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Perceived color of binocular hue mixture under different background luminance levels

Dingyu Hu, Shining Ma*, Yue Liu, Yongtian Wang, and Weitao Song
Beijing Engineering Research Center of Mixed Reality and Advanced Display, School of Optics and Photonics, Beijing Institute of Technology, Beijing, China
****shining.ma@bit.edu.cn***

Abstract

Three-dimensional (3D) displays employ the technique of binocular disparity, by presenting two separate images with parallax cues to the two eyes, resulting in the perception of stereo vision. The human brain can fuse these two images into a single stereoscopic image, provided that their color difference falls within the fusion limit. Prior research on binocular color fusion has mostly concentrated on assessing the fusion limit across different conditions, but limited attention has been given to investigating binocular color mixture, particularly concerning opposite color pairs. In order to explore the impact of background luminance on the binocular mixture of opposite colors, a series of color matching experiments were conducted for three background luminance levels using a custom-built stereoscopic display. The findings reveal that as the contrast of the background luminance decreases, the binocular color mixture is more affected by the sensory dominant eye.

Introduction

Nowadays, there has been a growing societal interest in three-dimensional (3D) displays, particularly in their application within virtual reality and augmented reality. Among various methods, the stereoscopic display method is the most commonly used in commercial applications by presenting two images with parallax clues to form a stereo sense in the brain [1]. When the color mismatch between two displays occurs, the fused color may differ from the color presented to either eye. Thus, to accurately quantify the perceived color of the stereoscopic display, it is necessary to explore the mechanism underlying the binocular color mixture.

Many studies have provided evidence that binocular luminance fusion depends on the luminance contrast between the stimulus and background. Under conditions with low luminance contrast, the perceived brightness of binocular mixture is consistently dominated by the stimulus with a higher contrast against the background, following a 'winner-take-all' pattern. With luminance contrast increasing, the perceived brightness of binocular mixture gradually transits to an alternative pattern of 'averaging' [2–4]. A similar trend has been found for the binocular saturation mixture that the binocular mixture of two iso-luminant patches with identical hue is close to that of the patch with higher saturation. While the binocular saturation mixture tends to shift towards the average saturation of two patches [5,6]. Regarding colors that vary in hue, several studies have indicated a consistent disparity between monoptic and binocular mixtures. For instance, when the green light was mixed with red or blue light, the binocular mixture required less amount of green light to match the reference stimulus compared to the monoptic mixture [7]. Liu et al. conducted research on the fusion results of different hue. They concluded that the fusion results are close to the midpoint of binocular stimuli, and each color direction have various fusion results [8].

In addition, sensory eye dominance (also called ocular dominance), referred to as the dominance of perception from one particular eye in the fused outcome, is an additional influential factor affecting the appearance of binocular color mixtures. It is important to note that the sighting dominant eye and sensory dominant eye are distinct concepts and, according to Yang's research, they appear to be unrelated [9]. In the case where the green light was presented to the dominant eye, a smaller amount of green light was needed to match the reference color. Conversely, when the green light was presented to the non-dominant eye, opposite results were obtained, indicating that the binocular mixture required a greater amount of green light to achieve a color match [10,11]. Furthermore, Lin et al. observed that the contrast of the binocular mixture was slightly biased by the patch contrast of the dominant eye [12].

However, previous investigations on binocular hue mixture have primarily focused on a limited number of hue combinations using monochromatic lights, and have not systematically extended to other pairs of hues. Additionally, the influence of luminance contrast on binocular hue mixtures has not been thoroughly examined. The aim of this study is to investigate how we perceive binocular mixtures of color patches with constant saturation but opposite colors, and explore the relationship between binocular hue mixtures and luminance contrast.

Method

Apparatus and viewing conditions

The equipment adopted in this experiment is a stereoscopic display, composed of a liquid crystal display (LCD) screen and two lens tubes for individual eyes, each of that packs a telecentric optical system. The LCD screen employed in this device has a size of 5.46 inches, and a resolution of 2560 (horizontal) × 1440 (vertical), resulting in a field of view of 18.9° (horizontal) × 21.1° (vertical). As depicted in Figure 1, the height of the stereoscopic display is adjustable to accommodate the comfortable viewing positions for each observer, ensuring that the viewing direction of each observer is approximately vertical to the LCD.

Figure 1. *A picture of an observer performing the experiment. Note that the observer's sight is approximately vertical to the LCD*

The stimuli employed in the experiment consisted of two small circles with a 2° field of view presented to two eyes. It is important to note that the parallax of the binocular circle was fixed at zero. The CIE 2006 2° color matching functions (CMFs), for the 32-year observer, were adopted for all colorimetric calculations in this study, as the stimulus size was smaller than 4° [13]. A pre-calibrated JETI specbos 1211-UV-2 tele-spectroradiometer was employed to measure the spectrum of the stimulus on the LCD screens at a 1.8° aperture. The LCD screen was characterized by establishing a Look-up-table (LUT) between the digital input and emission luminance for each primary channel [14,15]. Then PLCC (Piecewise Linear assuming Chromaticity Constancy) model was adopted to characterize the display color and build the conversion between RGB drive values and XYZ tristimulus. To compensate for the spatial non-uniformity of the display and enhance the color reproduction accuracy of two stimuli, display calibration was performed on the center point of the left and right halves separately. Furthermore, in order to minimize the color difference between the theoretical setting and the actual measurement, the RGB drive values were further optimized by adjusting one of the three channels (R, G, B) within a small range. The optimized RGB values of each stimulus were recorded as the input drive values to reproduce the theoretical setting, with the chromaticity error of each stimulus less than 0.0007 in terms of $u_F'v_F'$. Due to the high accuracy of display color characterization, the XYZ tristimulus of the stimulus perceived by the observer was considered as the target value of the theoretical setting.

Stimuli and procedure

Experiment I: Measurement of sensory dominant eye

The detection method employed to determine the sensory dominant eye was breaking continuous flash suppression (b-CFS), following the experimental procedures described by [9,16]. During the experiment, the target image was presented to one eye, while a dynamic Mondrian mask was displayed to the other eye, as shown in Figure 2. Both the target scene and the Mondrian mask were maintained at an average luminance of 50 *cd/m²*. The Mondrian mask had a white point of D65, and its luminance contrast ranged from -60% to 60%. The target image consisted of a left or right arrow with dimensions of 200 × 200 pixels, occupying approximately a 3° field of view. A total of 120 Mondrian masks were pre-generated for the following experiment.

At the beginning of each round, the luminance contrast of the target image was initially set to 0, rendering the arrow invisible. One Mondrian mask was randomly selected from the set of 120 pre-generated masks and presented on the other side. During the experiment, the luminance of the arrow within the target image gradually decreased, resulting in an increased luminance contrast against the background (always kept on a luminance of 50 *cd/m²*) by approximately 1% every 100 milliseconds. The final luminance contrast of the target image side would be 1. Simultaneously, the luminance contrast of the Mondrian mask presented to the other eye gradually decreased by approximately 0.6% every 100 milliseconds until it blended in with the background. To minimize afterimage bias, the position of the target arrow was intentionally varied slightly within the central field, allowing for a horizontal and vertical displacement of 20 pixels. Since the stereoscopic display used in this experiment had a limited field of view, a boundary of visual field was not employed to assist observers in fixing their gaze. The target image appeared with an equal possibility in both eyes, where the arrow direction was randomly selected for each round of presentation.

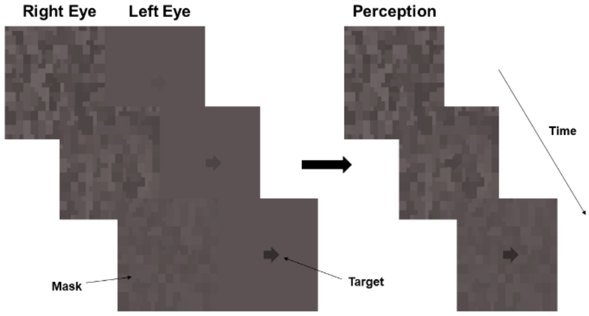

Figure 2. *The process to measure the sensory dominant eye. As time progresses (from behind to the front), the luminance contrast of the Mondrian mask gradually decreased while the contrast of the target arrow steadily increased. The perceived images by the observer were displayed in the right column. Consequently, the target image became clearer, while the mask became less noticeable.*

The task for each observer was to identify the arrow direction by pressing the corresponding arrow key as soon as the target image became visible. The program recorded both the direction of the pressed arrow key and the time taken to respond. The experiment switched to the next round either when the observer provided a response or after a fixed period of time (10 *s*). Before the start of each round, the observer was instructed to view a blank gray picture for 1.5 *s*. Each round of the experiment was repeated 50 times for each observer.

Experiment II: Measurement of binocular hue mixture

The display has a white point at D65. In the a^*b^* plane of the CIELAB color space, four groups of color pairs were selected, centered around the white point, along four opposite color directions: Red-Green (R-G), Yellow-Blue (Y-B), RedYellow-GreenBlue (RY-GB), and RedBlue-GreenYellow (RB-GY), as shown in Figure 3. The binocular colors have the same colorfulness as defined in the CIELAB space, but in different hues. Four groups correspond to four opposite hue pairs. Each color group contains three color pairs with the binocular color difference ΔE_{ab}^* at 8, 16, and 24, respectively. Note that the selected color difference was within the ellipse of binocular color fusion limit obtained from the study of Xiong et al [17]. Consequently, there were 24 sets of binocular color pair in total. To investigate the influence of the sensory dominant eye on the perceived color of binocular mixtures, the visual experiment for each color pair was repeated twice by swapping the colors presented to the left and right eyes. In addition, the color pairs with ΔE_{ab}^* at 16 along the Y-B direction were repeated twice in the experiment to evaluate repeatability for each observer. The stimuli had a fixed luminance (L_s) of 15 *cd/m²*. For each binocular color pair, three levels of background luminance (L_b) were selected: 0 *cd/m²*, 50 *cd/m²*, 100 *cd/m²*.

The scene displayed on the screen consisted of a pair of circular reference patches with opposite hues and a pair of test stimuli with identical colors, as shown in Figure 4. Two patches were presented on each side for the observer. The reference patches were consistently positioned above the test stimuli whose colors were adjusted to match the binocular mixture of the reference patches. Each circular patch had a fixed field of view of 2°, and there was a vertical separation of 4° between the test and reference stimuli on each side to prevent any mutual interference [18]. At the same time, a dip angle ranging from -5°

to 5° was implemented between the line connecting the centers of the two stimuli (test and reference) and the center perpendicular to reduce the impact of afterimage effects during the color pair switching process.

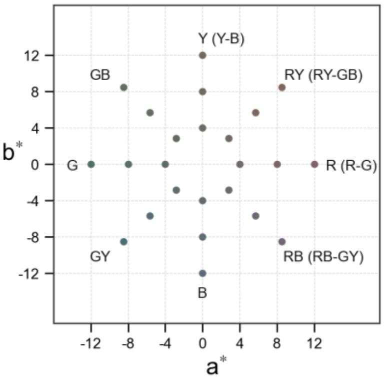

Figure 3. *All selected opposite color pairs with four opposite hues in the a*b* plane of the CIELAB color space.*

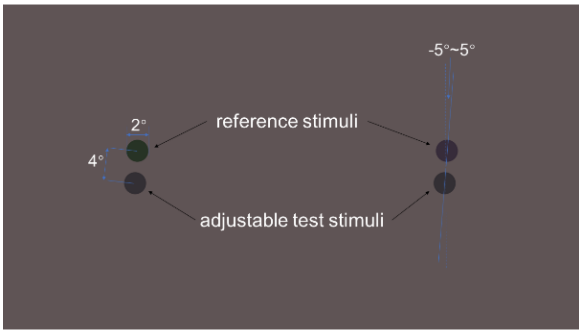

Figure 4. *A picture of binocular stimuli presented on the LCD screen, including a pair of reference stimuli with opposite hue and a pair of adjustable test stimulus with the same color (located below).*

The experiment was conducted in a dark room. Prior to the formal experiment, each observer was given an explanation of tasks to be performed. Following this, the observer was required to sit in front of the device and adjust the height of the eyepiece to ensure optimal viewing conditions. To begin each trial, the observer was given 5 *s* to adapt to the background. Subsequently, a test color pair was presented to the observer binocularly. Then the observer was asked to determine if the binocular colors can produce a stable fusion state. If fusion was achieved, the observer could start the matching task and adjust the color of test stimuli using the arrow keys on the keyboard until it matches the perceived color of the binocular hue mixture. The two arrow keys corresponded to the two directions along the connecting line between the two colors in a single reference binocular pair, while the other two arrow keys corresponded to the two perpendicular directions to the connecting line in the a^*b^* plane of CIELAB color space. Once a satisfactory match was made, press ‘1’ on the numpad to submit their responses. In cases where a stable fusion state was not achieved within 10 *s*, the observer pressed ‘2’. Then a new round started. The initial color of the test stimulus was randomly selected along the line connecting the two colors of the reference binocular color pair. The experiment comprised three separate sessions, each corresponding to a specific background luminance level. Within each session, the presentation order of the binocular color pairs was randomized to minimize any potential order effects. Additionally, the order of the three sessions was also randomized. During the experiment, observers were encouraged to take breaks whenever they felt uncomfortable.

During the experiment, the final matching results for each binocular color pair were meticulously recorded. Upon completion of the experiment, the spectra of the matching results were measured using a spectrometer. The measurements were performed repeatedly on each side of the display to ensure the accuracy and reliability of the data.

Observers

A total of 10 observers (5 males and 5 females) with normal color vision, as tested by the Ishihara test, participated in this experiment. The age of participants is between 21 and 25 years old (Mean = 23.3, STD = 1.1). The experiment was conducted with the approval of the BIT Institutional Review Board.

Results and discussion

The sensory dominant eye

For each observer, the probability of a correct answer was calculated, and it was found that the accuracy rate for each observer exceeded 98%. Subsequently, the mean spent time (MST) for the presence of the target image on the left or right eye was computed for correct answers. The MST values obtained from the left-eye and right-eye target images were summarized in Figure 5 (a). It can be observed that the MST values for the right-eye target image are always smaller than that for the left-eye target image for almost all the observers, with the exception of observer 3. Notably, for half of the observers (Observers 2, 7, 8, 9, and 10), the right eye has a substantial advantage in recognizing the target arrow with the MST difference between the left and right eye larger than 0.4 *s*. The above results indicate that for most observers in this experiment, the perception of the right eye predominantly influences the outcome of binocular fusion when perceiving the target image. Additionally, to further compare the average reaction time between the left and right eye, the MST ratio was calculated by dividing each observer's MST value for either eye by the sum of their MST values for both eyes. As shown in Figure 5 (b), it can be seen that the difference in MST ratio between the left and right eyes is not large, implying a less pronounced sensory dominance of the right eye. These findings align with the experimental results reported by Yang and Ding, confirming the consistency among these studies [9,16]. Therefore, we temporarily conclude that for most observers in the experiment, the right eye serves as the dominant sensory eye when perceiving color binocularly, except for Observer 3, while the degree of dominance is not prominently pronounced.

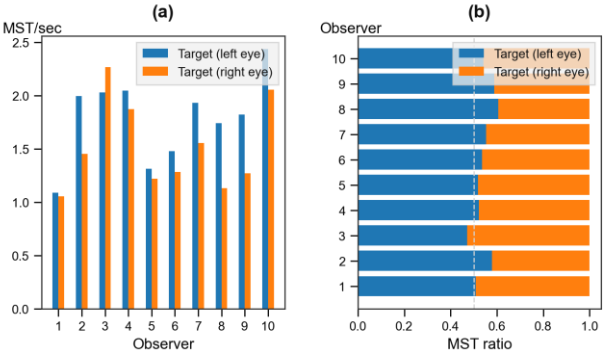

Figure 5. *(a) Mean spent time (MST) of each observer. (b) Mean spent time (MST) ratio of each observer for the left eye and right eye target image.*

Observer variability

Under each background luminance, the color matching experiment for Y-B opposite color pairs with a distance ΔE^*_{ab} of 16 have been repeated twice to assess the repeatability of the visual data for each observer. The intra-variability has been estimated by two metrics: repetition ratio and mean color difference. The former one refers to the proportion of color pairs that exhibited consistent binocular fusion or rivalry state between two repetitions. The larger repetition ratio value corresponds to lower intra-observer variability in terms of binocular perception state. The latter metric (mean color difference) represents the ΔE^*_{ab} color difference between two repeated matches averaged over all the selected color pairs (2 eye-swaps × 3 backgrounds = 6 pairs). A higher mean color difference value indicates larger intra-observer variability, suggesting a lower consistency in color matching. The repetition ratio and mean color difference for each observer were summarized in Table 1.

Table 1. The repetition ratio and mean color difference for each observer. The mean color difference value was presented in the form of *a* ± *b* where *a* refers to the mean value of all the six pairs and *b* refers to the standard deviation

Observer	reception ratio	a ± b
1	1.00	1.31 ± 0.79
2	1.00	2.26 ± 1.62
3	1.00	3.00 ± 1.87
4	1.00	1.92 ± 1.39
5	0.33	1.87 ± 1.80
6	1.00	1.51 ± 0.95
7	0.83	1.31 ± 1.41
8	1.00	2.04 ± 2.23
9	0.83	0.82 ± 0.48
10	1.00	1.04 ± 0.40

As shown in Table 1, it could be observed that the majority of observers exhibit a repetition ratio higher than 0.8 except for Observer 5 whose repetition value is only 0.33. These findings suggest that Observer 5 struggles to consistently judge the binocular fusion/rivalry state. Therefore, the visual data from observer 5 has been excluded from further analysis. Furthermore, regarding the intra-observer variability of color matching results, all the observers have a mean color difference smaller than 3 ΔE^*_{ab}, which falls within a reasonable range. This indicates a high level of repeatability in the color matching results for all the observers.

Data preprocessing

Before the analysis of color matching results, strict data preprocessing techniques were implemented to filter out reliable data. The data selection criteria consisted of the following rules:

(1) If an observer reported the inability to fuse a specific binocular color pair, the color matching data for that pair was considered missing;

(2) If a color pair cannot be fused, it was logically assumed that color pairs with a larger color difference along the same direction would also cannot be fused. Consequently, the color matching data for such pairs, if present, was excluded;

(3) If a color pair cannot be fused, the color pair with swapped colors would also be unable to achieve fusion. As a result, the color matching data for these pairs was discarded.

Furthermore, it was assumed that the perceived color of the binocular mixture should lie on the line connecting the two colors. Consequently, the final match was projected onto the connecting line, even though the experiment allowed for adjustments in perpendicular directions. Following the aforementioned preprocessing steps, the final color matching results were obtained.

Role of dominant eye in binocular hue mixture

After data projection, the adjusted matches are always located on the line connecting two colors. For each binocular color pair, the chromaticity of the perceived color match could be quantified in terms of the color difference between the match of the binocular hue mixture and one hue (H1) in the pair, denoted as $\Delta E^*_{m,h1}$. To ensure consistency in calculations, the Red (R), Yellow (Y), RedYellow (RY), RedBlue (RB) hue directions were selected as H1 for the estimation of $\Delta E^*_{m,h1}$.

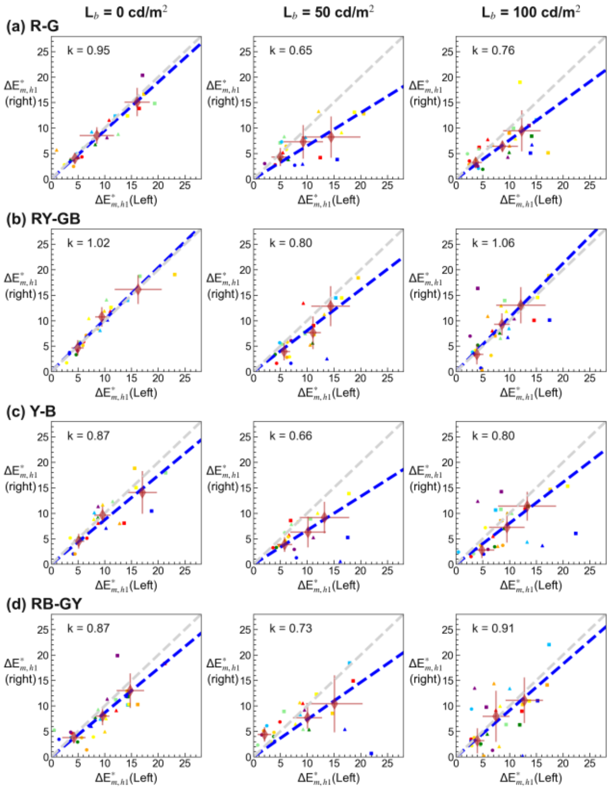

Figure 6. The relationship between the perceived color of the binocular hue mixture as quantified by $\Delta E^*_{m,h1}$ when H1 is presented to the right eye and when it is presented to the left eye. The dashed grey line represents the function of y = x, while the dashed blue line represents the function y = kx fitted to the data points of all observers. In each subfigure, the red diamond symbol represents the average results of nine observers for three levels of the binocular color difference, with the error bar of the standard deviation. The matching results from the same observer are denoted by points of the same color, with circle, triangle, and square shapes corresponding to ΔE^*_{ab} at 8, 16, and 24, respectively. The three columns represent three levels of background luminance, and the four rows correspond to four hue groups.

For the two repetitions with swapped colors (presented to the two eyes), the chromaticities of the two matches were calculated for each binocular opposite color pair. To investigate whether the perceived color of the binocular mixture could be influenced by swapping colors, the chromaticity of the perceived color match, represented by $\Delta E^*_{m,h1}$, with H1 presented to the right eye (y-axis), was plotted against that with H1 presented to the left eye (x-axis), as shown in Figure 6. Twelve subfigures correspond to three background luminance levels and four hue groups. The data points of different observers were marked with different colors to differentiate between them. In each subfigure, the data points from nine observers were fitted by a linear function $y = kx$. The dashed grey line represents the function of $y = x$. The data points located on the $y = x$ line indicate that the perceived color of the binocular mixture is irrelevant to color swapping. If the fitted k-value is less than 1, $\Delta E^*_{m,h1}$(left) values are consistently larger than $\Delta E^*_{m,h1}$(right) values, indicating that the matches are closer to H1 when H1 is presented on the right eye. The results imply a bias towards the perceived color of the binocular mixture by the right eye. Conversely, when the k-value is greater than 1, the situation is reversed, indicating that the binocular hue mixture is more influenced by the left eye.

For the dark background ($L_b = 0$ cd/m^2), the four fitting lines corresponding to four hue groups closely align with the reference line $y = x$, with the optimized k values ranging from 0.87 to 1.02, as shown in Figure 6. These results indicate that the binocular hue mixture is unaffected by the dominance of either eye, particularly in the R-G and RY-GB directions. However, when the background luminance is set to 50 cd/m^2, the k-values for all hue groups are smaller compared to the dark background, implying that the matches are more biased towards the right eye. When the background luminance increases to 100 cd/m^2, the k-values ranging from 0.76 to 1.06 are closer to 1 compared to the 50 cd/m^2 background, yet still smaller than those of 0 cd/m^2 background. As for the situation where the k value of RY-GB is slightly higher than that at dark background, it can be considered within a reasonable fluctuation range. In fact, the RY-GB direction is also relatively less affected by background luminance changes and the sensory dominant eye. Based on the above analysis, the k-value is positively correlated to the stimulus-background luminance contrast defined as the ratio of the absolute luminance difference between the stimulus and background to the sum of background luminance and stimulus luminance. In these three conditions, the background luminance of 50 cd/m^2 exhibits the lowest contrast, while having k-values that deviate the most from 1. Consequently, based on the findings of the sensory dominant eye experiment, it can be inferred that the binocular hue mixtures are more influenced by the sensory dominant eye (right eye) in this case. As the luminance contrast increases, matches to the binocular hue mixture are less influenced by the sensory dominant eye.

The matches of swapped colors obtained for individual observers were fitted using the $y = kx$ function. Figure 7 summarized the optimized k values for ten observers across three backgrounds and four hue groups. Specifically, Figure 7(a), (b), (c), and (d) correspond to the R-G, RY-GB, Y-B, and RB-GY hue groups, respectively. The analysis reveals that the majority of k-values are below 1.0, indicating that the right eye is commonly used as the dominant eye in these cases. Additionally, for most observers, the k-values for the L_b of 50 cd/m^2 are always lower than those for the L_b of 0 cd/m^2 or 100 cd/m^2. However, there are a few exceptions. Firstly, in the RB-GY direction, Observer 9 exhibits a k-value of 2.75 for the background luminance of 50 cd/m^2, which is much higher than the k-values for the other two backgrounds. This exception can be attributed to the fact that Observer 9 can only fuse the binocular color pair with the smallest color difference, where the k-value is more sensitive to variations in matching results. Secondly, in the R-G direction, Observer 3 displays a higher k-value for the background luminance of 50 cd/m^2 compared to the other two backgrounds. This exception can be well explained by the results of the sensory dominant eye experiment, which indicate that the dominant eye of Observer 3 is the left eye. Furthermore, it is worth noting that the variation of the red curve is smaller than that of the other two curves, suggesting that the inter-observer variability in matching results is lower under the dark background.

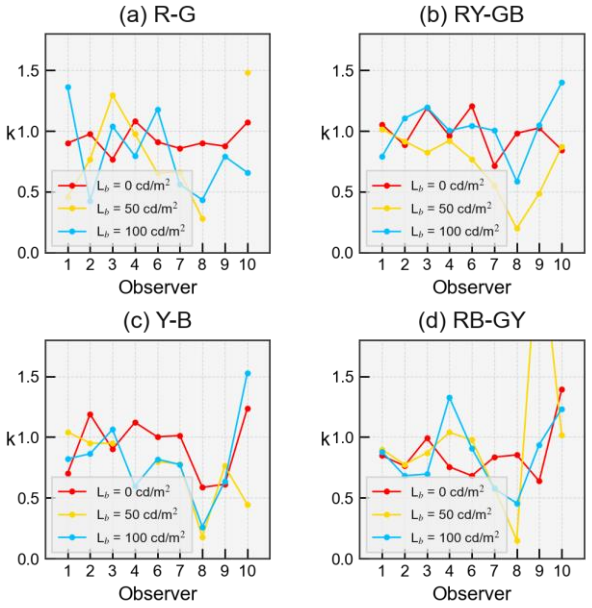

Figure 7. *The optimized k values of each observer under three levels of background luminance. The four subfigures correspond to four hue groups. It is worth noting that there are missing points in the figure, indicating that for certain observers, none of the binocular color pairs under this condition could be fused.*

Perceived color of binocular mixture under three backgrounds with different luminance

To further analyze the perceived color of the binocular hue mixture, the $\Delta E^*_{m,h1}$ value averaged over nine observers was plotted against the color difference between Hue 1 (H1) and Hue 2 (H2) in the binocular pair, denoted as $\Delta E^*_{h1,h2}$ in Figure 8.

Figure 8 consists of twelve subfigures representing twelve combinations of three backgrounds and four hue groups. The error bars correspond to the inter-observer standard deviation. If a data point is positioned on the light grey line ($y = 0.5x$), it indicates that the perceived color of the binocular hue mixture equals to the average of the binocular colors.

As shown in Figure 8, for the dark background ($L_b = 0$ cd/m^2), the curves are located slightly above $y = 0.5x$, regardless of either opposite hue, indicating that hue mixture is more biased towards H2 including the G, GB, B, and GY hue direction. It is noteworthy that the observed bias of Green in the R-G hue group aligns with findings from previous studies [7]. When the background luminance is set to 50 cd/m^2, a similar trend has been observed when H1 has been presented to the left eye that the binocular hue mixture is more influenced by H2. While for the condition with H1 on the right eye, the curve is located on or below the reference line $y = 0.5x$, indicating an impact of the sensory dominant eye. For the background luminance of 50 cd/m^2, both curves for swapping color pairs are close to or below the reference line. It could be speculated that the hue bias becomes less pronounced with the increasing luminance contrast, especially for the conditions with negative luminance contrast ($L_s < L_b$).

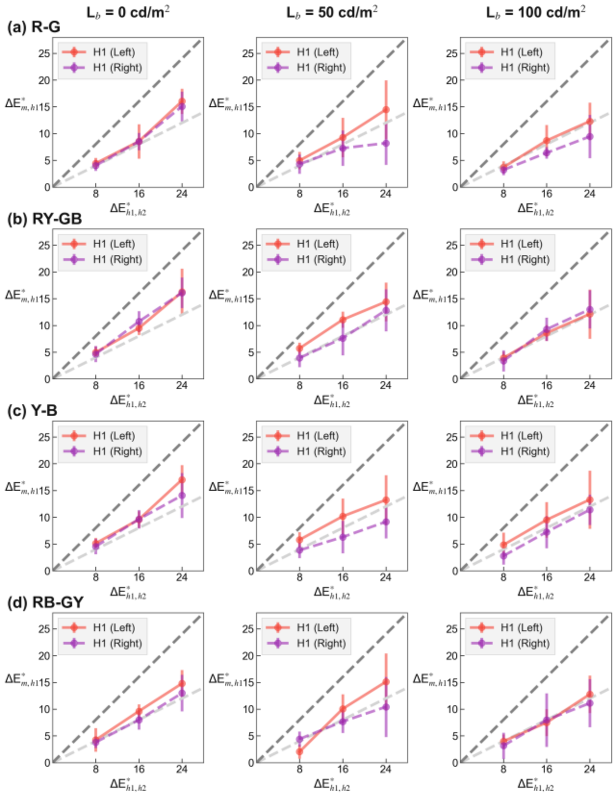

Figure 8. The relationship between the binocular hue mixture and the color difference between H1 and H2, denoted as $\Delta E^*_{h1,h2}$. The red line and purple line represent the two swapped color pairs with H1 to the left eye or right eye, respectively. The error bar represents the stand deviation of nine observers. The light gray dashed line represents the function of y = 0.5x, while the gray dashed line means y = x. The three columns represent three levels of background luminance, and the four rows correspond to four hue groups.

Conclusion

The perceived color of the binocular hue mixture was obtained through a series of color matching experiments conducted under three levels of background luminance. Four groups of opposite hues were selected in the CIELAB color space, with each hue group consisting of three color pairs having binocular color differences ΔE^*_{ab} of 8, 16, and 24.

Prior to the formal experiment, a Mondrian-mask experiment was conducted to determine the sensory dominant eye of each observer. The results revealed that, except for Observer 3, the majority of observers exhibited the right eye as their sensory dominant eye.

Subsequently, it was discovered that the binocular hue mixture is significantly influenced by the background luminance. As the luminance contrast increases, the bias of the binocular hue mixture towards the sensory dominant eye diminishes. Additionally, a specific hue, including G, GB, B, and GY within the four hue groups, exhibits a noticeable bias in the binocular hue mixture, particularly in conditions with low luminance contrast. The results suggest that the 'winner takes all' rule still holds for the binocular hue mixture, but is not as pronounced as that observed from the saturation or brightness mixture. This study takes a further step in understanding the mechanism of binocular color mixture, and provides datasets for developing a more comprehensive model of perceived color mixture. To further investigate the influence of luminance contrast on binocular hue mixture, multiple levels of stimulus luminance need to be included in the future experiment.

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Author Biography

Dingyu Hu is a master's student at the Beijing Engineering Research Center of Mixed Reality and Advanced Display, affiliated with the Beijing Institute of Technology. His research interest focuses on color vision.