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The impact of transition type on chromatic adaptation under dual lighting conditions

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Abstract

Over the years, many CATs (chromatic adaptation transform), typically based on the von Kries coefficient rule, have been developed to predict the corresponding colors under different illuminants. However, these CATs were derived for uniform stimuli surrounded by a uniform adapting field. To investigate the adaptation state under spatially complex illumination, an achromatic matching experiment was conducted under dual lighting conditions with three color pairs and two transition types. It has been found that the transition type has an impact on both the equivalent chromaticity and degree of adaptation. These results can help build a comprehensive von Kries based CAT model, with considering the spatial complexity of illumination.

Introduction

Chromatic adaptation is a perceptual phenomenon that contributes to keep the color appearance of objects approximately constant across changes in illumination [1], a phenomenon referred to as 'color constancy'. Different underlying mechanisms have been proposed for color constancy, which can generally be grouped in two categories: ones based on discounting the illuminant and others based on spatial comparisons [2]. While the spatial comparison type models, such as the Retinex model [3], [4], take the entire scene and its spatial structure and complexity into account – and therefore require images as input to the model – the first, simpler, type of model is often based on the von Kries coefficient rule that states that chromatic adaptation is due to an independent rescaling of each of the cone sensitivities. This is the approach adopted in typical color appearance models, such as the CIECAM02 [5] and CAM16 [6], and chromatic adaptation models, such as CMCAT2000 [7], CAT02 [5] and CAT16 [8], and is therefore the one which will be focused on in this paper.

To keep the color perception of an object stable, the visual system can compensate for the change in spectrum reflected from the object induced by different illuminants. The prerequisite is that visual system can estimate the trichromatic neural representation (*L, M, S* excitations) of the illuminant such that they can be resolved from the receptoral stimulations of the object [9], [10]. The idea may be that the visual system can estimate the neural representation of the illuminant from the light reflected from one or more objects, which depends on the product of the energy distribution of illumination and the reflectance spectrum [11]. Many theories have been proposed to estimate the illuminant from retina image. One simple illuminant estimation method is based on the average cone excitation of the entire scene, referred as the '*grey world assumption*' [10], [12], which is also the intrinsic principle of the *von Kries - Helson* model [13], [14] as shown below:

$$\begin{pmatrix} L_c \\ M_c \\ S_c \end{pmatrix} = \begin{pmatrix} k_L & & \\ & k_M & \\ & & k_S \end{pmatrix} \begin{pmatrix} L_0 \\ M_0 \\ S_0 \end{pmatrix} \tag{1}$$

$$k_L = 1/\overline{L_{vf}} \qquad k_M = 1/\overline{M_{vf}} \qquad k_S = 1/\overline{S_{vf}} \tag{2}$$

with *L, M* and *S* the responses of the long, medium and short wavelength-sensitive cones, respectively and with the subscripts *0* and *c* denoting the baseline (reference) and the stimulus-induced cone responses. $\overline{L_{vf}}$, $\overline{M_{vf}}$, $\overline{S_{vf}}$ are the average responses of the three cones over the visual field. The grey world assumption basically states that in general the average spectral reflectance of the whole visual field is neutral. However, this estimation method sometimes fails because the 'grey world assumption' cannot hold for all circumstances, especially when the average reflectance is far from neutral. Another method is based on the 'bright-is-white' assumption [4], where the surface with highest luminance, such as the specular highlight, may serve as the reference, as it is dominated by the spectrum of the illuminant.

Over the years, many chromatic adaptation transforms (CAT) adopting the von Kries coefficient law [15], such as CAT02 [5], [16], have been proposed to predict corresponding colors (CC). However, these CATs were mainly developed for uniform stimuli surrounded by a uniform adapting field, without considering its spatial complexity [1]. To develop a more comprehensive von Kries based CAT, valid in more complex, non-uniform illumination, it is necessary to characterize the interaction between chromatic adaptation and the spatial distribution of the adapting field, in terms of luminance and chromaticity. To extend a uniform illumination to a complex one, the first step could be to add a second illuminant in the adapting scene, which is a common occurrence in many natural viewing conditions. This raises lots of new questions. How to evaluate the impact of the two illuminants on the adaptation state? Can an equivalent chromaticity of the two illuminants provide a solution? If so, how is this best determined? Will the degree of adaptation change?

Several authors have addressed dual lighting conditions, but none could provide a comprehensive solution. A typical mixed adaptation condition to two illuminants occurs when a self-luminous display is viewed in a lit environment. Hunt [17] found that the adaptation white point moves to the display's white point with decreasing luminance level of the ambient lighting. To accurately predict the corresponding colors under mixed adaptation conditions, Katoh et al. [18], [19] proposed the S-LMS model which is based on the Hunt model. Sueeprasan and Luo [20] applied the conventional CATs, such as CMCCAT97, CMCCAT2000 in mixed adaptation conditions, which has equal, or even slightly better performance than S-LMS model.

Dual lighting conditions were also investigated in some color constancy studies [21], [22]. Yang et al. [21] investigates color perception in a scene with two different illuminants.

Asymmetric matching experiments were conducted in which the scenes were rendered with the three-dimensional rendering software RADIANCE. The interaction between the two illuminants was controlled from being completely separate to partially mixed. It was found that the degree of color constancy decreased when a region on one side of the wall had cues to both illuminants, but that color constancy can be improved by providing specular cues that are consistent under the two illuminations. Brainard [22] conducted a binocular asymmetric matching experiment across a spatial illumination gradient, which is typical for natural viewing conditions. Based on the visual data collected from this experiment, they proposed two models to estimate the asymmetric color matches: a diagonal model and an equivalent illuminant model. The results suggested that the two models have similar performance.

Few studies have considered dual lighting conditions in CATs, which were typically derived from uniformly illuminated adapting field. The aim of this paper is to determine the effectiveness and practical estimation of an equivalent chromaticity of dual lighting condition for application in a von Kries CAT, to derive a model for the degree of adaptation under these conditions and investigate the impact of the transition type (sharp versus gradient) between two illuminations on the adaptation state.

Experiment design

The background scene is a 3D stage covered by non-fluorescent white paper, with field of view at 80°. The stimulus is a grey cube with a 6° field of view (FOV) and was centrally positioned in the background scene, as shown in Figure 1. The reflectance spectra of the white background and grey cube are approximately constant. The illumination of the background and stimulus are provided by a data projector where the chromaticity of each pixel can be controlled separately by RGB-values. In the experiment, observers were asked to change the chromaticity of the stimulus by adjusting the RGB-values of the data projector corresponding to the pixels directly illuminating the stimulus. As the FOV of the stimulus is larger than 4°, the CIE 2006 10° color matching functions [23] were used for all colorimetric calculations. The reflectance spectra of the background and the object, as measured by a Hunterlab UltraScan Pro colorimeter, are plotted in Figure 2. The reflected spectral radiance of the stimulus was measured by a calibrated OceanOptics QE65Pro tele-spectroradiometer at 2 *m* measuring distance.

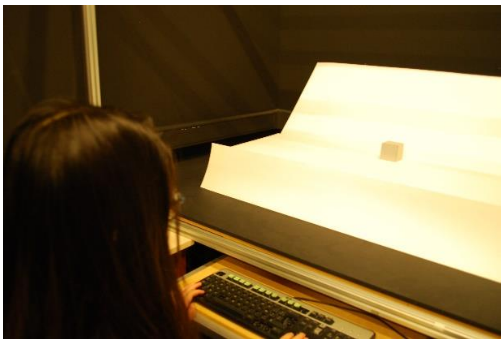

***Figure 1**. Experiment setup*

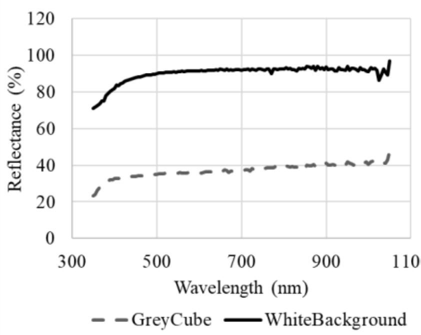

***Figure 2**. Reflectance spectra of the grey cube stimulus (dash line) and the background (solid line).*

The background was spatially non-uniformly lit by two horizontally aligned illuminations, each illuminating an equal area of the background. The background luminance was fixed at around 169 cd/m^2, but its chromaticity was varied during the experiments. The selected background chromaticity values corresponded to those of Planckian radiators at 2000 *K* (B2K) and infinite K (Binf); and highly chromatic red and green. Three pairs of dual lighting environments were chosen: (B2K, Red), (B2K, Binf), (Green, Red). For each illumination pair, there were two illuminations transition types: a sharp and a gradual (gradient) transition. Like the test stimulus, the transitions were horizontally centered with respect to the total illuminated background field. The transition type was such that it did not change the average chromaticity of the whole adapting field. Note that for each dual lighting condition, the achromatic matching experiment was repeated twice under the two mirror-symmetrical dual lighting conditions to counterbalance the left-right bias. All the illuminations with dual lighting are shown in Figure 3(a), 3(b) and 3(c) corresponding to three color pairs. To determine the equivalent chromaticity of a uniform background condition that provides the same adaptation state as the dual lighting conditions, for each illumination pair, the matching experiment was conducted under seven uniform backgrounds with their $u'_{F,10}v'_{F,10}$ chromaticity evenly distributed along a line connecting the two illumination chromaticities. Additionally, an achromatic match under a uniform white background, with the chromaticity of equal-energy-white (EEW), was collected for each observer to obtain a baseline for the CAT.

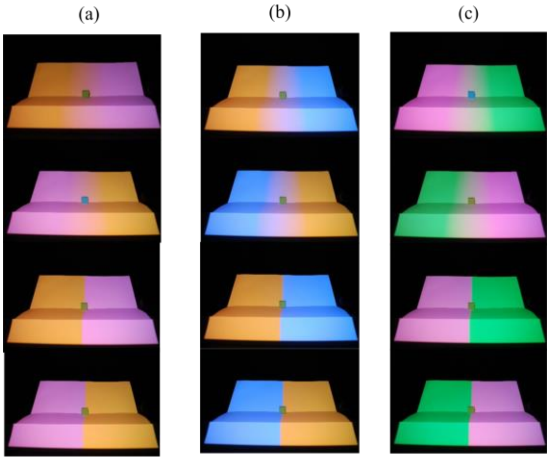

***Figure 3**. Non-uniform background scenes (adapting fields) under dual lighting conditions. The first two rows and last two rows represent the illumination with gradient transition and sharp transition respectively. (a). B2K and Red pair (b). B2K and Binf pair (c). Red and Green pair*

During the experiments, after 45 seconds of adaptation [24], [25], the observers were asked to adjust the color of the cube to neutral grey using a keyboard. To ensure all the observers were exposed to approximately identical adaptation conditions, during the adaptation period, they were required to stare at a black dot that moved across the scene in such a way that observers had their gaze toward the left and right halves of the scene for the same amount of time. When the black spot disappeared from the scene, observers could start to adjust the color of the stimulus (grey cube) to neutral grey by using the arrow keys in a keyboard to navigate in $u'_{F,10}v'_{F,10}$ space. To minimize the matching bias due to the initial color, each background condition was repeated 4 times starting from 4 symmetrically distributed chromaticities [26]. The illuminations and starting points were presented randomly to avoid order bias.

Ten color normal observers participated in the experiments. Their average age was 27.5 years with a standard deviation of 3.6 year.

Results

Observer variability

Inter- and intra-observer variability were estimated as the mean color difference from the mean (*MCDM*) [27] in the $u'_{F,10}v'_{F,10}$ space. The higher the *MCDM* value, the larger observer variation and the lower the observer repeatability. Higher *MCDM* value corresponds to larger observer variation (inter-observer), and lower repeatability (intra-observer). The inter-observer variability *MCDM* value was calculated as the color difference in $u'_{F,10}v'_{F,10}$ color space between the individual observer's average match from 4 starting points and the average match of all the observers. The intra-variability *MCDM* for each background condition has been evaluated using the color differences between the matches resulting from each of the four starting points and their average.

The mean inter- and intra-observer variability of the background with the sharp transition, gradient transition and uniform distribution are respectively 0.0096, 0.0087 and 0.0080 and 0.0100, 0.0094, 0.0078 $u'_{F,10}v'_{F,10}$ units. The larger inter- and intra-observer variability under the dual lighting background with the sharp transition indicates that it is more difficult to get stable and consistent matches. That may result from differences in eye movements across the scene during achromatic matching. The adaptation state of sharp transition is very sensitive to the gaze point as the stimulus is located right on the border line of the two illuminants.

Equivalent chromaticity

It is assumed that the spatially complex scene can be partially represented in a CAT model by a uniform adapting field whose chromaticity is equivalent to that of the complex scene, while the complex and uniform equivalent scenes may differ in their degree of adaptation. The equivalent chromaticity of a complex scene is calculated as follows: firstly, for each illuminant pair, a line was fitted to the matching chromaticities for the seven uniform backgrounds; secondly, for each dual lighting condition, the matching chromaticity was projected onto the fitted line of step 1, and the projected point was denoted as $u'v'_{dual}$. The projection of the seven uniform background matching chromaticities onto the line are denoted as $u'v'_j$ ($j = 1, 2, 3, \ldots, 7$); thirdly, the position of $u'v'_{dual}$ was specified in terms of the two neighboring projected matches for the uniform background ($u'v'_j$ and $u'v'_{j+1}$) as the ratio of the chromaticity differences between ($u'v'_{dual}$, $u'v'_j$) and between ($u'v'_j$, $u'v'_{j+1}$); fourthly, the equivalent chromaticity of the dual lighting condition was derived by a linear interpolation between the $u'_{F,10}v'_{F,10}$ chromaticities of the two uniform backgrounds (j and j+1) using the ratio derived in step three.

The matching results averaged over observers and their equivalent chromaticities under these dual lighting scenes in $u'_{F,10}v'_{F,10}$ space were plotted in Figure 4(a), 4(b) and 4(c), corresponding to (B2K, Red), (B2K, Binf), (Green, Red) respectively. Firstly, the left-right bias can be observed from Figure 4. For the pair (B2K, Red), the sharp transition with B2K on the left is substantially closer to B2K than that with Red on the left. While for the dual lighting conditions with a gradient transition, the points representing the two mirror-symmetrical scenes almost overlap with each other. Similar trends can be found in the other two color pairs. Figure 5 summarizes the color difference in $u'_{F,10}v'_{F,10}$ space ($DEu'_{F,10}v'_{F,10}$) of equivalent chromaticities of two mirror-symmetrical scenes for three color pairs. For the dual lighting conditions with gradient transition, the $DEu'_{F,10}v'_{F,10}$ values between two mirror-symmetrical scenes are fairly small or even negligible, less or very close to 0.0033, which corresponds to approximately one just noticeable difference (JND) or a three-step MacAdam ellipse [28]. But sharply transitioned backgrounds have much larger $DEu'_{F,10}v'_{F,10}$ values than gradient transitioned backgrounds, especially for the pair (B2K, Red). It suggests that the left side of the scene has a larger influence on chromatic adaptation than the right side, which may arise from the left side drawing more attention during the achromatic matching. The left bias has been found in many psychological studies including both perceptual judgment [29] and visuospatial attention tasks [30]. A possible explanation could that the right hemisphere is more activated and interconnected than the left hemisphere which has been indicated by many neuroimaging researches [31], [32]. As the dual lighting conditions with gradient transition don't have such large chromaticity differences in the narrow field surrounding the grey cube, they are not sensitive to the left bias. However, for sharp transitions, because the borderline of two illuminants is directly behind the grey cube, the left bias can generate quite different matching results under the two mirror-symmetrical scenes, due to the large color difference between the left side and the right side.

The impact of the transition type on equivalent chromaticity has also been investigated. To eliminate the left-right bias, the equivalent chromaticities of the two mirror-symmetrical scenes were averaged to represent that of the dual lighting condition. For (B2K, Red) pair, the equivalent chromaticity of the gradient transition is equal to the average chromaticity of the two illuminations, while for the sharp transition, the equivalent chromaticity is closer to the red illumination, with the $DEu'_{F,10}v'_{F,10}$ distance from that of the gradient transition at 0.0144. For (B2K, Binf) pair, the equivalent chromaticity of the gradient transition is also located in the middle of the two illuminations, but for the sharp transition, it is slightly biased towards the Binf illumination ($DEu'_{F,10}v'_{F,10} = 0.0084$). For the (Green, Red) pair, the equivalent chromaticities of both the gradient and the sharp transition are equal to the average chromaticity of the two illuminations ($DEu'_{F,10}v'_{F,10} = 0.0020$). In other words, the equivalent chromaticity of dual lighting conditions with a gradient transition in between can be predicted by the grey world assumption. But for sharp transition, the results don't always follow grey world assumption. Overall, for the sharp transition, the B2K illumination always had less impact on chromatic adaptation than other background chromaticities.

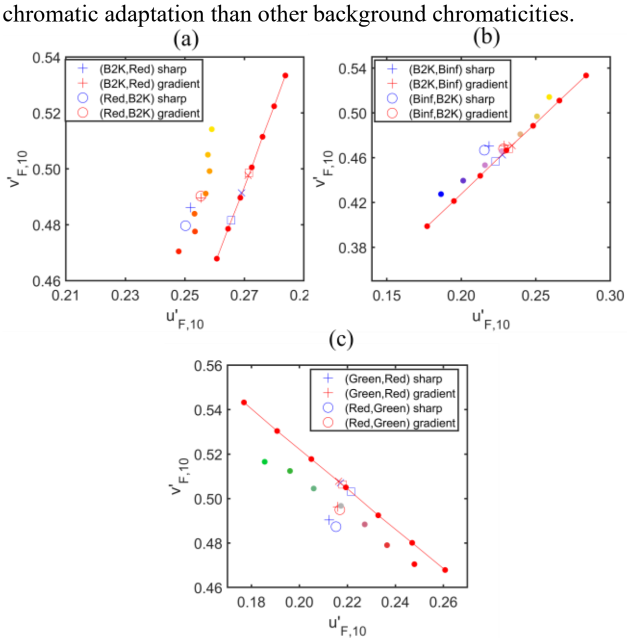

***Figure 4**. In each figure, the seven filled points with gradient color represent the matching results of uniform backgrounds averaged over observers. The blue symbols and red symbols represent the dual lighting conditions with sharp transition and gradient transition respectively. The legend implies the color distribution, where (B2K, Red) indicates that the left side is illuminated by B2K and the right side is illuminated by Red. The equivalent chromaticities of the dual lighting conditions are located on the line of the seven linearly distributed uniform backgrounds for each color pair. (a). (B2K, Red) (b). (B2K, Binf) (c). (Red, Green)*

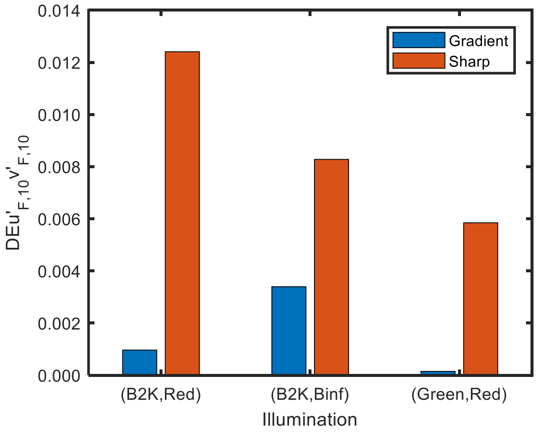

***Figure 5**. DEu'$_{F,10}$v'$_{F,10}$ between the equivalent chromaticities of the two mirror-symmetric scenes including two transition types and three color pairs.*

Model performance test

For each color pair, nine corresponding colors can be derived from the two dual lighting and the seven uniform backgrounds by taking the EEW chromaticity as the baseline. To transform *CIE 2006* $L_{F,10}M_{F,10}S_{F,10}$ to *CIE 2006* $X_{F,10}Y_{F,10}Z_{F,10}$, the transformation matrix defined in [23] was used, and its inverse matrix was used as the sensor space in CAT model. Note that the equivalent chromaticity of the dual lighting background was adopted as the adaptation chromaticity in the CAT. The degree of adaptation (D) in a von Kries type CAT was optimized by minimizing the prediction error for each illumination condition, denoted as D_{optim}. For each color pair, because the chromaticities of the seven uniform backgrounds and two dual lighting conditions are linearly distributed (shown in Figure 4), the background chromaticity can be represented by its relative distance to one illuminant (denoted as *Ratio*), as shown below:

$$Ratio = \frac{DE(u'v', u'v'_{Illum1})}{DE(u'v'_{Illum1}, u'v'_{Illum2})} \qquad (3)$$

with DE the color difference of two chromaticities, $u'v'$ the background chromaticity in $u'_{F,10}v'_{F,10}$ space, $u'v'_{Illum1}$, $u'v'_{Illum2}$ the chromaticity of the two illuminants in one color pair. For the (B2K, Red), (B2K, Binf), (Green, Red) color pairs, *Illuminant 1* refers to B2K, B2K and Green respectively.

The D_{optim} values of seven uniform backgrounds, plotted against *Ratio* in Figure 6, were well fitted with quadratic curves. The fitting error (*rmse* less than 0.050) is approximately 5% of the total scale (D_{optim} ranges from 0 to 1). The three subfigures of Figure 6 correspond to the (B2K, Red), (B2K, Binf) and (Green, Red) pairs, respectively. To compare with the D_{optim} values of the uniform backgrounds, the D_{optim} values of dual lighting conditions were also plotted in Figure 6. It can be observed that for each color pair, the red star, representing the gradient transition, is always located on or fairly close to the fitting curve, indicating that its D_{optim} can be well predicted by the quadratic function. In other words, for the three color pairs, the D_{optim} values of gradient transition are almost the same as that of a uniform background with the average chromaticity of the two illuminants. However, for the sharp transition, the corresponding red squares in Figure 6 are typically well below the fitting curve, with the D_{optim} being much smaller than that of the gradient transition, suggesting a substantial overestimation by the quadratic fitting function, except for the (B2K, Red) pair.

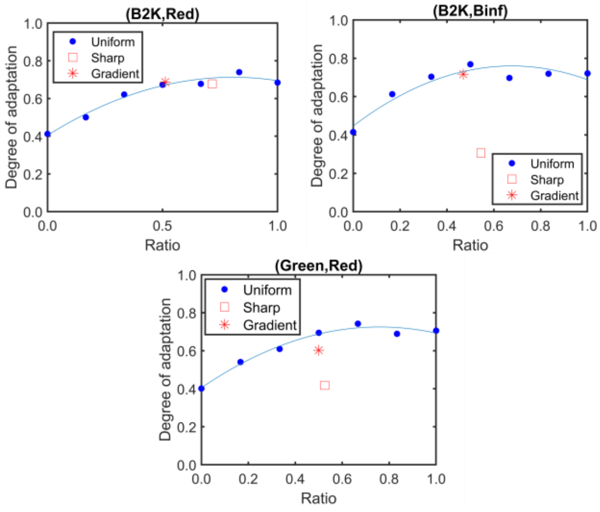

***Figure 6**. The three subfigures correspond to the three color pairs. In each subfigure, D_{optim} values were plotted against Ratio (ranging from 0 to 1) of the seven uniform and two dual lighting conditions. The blue points representing uniform background were well fitted by a quadratic curve. The red squares represent dual lighting conditions with sharp transition and the red stars represent gradient transition.*

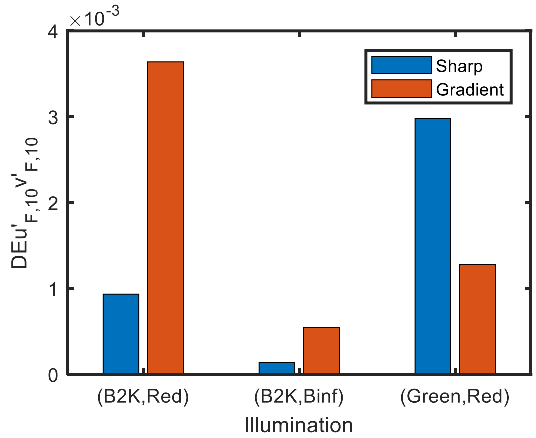

Figure 7. *The minimized prediction error of von Kries CAT in terms of* $DEu'_{F,10}v'_{F,10}$ *of the dual lighting conditions with two transition types for three color pairs.*

Figure 7 summarizes the $DEu'_{F,10}v'_{F,10}$ minimized prediction error of the one-step von Kries CAT model (from test illuminant to the baseline) under the two dual lighting conditions (two transition types) for three color pairs. Comparing the $DEu'_{F,10}v'_{F,10}$ of different transition types, it can be found that for each color pair, there is no substantial difference in the prediction error $DEu'_{F,10}v'_{F,10}$ between the gradient transition and the sharp transition. In addition, the prediction errors are quite small, less than or very close to 0.0033, corresponding to one JND in $u'_{F,10}v'_{F,10}$ space.

Conclusion

An achromatic matching experiment was conducted to collect corresponding color under the dual lighting conditions with two transition types (gradient, sharp) and three color pairs.

Firstly, it has been found that the left side of the scene has a larger influence on chromatic adaptation than the right side as it attracted more attention during the achromatic matching. The left bias can result in a substantial difference in equivalent chromaticities of mirror-symmetric dual lighting conditions with a sharp transition.

Secondly, for dual lighting with a sharp transition, the equivalent chromaticity tends to be less influenced by the B2K illumination compared to the others.

Furthermore, it is harder to adapt to a dual lighting with a sharp transition than with a gradient transition, likely due to the presence of simultaneous contrast. The dual lighting condition with a gradient transition has an identical impact on chromatic adaptation to a uniform background with its average chromaticity.

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