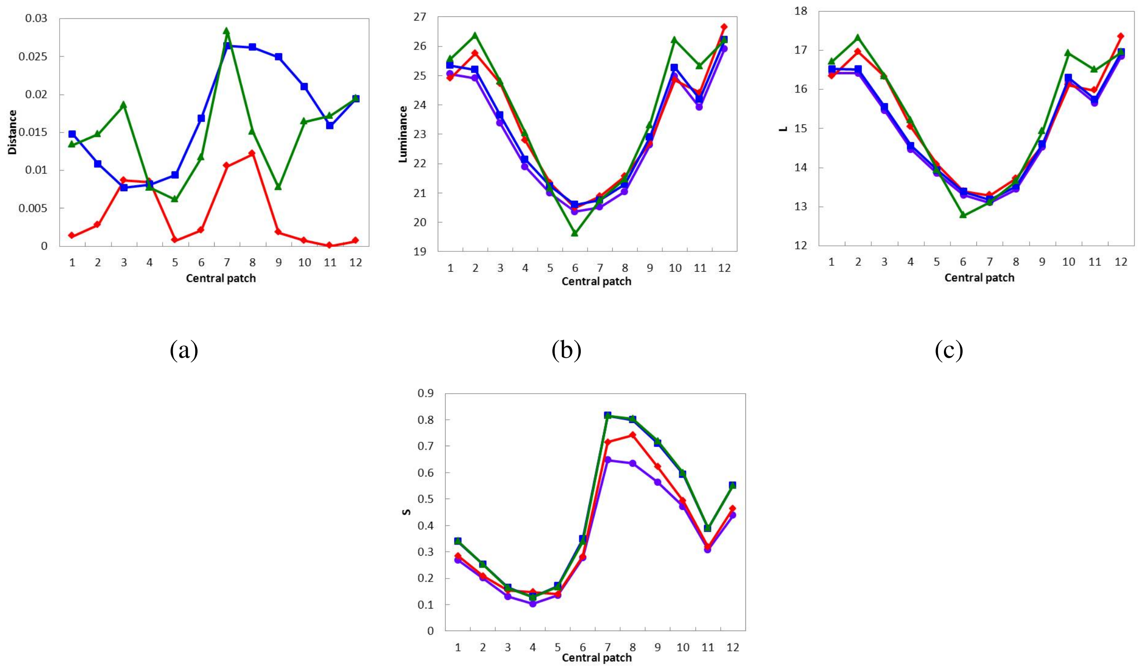


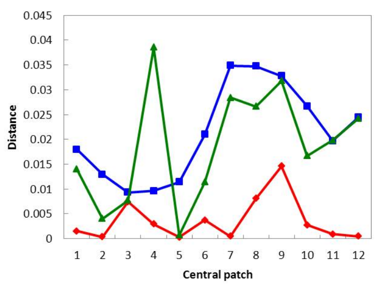
Figure 4.6 The fitting of matched data with two models under purplish blue illuminant (a) and greenish yellow illuminant (b), with the same format as Figure 3.15(a).



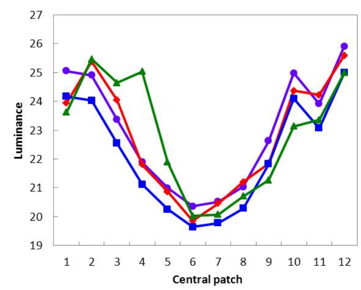
(a) (b) (c)

(d)

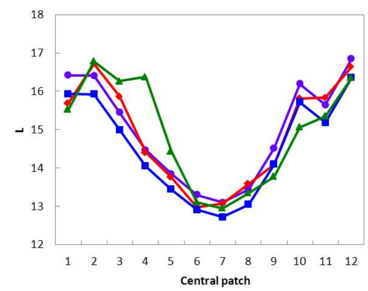
Figure 4.7 The chromatic shift and cone responses data for deutan LX under purplish blue illuminant, with the same denotations as Figure 3.9.



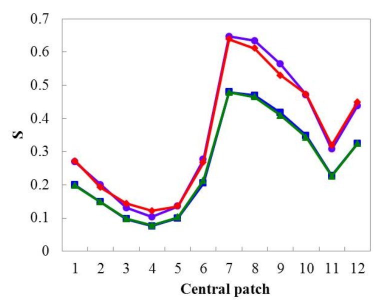
(a)



(b)

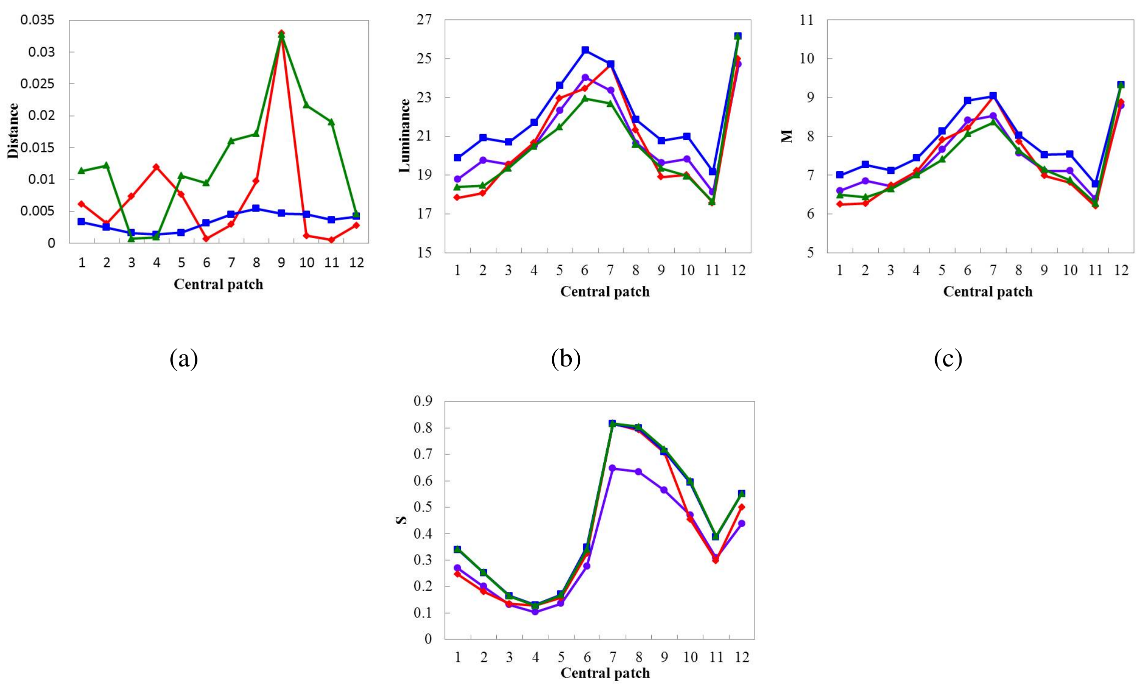


(c)



(d)

Figure 4.8 The chromatic shift and cone responses data for deutan LX under greenish yellow illuminant



(a) (b) (c)

(d)

Figure 4.9 The chromatic shift and cone responses data for protan KMY under purplish blue illuminant, with the same denotations as Figure 3.13.

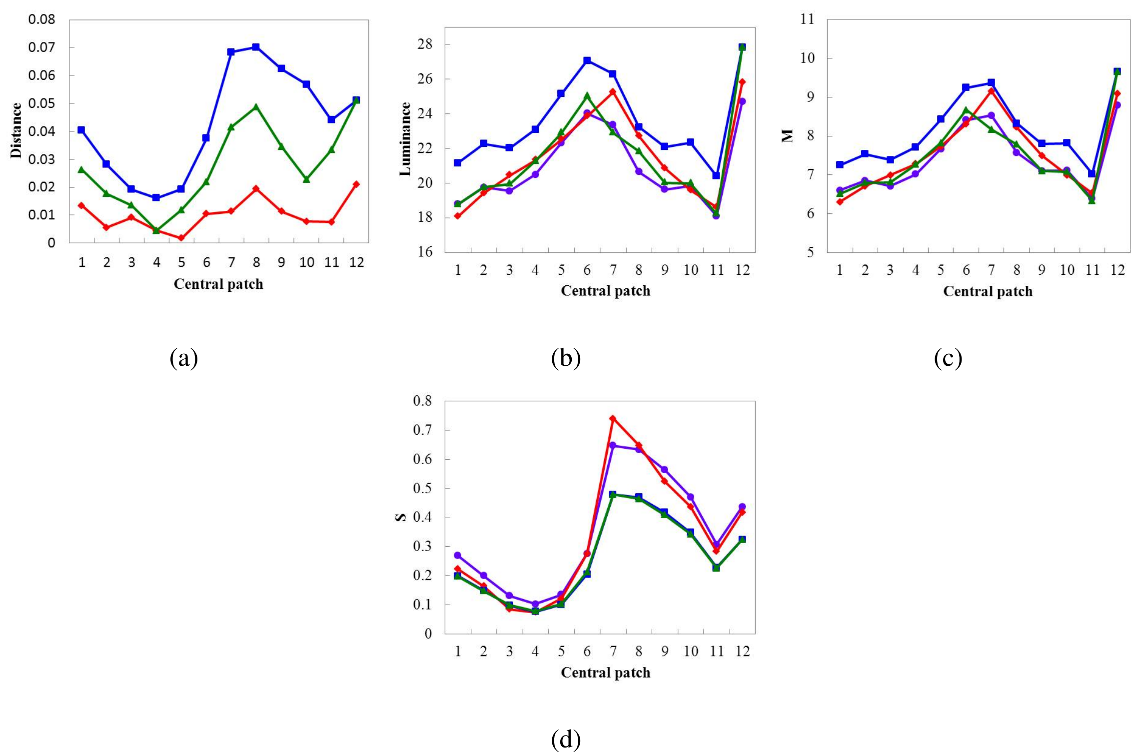


Figure 4.10 The chromatic shift and cone responses data for protan KMY under greenish yellow illuminant, with the same denotations as Figure 3.13

colors basically follows the von Kries or reflectance rule. Here, the von Kries and reflectance model predicted value does not have large difference. Figure 4.4b shows that the luminance of matched colors has a certain deviation from von Kries predicted luminance, but generally follows the von Kries rule. In Figure 4.4(c and d), note that purplish blue illuminant does not induce large changes of L and M cone: the von Kries predicted L and M cone responses overlapped with the reflectance model predicted and those of standard colors. The L and M cone responses of matched colors have a small deviation from those of von Krie theoretical colors or standard colors. S cone responses appear to correspond fairly well to von Kries predictions. However, the strong constancy in S cone responses for twelve patches does not correspond to equally good color constancy in (u', v') diagram. It is reasonable to suppose that signals from L and M cone interfere with the color constancy performance.

Purplish blue and greenish yellow illuminants were obtained by changing the same amount of S cone stimulation of D65 illuminant. However, Figure 4.5a shows almost no color constancy under greenish yellow illuminant. Figure 4.5 has the same format with Figure 3.8. The distances from standard colors to matched colors are very small. The observer tended to ignore the changes induced by test illuminant and made little adjustment toward test illuminant. The luminance matches in Figure 4.5b and L, M cone responses in Figure 4.5(c and d) are similar with those under purplish blue illuminant. The most noticeable aspect is that S cone responses of matched colors are perfectly consistent with those of standard colors, not von Kries cone adaptation/gain control model. If observers made adjustment according to von Kries cone adaptation/gain control, the S cone should also obey the von Kries rule, like that under purplish blue illuminant. S cone changes here may be determined by a higher level mechanism. Poor detection of tiny surface color changes contributes to the failure of S cone matches.

Figure 4.6 shows the fitting of matched data under purplish blue illuminant (a) and greenish yellow illuminant (b) respectively. It can be seen that two models cannot be separated very well.

Purplish blue and greenish yellow illuminants are not along confusion lines. Therefore, the fitting data under purplish blue and greenish yellow illuminants is not separated for deutan confusion line and protan confusion line.

The performance of LX (deutan) under purplish blue illuminant is shown in Figure 4.7. In Figure 4.7a, the chromatic shift of matched colors appears to have a certain degree consistence with physical reflectance model, but this trend is very vague. In Figure 4.7b, the luminance of matched colors generally fits the cone adaptation/gain control model, except some points on left side which lay on the reflectance model curve. Figure 4.7(c and d) show that L cone responses of matched colors show an analogous pattern with the luminance; S cone responses basically remain the same as those of standard colors.

From Figure 4.8a, it can be seen that there is almost no color constancy. Luminance of matched colors in Figure 4.8b approaches to that of standard colors. Figure 4.8(c and d) show that L and S cone responses of matched colors basically are the same as those of standard colors. These results indicate that the observer LX hardly has L cone adaptation and also fails to estimate theoretically calculated color under greenish yellow illuminant condition.

By observing GY's data under purplish blue and greenish yellow illuminants in Appendix, it was found that the matched luminance and L cone responses show the same characteristic as those of color normal observers. That means under purplish blue and greenish yellow illuminants, the luminance system of protanomalous observer GY is as normal as that of color normal observers. Figure 4.9 presents the data of KMY under purplish blue illuminant. In Figure 4.9a, KMY tries to use some estimation mechanisms to adjust the color of test surface toward test illuminant. The mechanism contributing to this partial compensation is not sure. In Figure 4.9b, the matched luminance seems to follow reflectance model. Accordingly, the M cone responses of matched colors tend to follow reflectance model in Figure 4.9c. The S cone has relatively good cone adaptation. Figure 4.10 shows the matches of KMY under greenish yellow illuminant. The chromatic shift of matched colors is small, shown in Figure 4.10a. The matched luminance does not follow the von Kries model and remains the same as that of standard colors. M cone and S cone have no cone adaptation in Figure 4.10c.

In addition, it should be noted that the M cone responses characteristic of protan OTK is apparently different from that of color normal observers and protan KMY. The M cone responses characteristic of KMY are the same as that of color normal observers. KMY's color vision is really a reduction form of trichromatic color vision. OTK may have M cone with variant sensitivity.

4.3 Discussion

4.3.1 The effect of color discrimination ability on the color constancy

Dichromats' blue-yellow color discrimination ability has a certain effect on their color constancy. When the blue-yellow discrimination ability is lower, there should be many color chips whose appearance under two different illuminants looks the same. In the previous red-green illuminant changes condition in Chapter 3, the partial color constancy was attributed to S cone stimulation changes of background or cone adaptation/gain control. Although the dichromats cannot discriminate the color difference between two illuminants along the same confusion line, the color of illuminated background surfaces will change consistently toward the same direction. The color constancy under present blue-yellow illuminant condition is better than that under red-green illuminant condition, because dichromats can perceive the color of illuminant and maybe use both of illuminant color perception and background information to obtain color constancy. Color normal observers' color constancy under red-green illuminant is stronger and more stable than that under blue-yellow illuminant. There is one explanation that color normal observers are not so much familiar to use the information of background color changes. Dichromats are more sensitive to the S cone stimulation changes of surfaces than color normals.

4.3.2 The relationship between S cone responses and color constancy

Different from green and red illuminant conditions, S cone plays a key role in the color constancy under purplish blue and greenish yellow illuminants. Purplish blue and greenish yellow illuminants do not produce strong stimulation for L and M cone. The color constancy should be mediated by the behavior of S cone excitation. However, signals from L and M cone may have effect on the S cone responses. Consequently, the degree of S cone responses does not correspond well to the degree of color constancy. If the cone adaptation/gain control takes effect, the S cone responses should match with the von Kries predicted cone responses even the illuminant cannot be estimated well, such as purplish blue illuminant condition in the present study. Only in the case when the observers try to exploit higher level cognitive mechanisms, it is possible that the S cone responses never change as illuminant changes. This is because the observer cannot estimate the theoretically calculated color accurately, such as the case under greenish yellow illuminant condition here.

From purplish blue and greenish yellow illuminants to D65 illuminant, L cone stimulation changes are not noticeable. The L cone responses of standard colors, two models predicted colors and matched colors coincide with each other. Deutans show S cone constancy only under purplish blue illuminant. Under greenish yellow illuminant, the S cone has no constancy. Under purplish blue and greenish yellow illuminants which do not stimulate L and M cone much, the L cone responses are normal like color normal observers; the luminance of protanomalous GY was contributed by the L cone and M cone responses. For the other protanomalous observer PA, the luminance was always contributed by the variant L cone responses under four test illuminant conditions.

Chapter 5

Conclusion and general discussion

5.1 Conclusion

According to the experimental results, it was found that the color constancy was mediated by different mechanisms in different conditions. Observers are familiar with red and greenish yellow illuminants whose color temperature is close to that of daylight. Under red and greenish yellow illuminants, observers had a good ability to estimate the reflectance and illuminant as the result of color constancy. Because the color of the greenish yellow illuminant is very similar with that of D65 illuminant, observers need not adjust the color so much and adjusted mainly the luminance, which was enough satisfactory for paper match.

However, under purplish blue and green illuminants, which are not common for people in daily life, observers could not estimate the reflectance and illuminant well and just used the cone adaptation/gain control for the color constancy. Under the purplish blue illuminant condition, observers mainly used S cone matching to obtain color constancy because blueness is the most important if the case reflectance and luminance cannot be obtained well under the blue illuminant.

It is strongly suggested that the color and luminance in the constancy is treated independently.

The color constancy was mediated by cone adaptation/gain control, reflectance and illuminant estimation, or the amount of S cone stimulation changes according to different conditions. Instead, the luminance was always mediated by cone adaptation/gain control.

The conclusion, that is relatively simple, is that contributing factors like cone adaptation/gain control, luminance and the amount of S cone stimulation changes mainly determined the color constancy. It means high-level cognitive process is not necessarily needed to explain the color constancy in the present study. This result is conflictive to some previous literature. It is expected the difference is caused by the difference in stimuli and experimental conditions; environment surroundings and 3-D perception in their experiments would help high-level cognitive process for color constancy.

The experimental method and analysis in this study can firstly separate the two hypotheses, cone adaptation/gain control model and reflectance and illuminant estimation model clearly. Thus, the present study clarifies that one of cone adaptation/gain control effect or reflectance and illuminant estimation was used for the color constancy depending on experimental conditions, not like mixture of both of them. Surprisingly, the color constancy for different illuminants (red, greenish yellow, green and purplish blue) was treated differently in the mechanism. It suggests that human vision is taking an adaptive strategy to process color constancy, concerning to the experience to illuminants.

5.2 Selective utilization of cone adaptation/gain control to illuminant and estimation on theoretically calculated color

From experimental results, it can be seen that for color normal observers, under green illuminant, the von Kries adaptation was used to mediate the color constancy; under red illuminant, the theoretically calculated color estimation mechanism was utilized to obtain the color constancy. von

Kries adaptation model pays more attention to the effect of illuminant, irrespective of image surfaces. The present findings show that the visual system mainly considers the effect of illuminant under green illuminant, ignoring the effect of image surfaces. It was reported that the long periods and full-field adaptation can help to achieve almost complete color constancy (Murray et al. 2006). Bäuml suggested that the von Kries cone adaptation might be not enough to explain the illuminant adjustment in surface matches and higher level mechanisms may be needed (Bäuml 1999b). Under red illuminant, the theoretically calculated color estimation plays a main role in the color constancy. In this study, the visual system chooses to use different mechanisms to mediate the color constancy according to illuminant conditions. Both of von Kries cone adaptation/gain control and higher level cognitive mechanisms can be used to accomplish color constancy, but apply to different illuminant conditions. Some researchers investigated color constancy in natural scenes (Amano et al. 2006) or by using 3-D objects (Hedrich et al. 2009). In these 3-D or natural scenes, almost same degree of color constancy was obtained, but adopted mechanisms might be completely different: more likely, different combinations of cone adaptation and various cognitive strategies. If 3-D objects or scenes were illuminated by the same green illuminant as that in present study, it is expected that a cognitive mechanism and cone adaptation are combined to mediate the color constancy. These two mechanisms can only be separated when the illuminant mainly stimulates L cone (red illuminant) or M cone (green illuminant). When the illuminant mainly stimulates S cone, the colors predicted by two mechanisms are very close. The usage of two mechanisms cannot be separated. This situation happens to purplish blue and greenish yellow illuminants here and illuminants along daylight locus.

From the comparison between chromatic shift in CIE 1976 (u', v') diagram and corresponding cone responses, it can be supposed that under the condition when the von Kries cone adaptation takes main effect in the surface match, the L, M and S cone responses firstly change by a constant as a result of the photoreceptoral adaptation to illuminant at retina level and then provide a kind of sensory information into a higher level cortical area; under the condition when the cognitive estimation on surface color plays a main role, some cue information from image surfaces firstly is sent to a certain cortical area, which in turn determines the change amount of L, M and S cone.

The degree of color constancy of the protanomalous observer GY is almost as good as that of color normal observers, but he tended to use the theoretically calculated color estimation mechanism under both green and red illuminant conditions. Maybe the protanomalous observer GY is more sensitive to the theoretically calculated color changes induced by illuminant changes than color normal observers.

It was thought that adaptation of the retinal photoreceptors is presumably a significant factor in color constancy for color deficient observers (Morland et al. 1997). In the present study, deutans showed the L cone adaptation under the green and red illuminant conditions. However, L cone adaptation was used to compensate for luminance changes. The M cone adaptation of protans was also used to contribute to luminance changes. Consequently, only S cone adaptation may mediate the color constancy. Of course, the possibility that signals from adapted L cone have some effects on the color constancy cannot be excluded. S cone responses of matched colors of deutans did not comply with cone adaptation rule under green illuminant, red illuminant and greenish yellow illuminant, which indicated that deutans attempted to cognitively catch some information from the consistent color changes of background surfaces caused by green or red illuminant. This may be demonstrated by the statement of observer LX. He said:" I cannot tell you accurately the color of illuminant, but I know the luminance changes caused by illuminant are not like pure luminance changes. When I adjust the color, I have to use blue-yellow buttons; only luminance buttons are not enough." Protans had S cone adaptation under green illuminant and purplish blue illuminant. S cone adaptation of protans is stronger than that of deutans. Under red illuminant, purplish blue illuminant and greenish yellow illuminant, the M cone responses of protans comply with the reflectance model. It seems that protans tend to cognitively use luminance information.

For color changes induced by S cone stimulation changes, protans are likely to use cone adaptation to compensate for them. It may be concluded that deutans mainly cognitively estimate the color changes caused by S cone stimulation changes to obtain the color constancy; protans tend to use S cone adaptation and luminance-related estimation mechanism to achieve the color constancy. The result that protans performed as well as color normal observers in the color constancy under illuminant changes along daylight locus (Baraas et al. 2004) may be caused by the mechanism illustrated here.

5.3 The role of luminance in the selection of color constancy mechanisms

It is not sure about the reason why the visual system selects the cone adaptation/gain control under green illuminant and theoretically calculated color estimation mechanism under red illuminant. Is it because the scenes illuminated by red illuminant look vivid and familiar for observers and the scenes illuminated by green illuminant look strange? The consistent deviation of matched luminance from the von Kries predicted luminance under red illuminant leads to another possibility that the luminance may be an important factor providing information for theoretically calculated color estimation. Uchikawa et al. found that the scene illuminant was estimated by the visual system based on optimal colors in the scene (Uchikawa et al. 2012). Golz and MacLeod reported that the redness-luminance correlation was useful for estimating the illuminant color (Golz and MacLeod 2002). It was reported that whether or not the observer utilized luminance information in their match strongly influenced the degree to which the cone contrast rule held (Kulikowski et al. 2012). By the experiments in this study, this conclusion can be extended: whether or not the observer utilizes luminance information in their match has a strong effect on the selection of mechanisms contributing to color constancy. Protanomalous observers and protans may have advantage in extracting luminance information because of their special luminance system and the luminance cue further helps their color constancy. From the LMS cone responses data of deutans and protans, it may be concluded that deutans tend to use L cone adaptation to mediate the luminance and use estimation mechanism on color changes to mediate the color constancy; protans are better at the cognitive utilization of luminance cues and tend to use S cone adaptation mechanism to contribute to the color constancy.

5.4 The effect of S cone stimulation on color constancy

Green illuminant and red illuminant give considerably larger stimulations to L and M cone than S cone. For color normal observers, S cone responses seem to have a very small effect on the color constancy under green illuminant and red illuminant. The changes from D65 to purplish blue and greenish yellow illuminants mainly alter the S cone response and have few effect on the L and M cone responses. S cone responses play a more important role in the color constancy under purplish blue and greenish yellow illuminants.

Under purplish blue illuminant, the S cone responses follow von Kries cone adaptation principle. Under greenish yellow illuminant, the S cone does not have von Kries cone adaptation. This failure may be because the observer can not perceive the illuminant changes or estimate the theoretically calculated color under test illuminant. Overall, the color constancy performance has agreement with the S cone responses performance: the complete von Kries cone adaptation under purplish blue illuminant contributes to the color constancy basically complying with the von Kries model; the failure of S cone responses under greenish yellow illuminant contributes to no color constancy. Quantitatively, the good fitting of S cone responses to von Kries cone adaptation does not correspond to equally good color constancy under purplish blue illuminant. This may be because S cone responses were influenced by the signals from the L and M cone. Kuriki and Uchikawa reported that S cone system's performance was not enough to achieve perfect color constancy (Kuriki and Uchikawa 1996). S cone system is relatively more influenced by illuminant conditions than red-green system (Kuriki and Uchikawa 1996; Nieves et al. 2000). The human visual system has developed a higher sensitivity along the yellow/blue dimension (Troost et al. 1992). The S cone system is more sensitive to illuminant changes along daylight locus.

For dichromats, the S cone always plays a very important role in the color constancy. The question is whether dichromats obtain the color constancy by S cone adaptation or perception of bluish or yellowish changes of scene color induced by illuminant. The present result shows that deutans mainly used cognitive mechanisms to estimate the color changes caused by S cone stimulation changes to obtain the color constancy; protans used S cone adaptation and luminance-related cognitive mechanism to mediate the color constancy. Color perception activity in daily life makes dichromats more sensitive to bluish and yellowish color than color normal observers. It can be noted that the S cone responses of color chips 7 (10B 5/6), 8 (7.5PB 5/6), 9 (5P 5/6) have no deviation from the basic line. It seems that the color constancy performance of dichromats is related with the S cone stimulation of illuminant. The illuminant changes along daylight locus are primarily in the S cone responses. It was reported that dichromats have relatively good color constancy under illuminant changes along daylight locus (Rüttiger et al. 2001). For the investigation of color constancy of dichromats, it may be better to guarantee that the S cone stimulation changes caused by illuminants are large enough to induce the chromatic changes of background surfaces.

5.5 Arend's color constancy index calculation method can not be applied to any illuminant condition

In Arend's color constancy index calculation method, theoretical colors are set as the theoretically calculated chromaticity coordinates of patches under test illuminant. This method accepts that the perfect constancy is obtained when the observer can perfectly estimate the theoretically calculated color of patch under test illuminant. The usage of this method means the acceptance of the reflectance model. This method can be only applied to the condition where the observer uses the estimation mechanism on theoretically calculated color under test illuminant to obtain the color constancy. If the observer uses the cone adaptation/gain control mechanism, the perfect theoretical color which corresponds to perfect constancy will only correspond to cone adaptation/gain control predicted point and never match with the theoretically calculated color. Maybe the cone adaptation/gain control is completed and color constancy is perfect in the sense of cone adaptation, but the Arend's index shows unsatisfactory color constancy performance. When the matched color goes to the direction of von kries predicted color and is far from the theoretically calculated color, the Arend's index may become a minus value. The result in this study suggests that the surface matching principle of observers should be investigated firstly and then the appropriate index calculation method will be used. Different index calculation method should be used for different color constancy mechanism conditions. The most noticeable thing is: the reflectance model and von Kries model do not make large difference under illuminant changes along daylight locus. At present, only under illuminant changes along red-green direction, two models can be separated. If Arend's index method is used to measure the color constancy in the condition where the reflectance model takes effect, like red illuminant or illuminants along daylight locus, it can give a good description for the color constancy performance. However, if Arend's color constancy index calculation method is used to measure the color constancy where the von Kries model plays a main role, like green illuminant, it will conceal the real principle of observers' adjustment. Arend's index cannot be used to measure the color constancy performance of any illuminant condition.

The next question is to investigate which kind of condition can make the matched colors overlap with the von Kries model predicted colors or reflectance model predicted colors and when the perfect color constancy in the sense of cone adaptation/gain control or reflectance model will be obtained. Can it be achieved by using large field adaptation or long duration adaptation under green illuminant condition and cue-rich background image surfaces under red illuminant condition?

About the color constancy of color deficient observers, there is still one question to be addressed: investigate the constancy index calculation method to measure the color constancy performance of color deficient observers.

Appendix A

Data of other color deficient observers

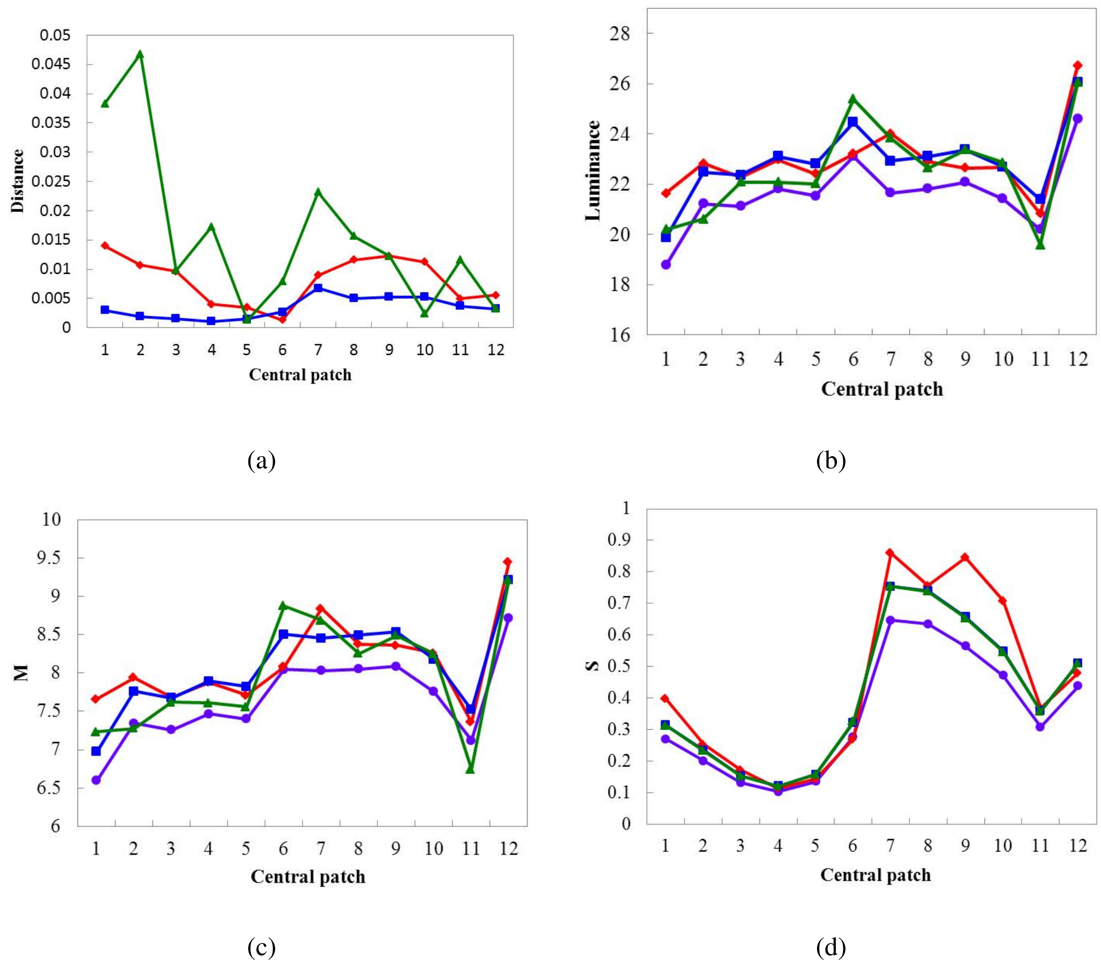


Figure A.1 The chromatic shift and cone responses data for protan OTK under green illuminant

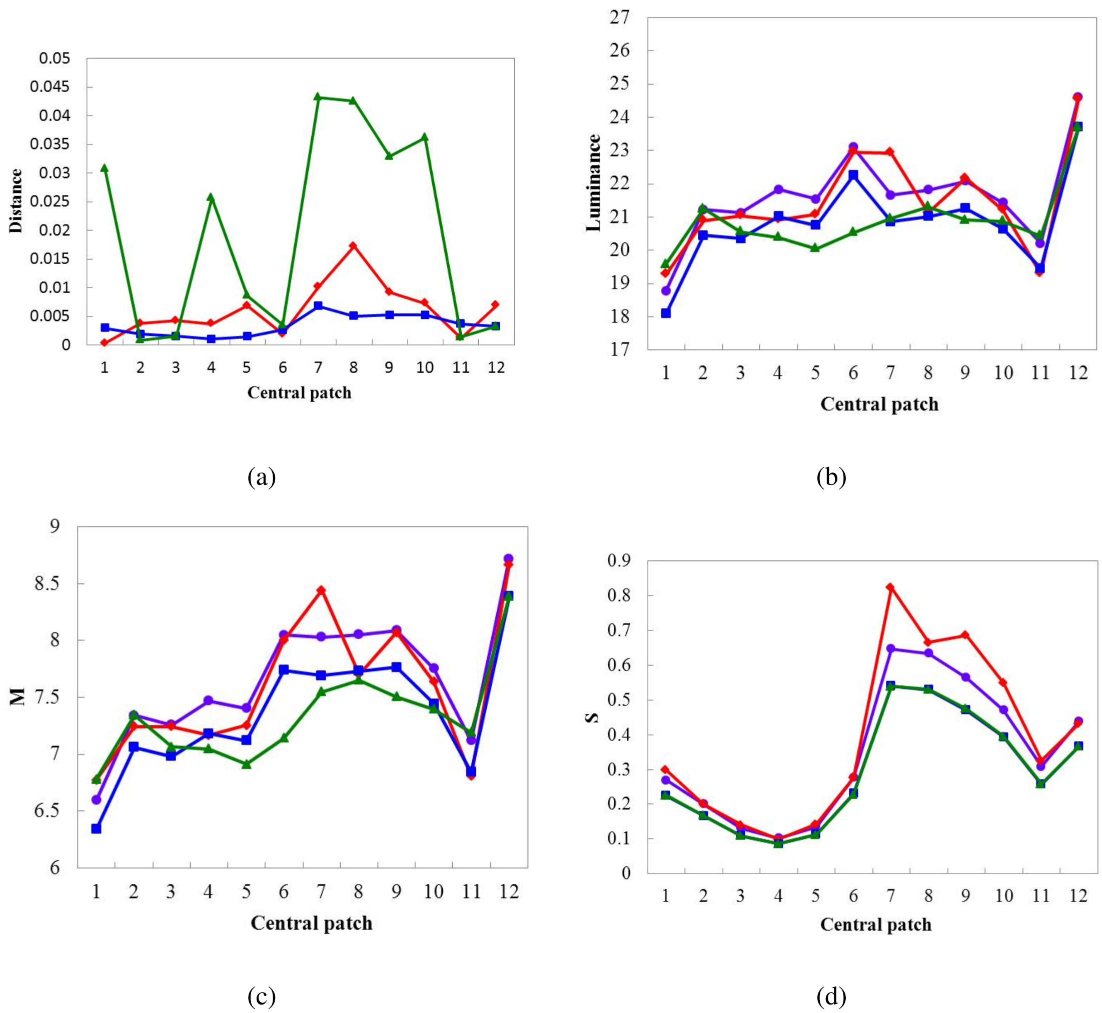


Figure A.2 The chromatic shift and cone responses data for protan OTK under red illuminant

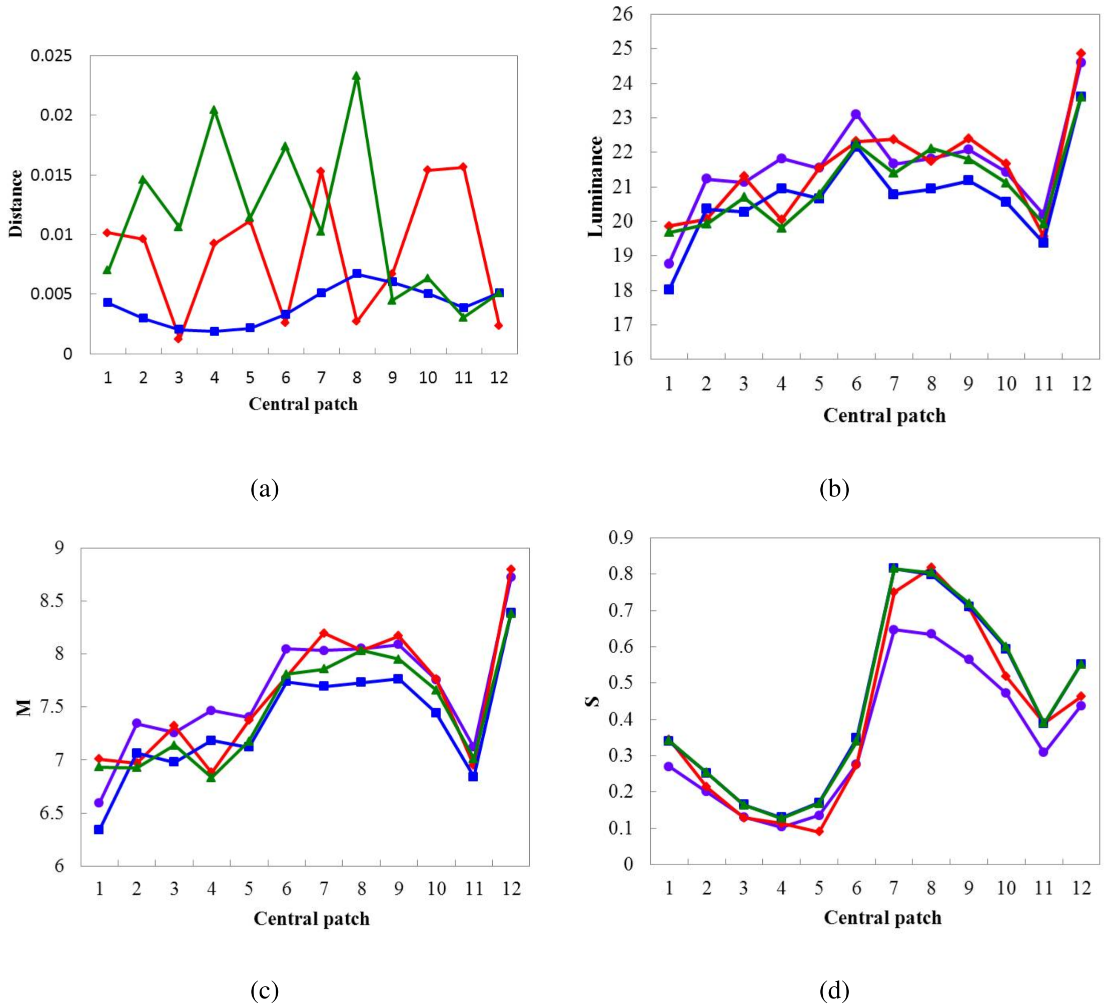
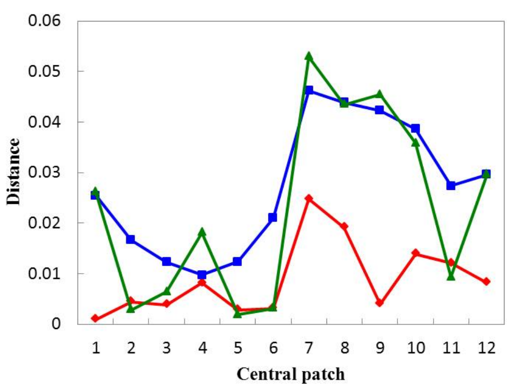
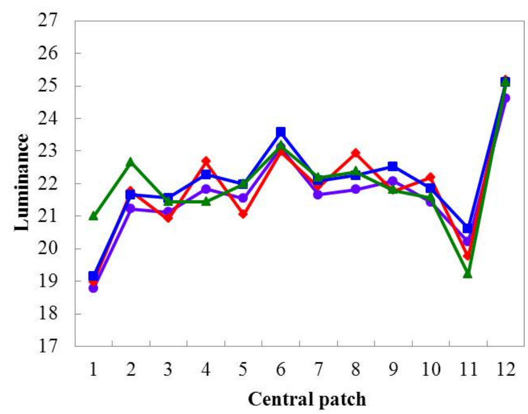


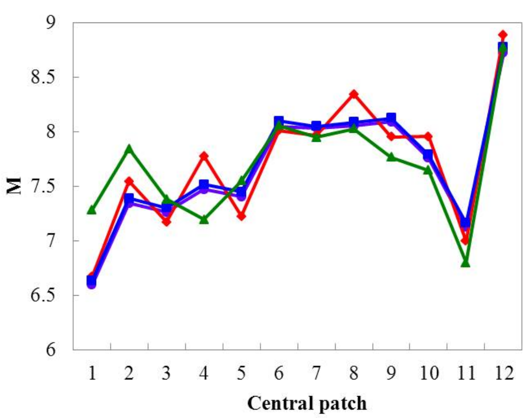
Figure A.3 The chromatic shift and cone responses data for protan OTK under purplish blue illuminant



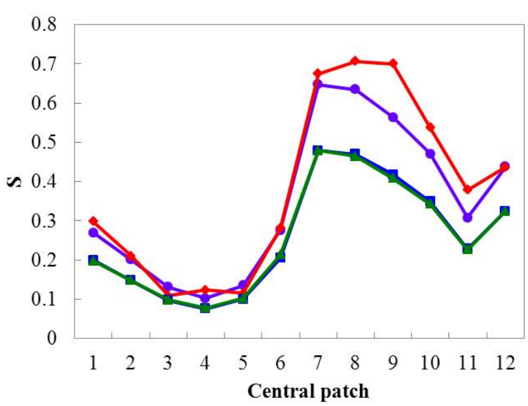
(a)



(b)



(c)



(d)

Figure A.4 The chromatic shift and cone responses data for protan OTK under greenish yellow illuminant

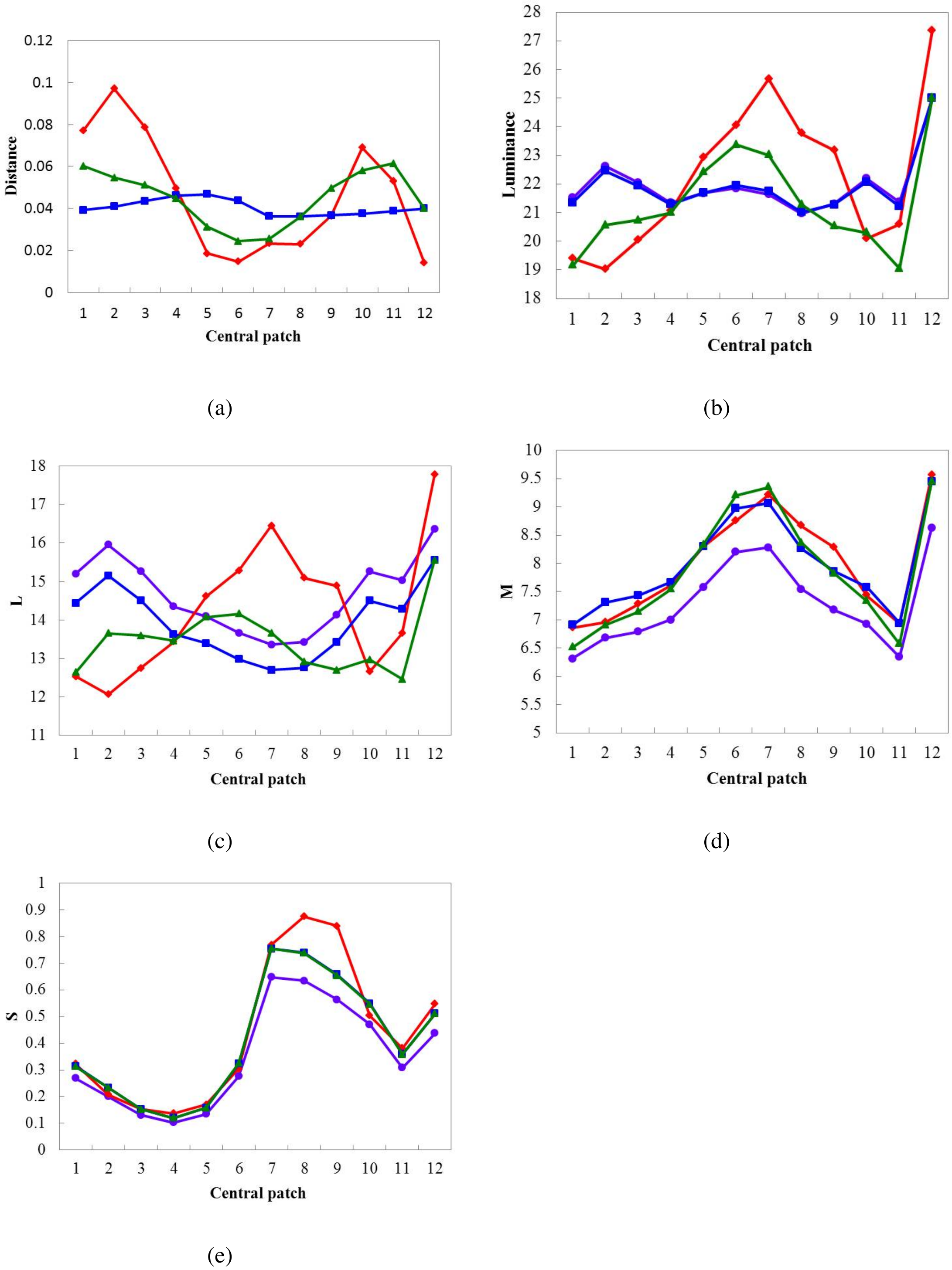
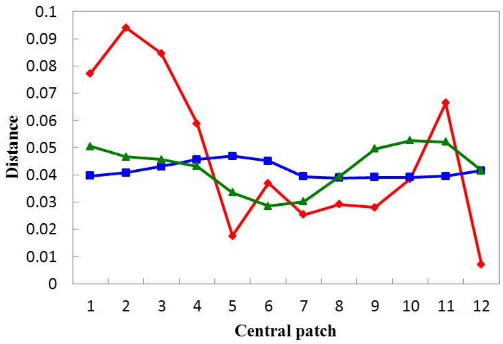
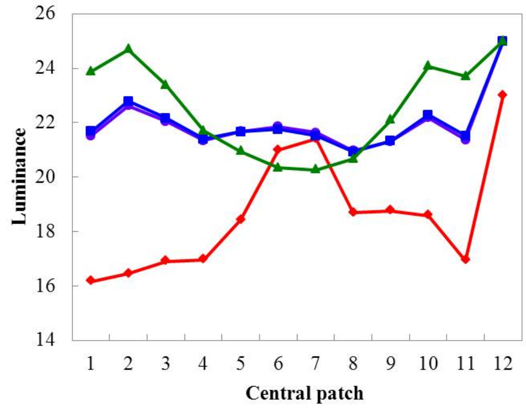


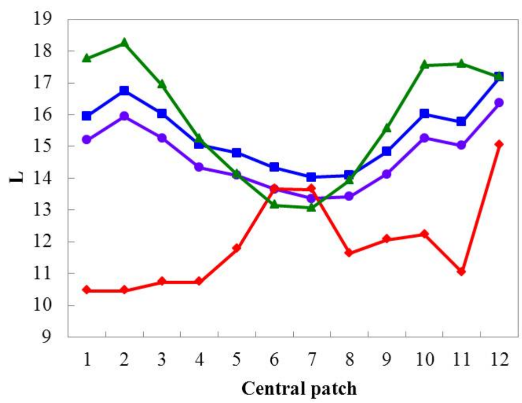
Figure A.5 The chromatic shift and cone responses data for protanomalous observer PA under green illuminant



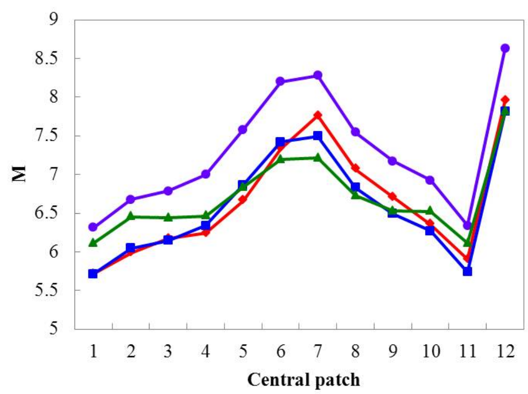
(a)



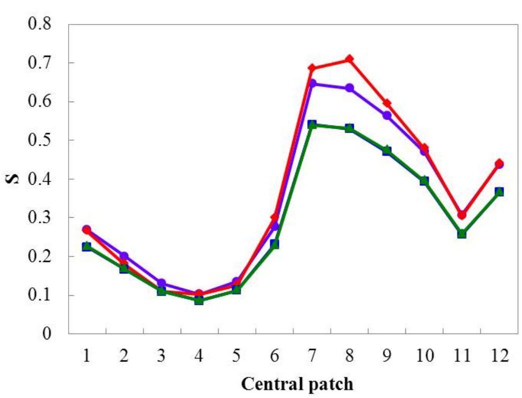
(b)



(c)



(d)



(e)

Figure A.6 The chromatic shift and cone responses data for protanomalous observer PA under red illuminant

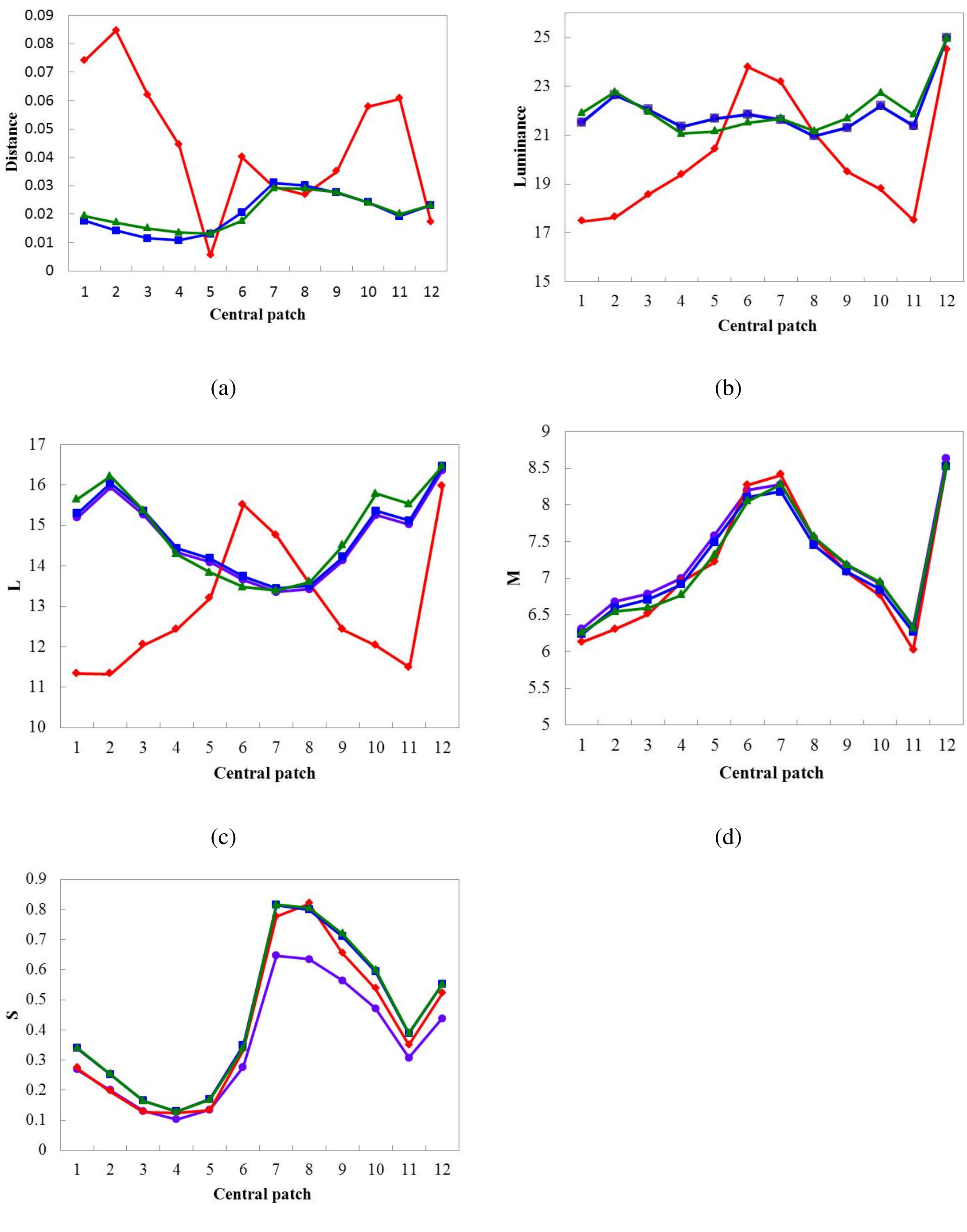
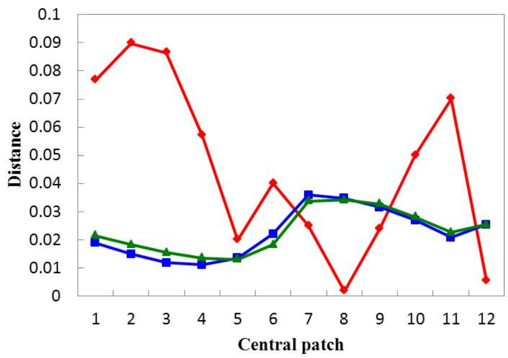
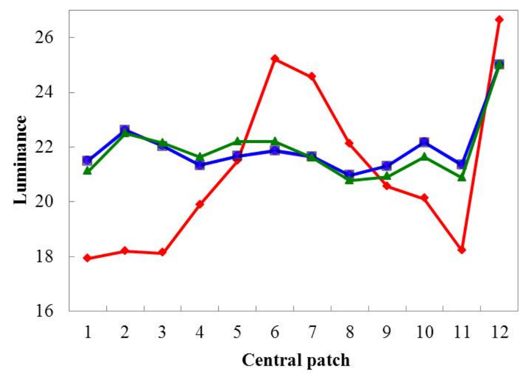


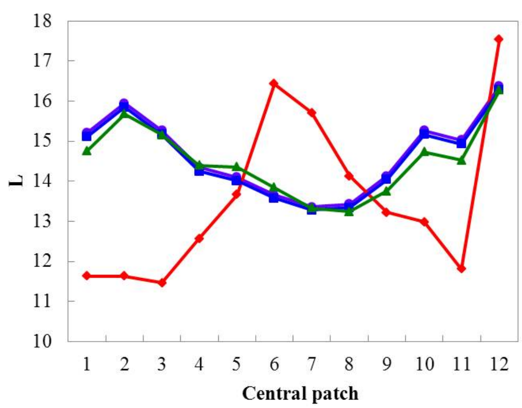
Figure A.7 The chromatic shift and cone responses data for protanomalous observer PA under purplish blue illuminant



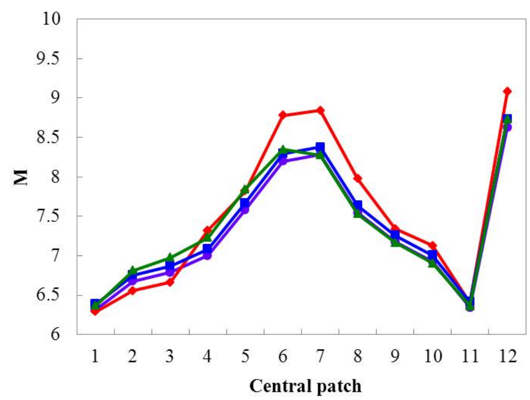
(a)



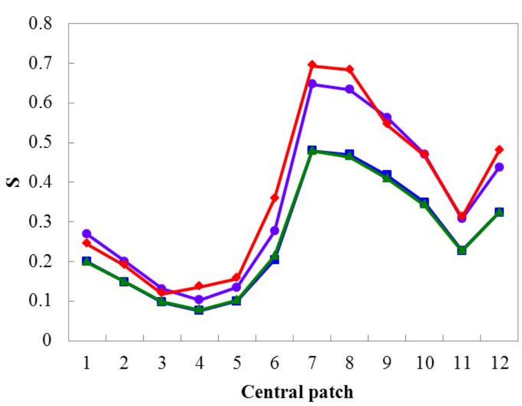
(b)



(c)



(d)



(e)

Figure A.8 The chromatic shift and cone responses data for protanomalous observer PA under greenish yellow illuminant

Bibliography

Allen, E. C., Beilock, S. L., and Shevell, S. K. (2012). Individual differences in simultaneous color constancy are related to working memory. *J. Opt. Soc. Am. A*, 29(2):A52–A59.

Amano, K., Foster, D., and Nascimento, S. (2003). Red-green colour deficiency and colour constancy under orthogonal-daylight changes.

Amano, K., Foster, D. H., and Nascimento, S. M. C. (2006). Color constancy in natural scenes with and without an explicit illuminant cue. *Visual Neuroscience*, 23:351–356.

Arend, L. E. and Reeves, A. (1986). Simultaneous color constancy. *J. Opt. Soc. Am. A*, 3(10):1743–1751.

Arend, L. E., Reeves, A., Schirillo, J., and Goldstein, R. (1991). Simultaneous color constancy: papers with diverse munsell values. *J. Opt. Soc. Am. A*, 8(4):661–672.

Baraas, R. C., Foster, D. H., Amano, K., and Nascimento, S. M. C. (2004). Protanopic observers show nearly normal color constancy with natural reflectance spectra. *Visual Neuroscience*, 21:347–351.

Baraas, R. C., Foster, D. H., Amano, K., and Nascimento, S. M. C. (2006). Anomalous trichromats' judgments of surface color in natural scenes under different daylights. *Visual Neuroscience*, 23:629–635.

Baraas, R. C., Foster, D. H., Amano, K., and Nascimento, S. M. C. (2010). Color constancy of red-green dichromats and anomalous trichromats. *Investigative Ophthalmology & Visual Science*, 51(4):2286–2293.

Bäuml, K. (1999a). Color constancy: the role of image surfaces in illuminant adjustment. *J. Opt. Soc. Am. A*, 16(7):1521–1530.

Bäuml, K. (1999b). Simultaneous color constancy: how surface color perception varies with the illuminant. *Vision Research*, 39(8):1531 – 1550.

Brainard, D. and Wandell, B. (1992). Asymmetric color matching: how color appearance depends on the illuminant. *J. Opt. Soc. Am. A*, 9(9):1433–1448.

Brainard, D. H. (1998). Color constancy in the nearly natural image. 2. achromatic loci. *J. Opt. Soc. Am. A*, 15(2):307–325.

Brainard, D. H., Brunt, W. A., and Speigle, J. M. (1997). Color constancy in the nearly natural image. 1. asymmetric matches. *J. Opt. Soc. Am. A*, 14(9):2091–2110.

Breneman, E. (1987). Corresponding chromaticities for different states of adaptation to complex visual fields. *J. Opt. Soc. Am. A*, 4(6):1115–1129.

Burnham, R. W., Evans, R. M., and Newhall, S. M. (1957). Prediction of color appearance with different adaptation illuminations. *J. Opt. Soc. Am.*, 47(1):35–42.

Chichilnisky, E. J. and Wandell, B. A. (1995). Photoreceptor sensitivity changes explain color appearance shifts induced by large uniform backgrounds in dichoptic matching. *Vision Research*, 35(2):239 – 254.

Delahunt, P. B. and Brainard, D. H. (2004a). Color constancy under changes in reflected illumination. *Journal of Vision*, 4(9).

Delahunt, P. B. and Brainard, D. H. (2004b). Does human color constancy incorporate the statistical regularity of natural daylight? *Journal of Vision*, 4(2).

Fairchild, M. D. and Lennie, P. (1992). Chromatic adaptation to natural and incandescent illuminants. *Vision Research*, 32:2077–85.

Fairchild, M. D. and Reniff, L. (1995). Time course of chromatic adaptation for color-appearance judgments. *J. Opt. Soc. Am. A*, 12(5):824–833.

Foster, D., Amano, K., and Nascimento, S. (2001a). How temporal cues can aid color constancy. *Color Research and Application*, 26:S180–S185.

Foster, D. H., Amano, K., and Nascimento, S. (2001b). Colour constancy from temporal cues: better matches with less variability under fast illuminant changes. *Vision Research*, 41(3):285 – 293.

Foster, D. H., Amano, K., and Nascimento, S. M. C. (2006). Color constancy in natural scenes explained by global image statistics. *Visual Neuroscience*, 23:341–349.

Foster, D. H. and Nascimento, S. M. C. (1994). Relational colour constancy from invariant cone-excitation ratios. *Proceedings of the Royal Society of London. Series B: Biological Sciences*, 257(1349):115–121.

Goddard, E., Solomon, S., and Clifford, C. (2010). Adaptable mechanisms sensitive to surface color in human vision. *Journal of Vision*, 10(9).

Golz, J. (2008). The role of chromatic scene statistics in color constancy: Spatial integration. *Journal of Vision*, 8(13).

Golz, J. and MacLeod, D. I. A. (2002). Influence of scene statistics on colour constancy. *Nature*, 415:637–640.

Granzier, J. J. M., Brenner, E., Cornelissen, F. W., and Smeets, J. B. J. (2005). Luminance-color correlation is not used to estimate the color of the illumination. *Journal of Vision*, 5(1).

Granzier, J. J. M., Brenner, E., and Smeets, J. B. J. (2009). Can illumination estimates provide the basis for color constancy? *Journal of Vision*, 9(3).

Hansen, T., Walter, S., and Gegenfurtner, K. R. (2007). Effects of spatial and temporal context on color categories and color constancy. *Journal of Vision*, 7(4).

Hedrich, M., Bloj, M., and Ruppertsberg, A. I. (2009). Color constancy improves for real 3d objects. *Journal of Vision*, 9(4).

Jin, E. W. and Shevell, S. K. (1996). Color memory and color constancy. *J. Opt. Soc. Am. A*, 13(10):1981–1991.

Kraft, J. M. and Brainard, D. H. (1999). Mechanisms of color constancy under nearly natural viewing. *Proceedings of the National Academy of Sciences*, 96(1):307–312.

Kulikowski, J., Daugirdiene, A., Panorgias, A., Stanikunas, R., Vaitkevicius, H., and Murray, I. (2012). Systematic violations of von kries rule reveal its limitations for explaining color and lightness constancy. *J. Opt. Soc. Am. A Opt Image Sci Vis*, 29(2):A275–89.

Kuriki, I. (2006). The loci of achromatic points in a real environment under various illuminant chromaticities. *Vision Research*, 46(19):3055–3066.

Kuriki, I. and Uchikawa, K. (1996). Limitations of surface-color and apparent-color constancy. *J. Opt. Soc. Am. A*, 13(8):1622–1636.

Lee, R. and Smithson, H. (2012). Context-dependent judgments of color that might allow color constancy in scenes with multiple regions of illumination. *J. Opt. Soc. Am. A*, 29(2):A247–A257.

Lucassen, M. P. and Walraven, J. (1996). Color constancy under natural and artificial illumination. *Vision Research*, 36(17):2699 – 2711.

Martinovic, J., Mordal, J., and Wuerger, S. M. (2011). Event-related potentials reveal an early advantage for luminance contours in the processing of objects. *Journal of Vision*, 11(7).

Murray, I. J., Daugirdiene, A., Vaitkevicius, H., Kulikowski, J. J., and Stanikunas, R. (2006). Almost complete colour constancy achieved with full-field adaptation. *Vision Research*, 46(19):3067 – 3078.

Nascimento, S. M. C., P., F. F., and Foster, D. H. (2002). Statistics of spatial cone-excitation ratios in natural scenes. *J. Opt. Soc. Am. A*, 19(8):1484–1490.

Nieves, J. L., García-Beltrán, A., and Romero, J. (2000). Response of the human visual system to variable illuminant conditions: An analysis of opponent-colour mechanisms in colour constancy. *Ophthalmic and Physiological Optics*, 20(1):44 – 58.

Olkkonen, M., Hansen, T., and Gegenfurtner, K. R. (2008). Color appearance of familiar objects: Effects of object shape, texture, and illumination changes. *Journal of Vision*, 8(5).

Rinner, O. and Gegenfurtner, K. R. (2002). Cone contributions to color constancy. *Perception*, 31(6):733– 746.

Rüttiger, L., Mayser, H., Srey, L., and Sharpe, L. T. (2001). The color constancy of the red-green color blind. *Color Research and Application*, 26:S209–S213.

Smith, V. C. and Pokorny, J. (1975). Spectral sensitivity of the foveal cone photopigments between 400 and 500 nm. *Vision Research*, 15(2):161 – 171.

Smithson, H. and Zaidi, Q. (2004). Colour constancy in context: Roles for local adaptation and levels of reference. *Journal of Vision*, 4(9).

Sobagaki, H., Yamanaka, T., Takahama, K., and Nayatani, N. (1974). Chromatic-adaptation study by subjective-estimation method. *J. Opt. Soc. Am. A*, 64(6):743–9.

Troost, J. M., Li, W., and De Weert, C. M. M. (1992). Binocular measurements of chromatic adaptation. *Vision Research*, 32(10):1987 – 1997.

Troost, J. M. and Weert, C. M. M. (1991). Naming versus matching in color constancy. *Perception and Psychophysics*, 50:591–602.

Uchikawa, K., Fukuda, K., Kitazawa, Y., and MacLeod, D. I. A. (2012). Estimating illuminant color based on luminance balance of surfaces. *J. Opt. Soc. Am. A*, 29(2):A133–A143.

Webster, M. A. and Mollon, J. D. (1995). Colour constancy influenced by contrast adaptation. *Nature*, 373(23):694 – 698.

Werner, J. S. and Walraven, J. (1982). Effect of chromatic adaptation on the achromatic locus: The role of contrast, luminance and background color. *Vision Research*, 22(8):929 – 943.

Yang, J. N. and Maloney, L. T. (2001). Illuminant cues in surface color perception: tests of three candidate cues. *Vision Research*, 41(20):2581 – 2600.

Yang, J. N. and Shevell, S. K. (2003). Surface color perception under two illuminants: The second illuminant reduces color constancy. *Journal of Vision*, 3(5).

Zaidi, Q., Spehar, B., and DeBonet, J. (1997). Color constancy in variegated scenes: role of low-level mechanisms in discounting illumination changes. *J. Opt. Soc. Am. A*, 14(10):2608–2621.