ChromaGazer-HMD: Visual Modulation using Unobtrusive Color Vibration for Gaze Guidance with Head-Mounted Displays

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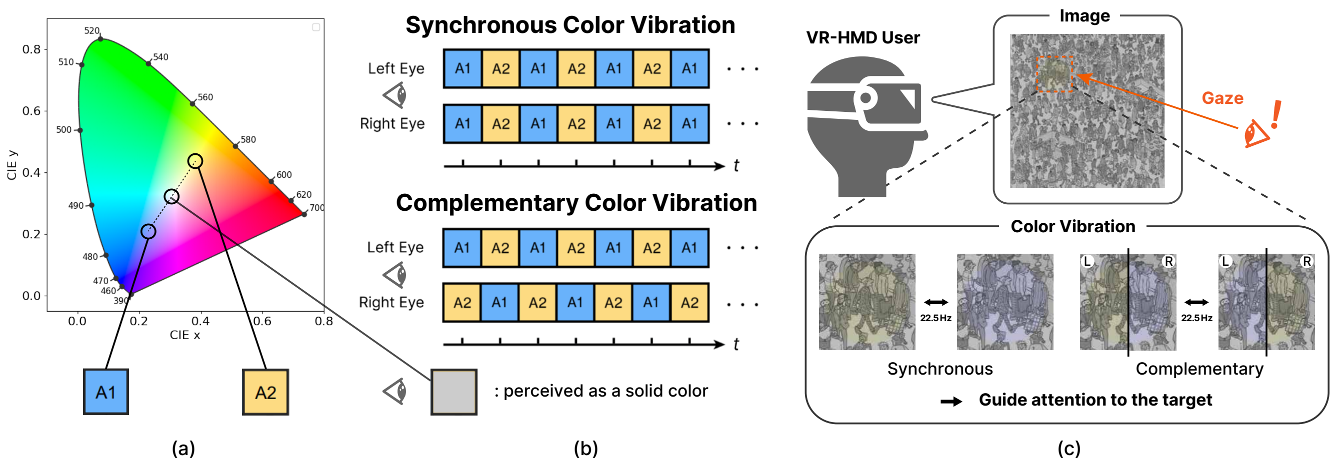

Figure 1: Principles and design methodology of ChromaGazer-HMD: (a) A pair of colors for the color vibration was selected from the xy chromaticity diagram. (b) The selected color pair was presented on the HMD using two methods: Synchronous color vibration (Both eyes receive the same color vibration in phase) and Complementary color vibration (Each eye receives color vibrations in opposite phases). When the color vibration is fast enough, it is perceived by humans as a time-averaged solid color. (c) By applying color vibration with the amplitude ratio r determined for the ROI within the image, we achieved VG without significantly altering the perceptual appearance of the image. We investigated two types of color vibration at 22.5 Hz: synchronous and complementary.

Abstract

VR content often involves vast spaces for users to explore, making it uncertain whether they will notice areas or objects highlighted by content creators. While various methods for guiding users' gaze have been proposed, those that significantly alter the appearance of the content can reduce its naturalness and negatively impact the user experience. In this study, we explored a Visual Guidance (VG) approach using color vibration, based on the human visual system's inability to perceive rapid chromatic changes. We evaluated its applicability to HMD environments and introduced a method called complementary color vibration, where opposite-phase vibrations are applied to the left and right displays of the HMD. We further investigated optimal parameters for VG and assessed its effectiveness in search tasks. Our experiments revealed that color vibration in HMD environments significantly reduced search times and areas compared to conditions without guidance, while maintaining the naturalness of the content. Furthermore, complementary color vibration was found to preserve naturalness significantly better than conventional synchronous color vibration. These findings indicate that VG using color vibration is effective in HMD environments and that complementary color vibration is less obtrusive than traditional synchronous color vibration.

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CCS Concepts

• **Human-centered computing** → **Virtual reality**; • **Applied computing** → *Computer-assisted instruction.*

Keywords

gaze guidance, color vibration, perceptual response, VR, head-mounted display

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1 Introduction

Visual guidance (VG) plays an essential role in directing user attention to specific areas of interest in virtual and video content. While VR-HMDs provide immersive 360-degree experiences [19, 28], they also present a challenge: users may miss important information due to unrestricted viewpoint movement. In the vast exploration space of VR environments, users do not necessarily focus on the regions of interest (ROIs) intended by content creators [15, 16, 24]. This can lead to a variety of problems, such as missing important gameplay cues in VR games, missing key scenes in 360-degree videos, or missing important information in education and training applications.

Previous research on VG in displays has taken two main approaches. The first uses explicit visual cues such as arrows [13], icons [14], moving objects [12], or character gestures and voice guidance within VR spaces [24, 26]. However, these methods often depend on content context or obstruct parts of the display, which can break immersion and increase cognitive load. The second approach uses implicit guidance based on human visual perception, including methods that manipulate image saliency by adjusting color and contrast [23, 29], or techniques that combine multiple visual parameters such as saturation, contrast, and blur [22]. While these implicit methods provide more subtle guidance than explicit cues, they still alter the visual appearance of the content.

Recent research has explored "unobtrusive" VGs that use human visual characteristics to modulate images to the range around the threshold that humans consciously perceive. While flicker-based VG [3, 21, 27] are promising, they require display refresh rates twice that of the human Critical Flicker Fusion frequency (CFF: 60-90 Hz) [17], making them impractical for typical 90 Hz HMDs. In contrast, ChromaGazer [25] achieved VG on standard displays using imperceptible color vibration, a phenomenon in which rapidly alternating colors of the same luminance at frequencies above the Critical Color Fusion Frequency (CCFF: approximately 25 Hz) [4] are perceived as a single intermediate color. However, their work was limited to 60 Hz sRGB monitors and did not investigate the perception of color vibrations in standard HMDs, which typically operate at 90 Hz, or the possible effects of binocular viewing. Furthermore, unlike conventional displays, HMDs introduce a fundamental difference in viewing conditions, as each eye perceives a separate display. This distinction may significantly influence the perception of color vibrations and warrants further investigation.

This study proposes ChromaGazer-HMD, a color-vibration-based VG optimized for HMD environments. Figure 1 illustrates the principles and design methodology of ChromaGazer-HMD. Since HMDs present separate images to each eye, it is important to consider how binocular presentation may affect color vibration perception when adapting ChromaGazer to an HMD setting. Our approach extends the original ChromaGazer concept by exploring possibilities unique to HMDs. Specifically, we investigate color vibrations at 45 Hz and 22.5 Hz, which are synchronized with the 90 Hz refresh rate of the displays, and introduce a novel presentation method called complementary color vibration, which exploits binocular vision by presenting color vibrations of opposite phase to each eye.

We evaluated our approach in two experiments. The first systematically investigated the relationship between color vibration parameters based on MacAdam ellipses and perceptual properties in HMD environments, determining optimal presentation conditions for different viewing angles and binocular presentation methods. The second experiment evaluated the effectiveness of guidance through search tasks using eye-tracking data. Results showed that complementary color vibration at 22.5 Hz achieved effective attentional guidance while maintaining the natural appearance of the content.

Our main contributions include:

- Development and perceptual mechanism analysis of color vibration-based VG optimized for HMD environments
- Introduction and validation of complementary color vibration for VG that exploits the characteristics of binocular vision
- Experimental validation of color vibration-based VG in VR-HMD environments through eye-tracking analysis and questionnaires
- Identification of practical application scenarios and future research directions

2 Related Work

2.1 VG in HMDs

The effectiveness of VG in VR-HMDs and 360-degree videos has been demonstrated across various applications including guidance systems [6], cinematic VR experiences [18], and game narratives [5]. VG approaches in immersive VR environments can be divided into two categories: explicit methods that deliberately control user attention, and implicit methods that naturally guide attention through visual properties.

2.1.1 Explicit VG. Explicit VG uses two main approaches: geometric indicators and social cues. Geometric methods overlay arrows or circular markers on the display. For example, Lin et al. presented a method that uses predictive arrows to guide viewers' gaze in 360-degree videos [13]. Another approach involves displaying cropped images of off-screen ROI within the viewport [14].

Social cueing methods achieve natural guidance through the behavior of avatars or characters in VR spaces, drawing on human social interaction patterns. Tong et al. developed guidance through character pointing and head orientation [24], while Sheikh et al. proposed attention guidance through character speech [26]. While these methods are effective, they are highly dependent on content context and can reduce immersion by occluding parts of the display.

2.1.2 Implicit VG. Implicit VG often relies on saliency map-based approaches. In HMD-specific research, Sutton et al. developed and validated a method for AR-HMDs that modulates multiple visual parameters, including saturation, contrast, and blur [22]. Yokomi et al. proposed to dynamically adjust brightness based on the user's gaze position in 360-degree videos [29]. While more subtle than explicit methods, these approaches still modify content in ways that users can perceive, potentially compromising visual naturalness and context.

2.2 VG Using Perceptual Thresholds

Research has explored the use of temporal characteristics of human visual perception to create less obtrusive guidance stimuli and explored VG approaches that guide the user's gaze to the ROI by rapidly flickering two colors of different luminance or chromaticity.

For luminance-based approaches, Bailey et al. [3] showed that applying 10 Hz luminance flicker to specific regions could attract attention. This takes advantage of the higher sensitivity of peripheral vision to luminance changes compared to central vision. While the method can guide gaze without user awareness by removing the flicker after guidance, it requires eye-tracking to control the flicker based on gaze position. Waldin et al. demonstrated that high-frequency flicker (60-72 Hz) can provide effective guidance in peripheral vision while being less noticeable in central vision without eye-tracking [27]. However, these methods require displays with refresh rates greater than 120 Hz due to the human critical fusion frequency (CFF) of 60-90 Hz [17].

Chromaticity-based approaches operate at lower frequencies, because the critical color fusion frequency (CCFF) at which humans cannot perceive color flicker is about 25 Hz, almost half the CFF [4]. Using this property, Abe et al. achieved information embedding through 30 Hz color vibration [1, 2]. Hattori et al. further defined color vibration amplitude based on MacAdam ellipses, and experimentally confirmed the amplitude threshold at which humans do not perceive color vibration [9].

Tosa et al. applied this color vibration to VG and experimentally demonstrated an intermediate perceptual state between complete color fusion and clear flicker, where the color appears different from the solid color but without clear flicker [25]. They also proposed ChromaGazer and validated its effectiveness for unobtrusive VG in monitor environments. However, previous research has assumed 60 Hz displays, leaving the perception of color vibration in 90 Hz, which is standard for VR-HMDs, unexplored.

2.3 VG Using Binocular Vision

A key feature of VR-HMD is their ability to present independent images to each eye. Research has explored the use of binocular rivalry, the perceptual competition when different images are presented to each eye for VG.

Krekhov et al. proposed to emphasize certain objects by presenting them to only one eye [11]. This method benefits from automatic pre-attentive processing of visual information. Grogorick et al. achieved VG through binocular rivalry by adjusting brightness asymmetrically between the eyes [7]. Their method uses minimal brightness modulation just above perceptual thresholds to minimize interference with scene content, proving effective in wide field-of-view VR environments.

While these studies effectively exploit the properties of binocular vision, they focus on static presentation, and the potential of dynamic binocular stimuli such as color vibration remains unexplored. This research proposes complementary color vibration for HMDs, where counter-phase vibrations are presented to each eye, and evaluates them against conventional synchronous color vibrations.

3 ChromaGazer-HMD

In this study, we propose ChromaGazer-HMD, a novel system that extends ChromaGazer [25] by introducing specialized features for HMD environments operating at a refresh rate of 90 Hz. For such a refresh rate, the maximum frequency achievable with this device is 45 Hz, generated by alternating images on each frame, followed by 22.5 Hz when images are alternated every two frames. Generally, the critical flicker fusion frequency (CFF), where color vibration becomes imperceptible, is around 25 Hz [10]. Considering that perceptual response to visual stimuli is necessary for effective VG, we examine the characteristics of color vibration at both 45 Hz and 22.5 Hz, the latter being below the CFF.

3.1 Selection of Perceptual Color Vibration Pairs

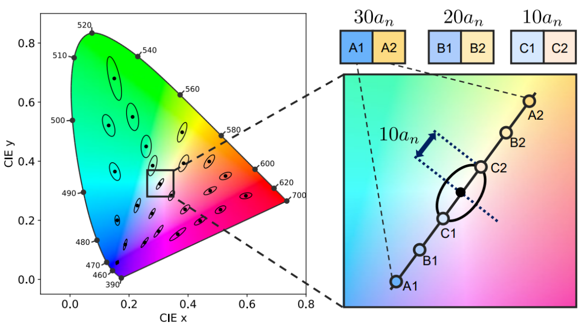
Figure 2a illustrates MacAdam ellipses on the xy chromaticity diagram. These ellipses represent the range of color differences that are indistinguishable to the human eye around a given color center, indicating that the perceptual uniformity of color differences varies across the xy chromaticity space. For example, the ellipses are larger in the green region than in the blue region, indicating that small color differences in green are harder to perceive compared to blue. By using these MacAdam ellipses, we can determine pairs of colors for color vibration that account for these non-uniform perceptual responses. Each MacAdam ellipse $\mathcal{E}_n = \mathbf{c}_n, \theta_n, a_n, b_n$ $(n = 1 \cdots 25)$ is defined by its center $\mathbf{c}_n = [c_{nx}, c_{ny}]$, the angle θ_n between the minor axis and the x-axis, and the lengths of its major a_n and minor b_n axes. Color pairs for color vibration, $\mathbf{p}_n^+(r), \mathbf{p}_n^-(r)$, are selected along the major axis scaled by a ratio r (Figure 2a), as expressed in Eq. 1:

$$\mathbf{p}_n^{\pm}(r) = [c_{nx} \pm r \cdot a_n \sin\theta_n, ; c_{ny} \pm r \cdot a_n \cos\theta_n]. \tag{1}$$

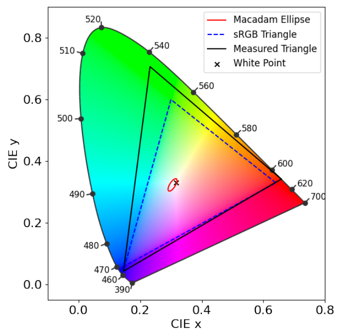
The xy chromaticity diagram is derived from the normalized luminance $0 \le Y \le 1$ in the CIExyY color space. When Y approaches 0, the color becomes nearly black, and as Y approaches 1, the color becomes nearly white. To ensure a consistent luminance when selecting color pairs for color vibration, we fix Y at 0.4, following previous studies. The conversion from the xyY to the XYZ color space is performed using the following equation:

$$X = xY/y,\ Z = (1 - x - y)Y/y. \tag{2}$$

For this study, we used a VIVE Pro Eye (HTC Corporation) as an HMD. This HMD has an eye-tracking function and is a widely used HMD, with a display refresh rate of 90 Hz. Since the color reproduction characteristics of HMD displays differ from those of standard monitors, we measured the primary colors (red, green,



(a) MacAdam ellipses



(b) HMD color gamut

Figure 2: (a) MacAdam ellipses plotted on the xy chromaticity diagram. These ellipses represent the range of color differences that are indistinguishable to the human eye around a given color center. For clarity, the ellipses are shown at 10 times their actual size. The two colors used for the color vibration are determined along the major axis of the ellipse, based on its major diameter. (b) The HMD used in the experiment (Vive Pro Eye, HTC Corporation) was calibrated by displaying primary colors and the white point, which were measured using a spectroradiometer. The area connecting these points is represented as a black triangle in the figure. Additionally, one of the MacAdam ellipses, serving as the basis for the color vibration, is shown as a red ellipse. It can be observed that the color gamut of the HMD is wider than the sRGB color gamut, indicated by the blue dotted line.

blue) and white point of the HMD using a spectroradiometer (UPRtek MK350N Premium). The displayable color gamut of the HMD is shown in Figure 2 (b), with the primary color coordinates determined as $(x_R, y_R) = (0.658, 0.342)$, $(x_G, y_G) = (0.232, 0.707)$, $(x_B, y_B) = (0.146, 0.043)$, $(x_W, y_W) = (0.316, 0.330)$. Using these values, the color pairs selected in the CIEXYZ space were converted to the HMD's color space.

Next, gamma correction was applied to each channel $C \in R, G, B$ using the following procedure:

$$C_{HMD} = \gamma(C_{\text{linear}}) \tag{3}$$

$$= \begin{cases} 1.055 \cdot C_{\text{linear}}^{1/2.4} - 0.055 & \text{if } c \geq 0.0031308, \\ 12.92 \cdot C_{\text{linear}} & \text{otherwise} \end{cases} \tag{4}$$

The implementation relied on the Python-colour library [1], utilizing functions based on the CIE 1931 2° observer function under D65 illumination. Since color vibration perception varies with hue, saturation, and individual differences, this study focuses solely on grayscale vibrations. For the base color used to generate vibrations, we selected the center point of a MacAdam ellipse, $(x, y) = (0.305, 0.323)$, close to the center of the xy chromaticity diagram. This ensures that even with a relatively large r, the two colors used for vibration remain within the displayable color gamut of the HMD.

Based on this method, we propose two approaches to color vibration, considering both the intensity of the vibration and the presentation method, in light of variations in perceptual response due to the differences between the two vibrating colors.

3.2 Color Vibration for Full and Intermediate Perception

In this proposed method, the perceptual states for full and intermediate perception are defined as follows:

- **Color Vibration for Full Perception (Discomfort)**: Color vibration that is clearly perceived as flicker.
- **Color Vibration for Intermediate Perception (Awareness)**: Color vibration that is not consciously perceived as flicker but is subconsciously distinguished from uniform colors.

First, we determine the r required to achieve these perceptual states. Then, through a search task, participants evaluate how these varying intensities of color vibration influence VG.

3.3 Synchronous and Complementary Color Vibration

In this proposed method, we use two types of color vibration: one where the same image is presented to both eyes and one where different images are presented. These are defined as follows:

- **Synchronous Color Vibration**: Both eyes receive the same color vibration in phase.
- **Complementary Color Vibration**: Each eye receives color vibrations in opposite phases.

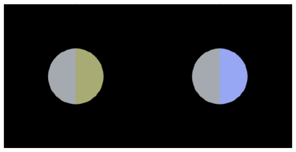
4 Evaluation of Intermediate Perception in Color Vibration

In this experiment, we determine the r values for each perceptual state. Specifically, we investigate how combinations of 45 Hz and 22.5 Hz color vibrations, as well as synchronous and complementary presentations, affect perceptual responses across various visual field angles. Ethical approval for the study was obtained from (omitted for the review).

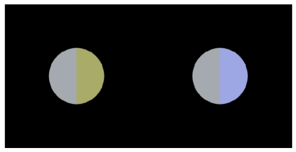
4.1 Experiment Setup

4.1.1 Participants. To avoid the potential bias of participants becoming accustomed to a particular frequency, we ensured that no participant participated in both the 45 Hz and 22.5 Hz conditions.

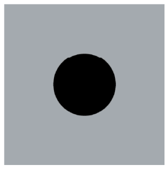
[1] Colour 0.4.4 by Colour Developers, https://zenodo.org/records/10396329



(a) $w = 0.5$



(b) $w = 0.6$



(c) inverted image

Figure 3: To adjust for individual differences in color perception, the center of the color vibration was personalized by tuning w so that the vibrating right half-circle matched the solid color of the left half-circle. The images depict color vibration pairs when $r = 50$: (a) shows the case where the center of the color vibration remains unchanged, and (b) shows the case where the center is shifted toward yellow. After each adjustment, the inverted image shown in (c) was presented to suppress afterimage effects.

45 Hz condition. 17 participants (12 male, 5 female; mean age: 24.4 years, SD: 2.91 years) participated in the study. All had normal color vision and corrected visual acuity and were able to remain seated throughout the experiment. 11 participants used corrective lenses (glasses or contact lenses).

22.5 Hz condition. 16 participants (10 male, 6 female; mean age: 23.3 years, SD: 2.87 years) participated in the study. All had normal color vision and corrected visual acuity and were able to remain seated throughout the experiment. 11 participants used corrective lenses (glasses or contact lenses).

4.1.2 Apparatus. The experiment was conducted using the VIVE Pro Eye (HTC Corporation). Before starting, the participants' interpupillary distances (IPDs) were adjusted using the VIVE Eye and Facial Tracking SDK with SRAnipal Runtime (HTC Corporation) to ensure proper alignment.

4.1.3 Experimental Conditions and Procedure. Before conducting the main experiment, the central point of color vibration was adjusted to account for individual differences in color perception. Participants were presented with a circular stimulus, 120 mm in diameter, displayed at the center of the screen. The circle was split into two halves: the left half displayed a static color without vibration, while the right half exhibited a color vibration at a specific r. Using the left and right arrow keys on a keyboard, participants adjusted a parameter w in increments of 0.01, making the colors of the two halves appear identical (Figure 3a, b).

The parameter w represents the ratio of distances along the major axis of the MacAdam ellipse between the target color and the two vibrating colors (one leaning towards yellow and the other towards blue), matched $w : (1 - w)$. The adjusted vibrating color pair, $\mathbf{p}^{\pm}_{adj}(r, w)$, is calculated as follows:

$$\mathbf{p}^{+}_{adj}(r, w) = [c_x + 2wr \cdot a \sin\theta,\ c_y + 2wr \cdot a \cos\theta]. \tag{5}$$
$$\mathbf{p}^{-}_{adj}(r, w) = [c_x - 2(1 - w)r \cdot a \sin\theta,\ c_y - 2(1 - w)r \cdot a \cos\theta].$$

When $w = 0.5$, the result matches Eq. 1. After each adjustment, an inverted stimulus was displayed for 100 milliseconds (Figure 3c) to reduce afterimage effects. The inverted image had a gray background matching the vibrating color, with a black circular outline.

The adjustment process involved seven trials, gradually decreasing r values ($r = 70, 60, 50, 40, 30, 20, 10$), under both synchronous and complementary presentation conditions. Through these trials, the center of color vibration was customized for each participant's perception. Participants also experienced how the vibration became progressively imperceptible, helping them understand the concept of color vibration. The w values determined for each r were then used in the main experiment. For amplitudes like $r = 15$, which were not tested in the pre-experiment, w values were interpolated linearly.

Once w values were personalized for each participant, the r required to achieve full and intermediate perception was determined. In the main experiment, circular stimuli with varying r and presentation angles were displayed. Participants classified their perception of the vibrating stimuli into three categories: Participants were asked to classify their perception of the color vibration into one of three categories:

- **Uniform**: The image appears as a uniform color with no noticeable differences.
- **Awareness**: The image appears slightly different form a solid color, but there is no noticeable flickering.
- **Discomfort**: The image has clearly noticeable flickering.

The proportion of participants reporting each perception state was calculated. A sigmoid function was used to estimate the threshold amplitude ratio r_{th} at which participants perceived the stimulus as either "clearly flickering" or "different from a solid color, but there is no noticeable flickering" with a probability of 50 %. These thresholds were defined as the amplitudes corresponding to full and intermediate perception.

Figure 4 shows examples of the images presented during the experiment. For both synchronous and complementary color vibrations, circular stimuli with a diameter of 100 mm were displayed 500 mm from the participants' viewpoint. The position of the circular stimuli was determined by the distance l from the display center to the center of the stimulus, with 6 positions tested: $l = 0, 71, 121, 171, 268, 364$ mm, corresponding to central vision (0°), near vision (8°), middle vision (13.5°), far vision (19°), very far vision (28°), and the limit of effective field of view (36°).

Perceptual responses to r values varied between the 45 Hz and 22.5 Hz conditions. To ensure accurate fitting of the sigmoid function, different sets of r values were tested for each frequency. Based on preliminary experiments with a small number of participants, the following r were selected: for 45 Hz, r = 0, 10, 20, 25, 30, 35, 40, 45, 50, 55, 60, 70; for 22.5 Hz, r = 0, 5, 10, 15, 20, 25, 30, 35, 40, 50, 60, 70. A total of 12 amplitudes were tested under each condition.

Participants selected their perception state using number keys during each trial. For non-central conditions, four circular stimuli

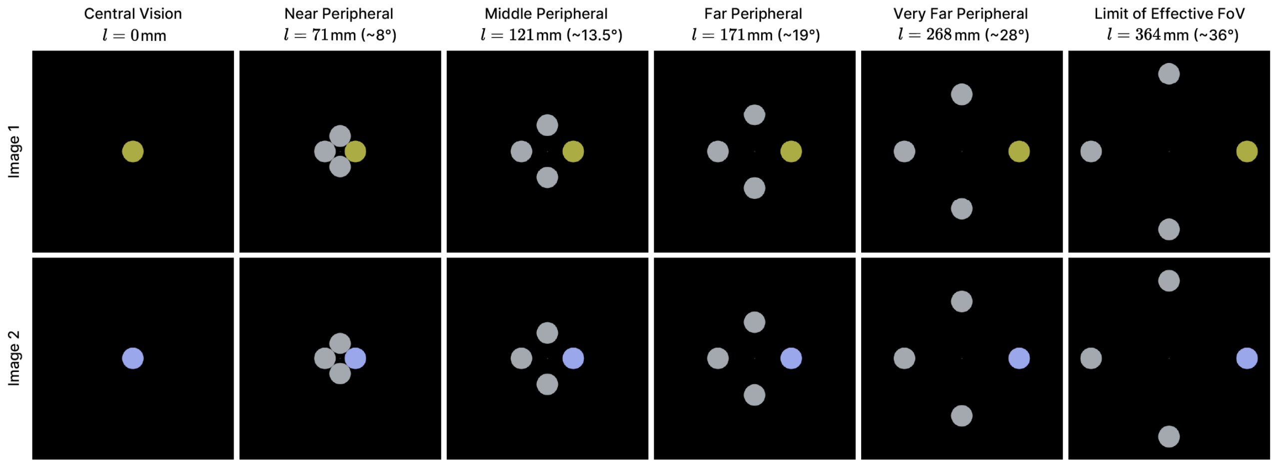


Figure 4: An example of the color vibration image pairs presented in the experiment of Sec. 3. We set six different distances l, from the center of display. For cases outside the central visual field, circles were positioned in four directions: up, down, left, and right. Participants were asked to identify which circle was perceived as color vibration.

were symmetrically arranged around the display center to avoid directional bias. Only one of these stimuli displayed color vibration, while the others showed solid colors. Participants identified the location of the vibrating stimulus using arrow keys. To minimize afterimage effects, an inverted stimulus image was shown for 100 milliseconds after each trial.

Each participant completed 144 trials (12 amplitudes × 6 positions × 2 repetitions) in random order. Short breaks were provided every 10 trials to reduce fatigue. The experiment was conducted for both synchronous and complementary presentation methods. To counterbalance potential order effects, half of the participants began with the synchronous condition, and the other half with the complementary condition.

4.2 Result and Discussion

The proportion of participants who reported each perceptual state was calculated for different values of r under each experimental condition. A sigmoid function was then fitted to the data to estimate the threshold r_{th}, where the proportion reaches 50 %. For conditions other than central vision, if participants failed to correctly identify which of the four circular stimuli exhibited color vibration, their response was treated as "The image appears as a uniform color with no noticeable differences."

Figure 5 illustrates the r obtained under each condition throughout the experiment. In cases where r_{th} exceeded 80 or could not be determined, $r_{th} = 80$ is plotted in the figure.

4.2.1 Effect of Display Position. The threshold r_{th} varied depending on the presentation angle. In central vision ($l = 0$ mm), sensitivity to color vibration was reduced compared to near, middle, and far peripheral vision ($l = 71, 121, 171$ mm). This reduced sensitivity may be attributed to the lack of adjacent circular stimuli for color comparison in the central vision condition, where only a single circle was presented.

At very far peripheral vision and beyond ($l = 268, 364$ mm), sensitivity to color vibration also decreased compared to near, middle, and far peripheral vision. This suggests that sensitivity to color vibration depends on the presentation angle, potentially due to the visual system's reduced spatial and temporal resolution in the periphery.

4.2.2 Effect of Presentation. The threshold r_{th} differed by the types of color vibration, with complementary presentation showing lower sensitivity to color vibration than synchronous presentation. This may result from the integration of different images presented to the left and right eyes into a single perception, leading to a stimulus perceived as the spatially averaged color closer to the original image.

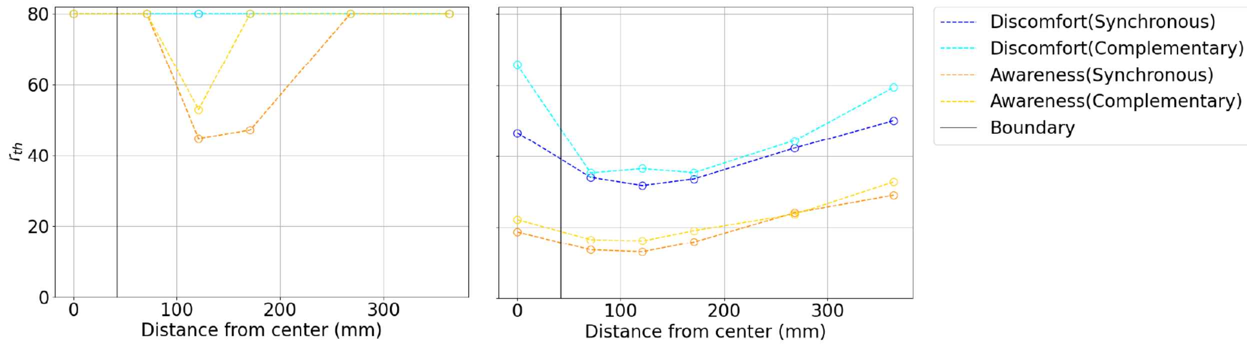
In other words, while the invisibility of color vibration has been previously explained by the visual system's tendency to perceive the two vibrating colors as a time-averaged color, complementary color vibration appears to involve an additional mechanism: the spatial averaging of the two colors. This indicates that complementary color vibration may enable more unobtrusive and natural VG compared to synchronous color vibration.

4.2.3 Effect of Frequency. The threshold r_{th} also varied by vibration frequency, with the 45 Hz condition showing lower sensitivity to color vibration than the 22.5 Hz condition. This aligns with the characteristics of the critical fusion frequency, where higher vibration frequencies are less likely to be perceived.

Notably, in the 45 Hz condition, r_{th} could not be determined for any presentation angle within the color gamut of the HMD display, as the color vibration was either fully imperceptible or perceived as a single fused color. In contrast, in the 22.5 Hz condition, r_{th} could be determined under all conditions for both full and intermediate perception states.

These findings suggest that, for VG using an HMD with a refresh rate of 90 Hz, 22.5 Hz color vibration is more suitable than 45 Hz color vibration.

4.2.4 Intermediate Perceptual State of Color Vibrations. The observed differences in the thresholds for perceiving "noticable flicker"



(a) Results for 45 Hz Color Vibration. **(b) Results for 22.5 Hz Color Vibration.**

Figure 5: Results of an experiment showing the threshold amplitude ratio r_{th} for the full perception (Discomfort) and intermediate perception (Awareness) with both synchronous and complementary color vibration at each display position of the circle l with 50 % possibility. The line indicates the boundary between central and peripheral vision. If r_{th} exceeded 80 or could not be determined, $r_{th} = 80$ is plotted in the figure.

and "different from a solid color" confirm the presence of an intermediate perceptual state. This suggests that color vibration involves not only a color difference from a solid color but also a distinct flickering characteristic as a stimulus.

These results demonstrate that the perception of color vibration is influenced not only by the amplitude ratio r but also by factors such as presentation angle, presentation method, and vibration frequency. This indicates that effective and unobtrusive VG can be designed by selecting an appropriate r value for each condition.

In subsequent experiments, the focus will be limited to color vibration at 22.5 Hz, for which r_{th} could be determined.

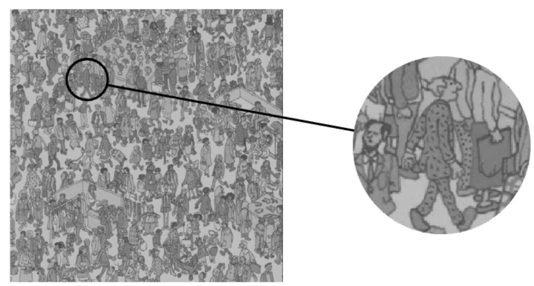
5 Evaluation of Color Vibration Vision Guidance

This experiment investigates whether color vibration at a frequency of 22.5 Hz, as determined by threshold values r obtained in the previous section, can effectively draw users' attention to specific targets in an image without compromising the image's naturalness. Participants were tasked with a search task to locate a target in an image and evaluate its naturalness and obtrusiveness.

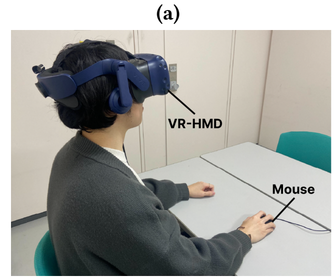
5.1 Experiment Setup

The effectiveness and unobtrusiveness of these VG were assessed using two approaches: a task involving the search for specific regions of interest (ROI) in images and a user evaluation. The r values were determined based on perceptual thresholds identified in Sec. 3 for various visual angles. Since it was not possible to generate color vibration corresponding to full or intermediate perceptual states at 45 Hz within the display's color gamut, this experiment focused on 22.5 Hz, where valid r were obtained. Ethical approval for the study was obtained from (omitted for the review).

5.1.1 Participants. 26 participants (18 male, 8 female; mean age: 24.4 years, SD: 2.35 years) participated in the study. All had normal color vision and corrected visual acuity and were able to remain seated throughout the experiment. 13 participants used corrective lenses (glasses or contact lenses).



(a)



(b)

Figure 6: (a) An example of the image used in the experiment of Sec. 4 and the selected ROI. The image has been converted to grayscale and cropped into a square. (b) The participants wore a VR-HMD and were instructed to search for the ROI within the images displayed on the screen. They selected the ROI by clicking with a mouse.

5.1.2 Apparatus. The experiment was conducted using the VIVE Pro Eye (HTC Corporation) under the same conditions as in Sec. 4, including IPD adjustments to ensure proper alignment.

5.1.3 Stimuli Preparation. Images were selected from Martin Handford's "Pocket Edition NEW Where's Wally!"[8] and scanned at a resolution of 600 dpi using a document scanner (ScanSnap iX1300, PFU Limited). Each image was cropped to 1200 px × 1200 px (Figure 6a, left) and converted to grayscale. To ensure an adequate range for color vibration, pixel values were linearly rescaled from the original range [0,255] to [60,196]. The ROI (Figure 6a, right) was defined as a circular region with a diameter of 44 mm, sufficient to enclose a single character, approximating the effective central vision area (a 39 mm diameter circle at a viewing distance of 500 mm).

The targets were not always Wally to ensure diverse search experiences, and their positions were varied across images to avoid spatial bias. Additionally, ROI positions were evenly distributed relative to the image center for all guidance methods.

6 types of VG methods were implemented as follows (Figure 7):

- **No Guindance (NG)**: Original image without any modification.
- **Unobtrusive Synchronous color vibration (US)**: ROI modulated with subtle color vibration using r_{th} corresponding to the "Awareness" condition and with synchronous presentation.
- **Unobtrusive Complementary color vibration (UC)**: ROI modulated with subtle color vibration using r_{th} corresponding to the "Awareness" condition and with complementary presentation.
- **Obtrusive Synchronous color vibration (OS)**: ROI modulated with subtle color vibration using r_{th} corresponding to the "Discomfort" condition and with synchronous presentation.
- **Obtrusive Complementary color vibration (OC)**: ROI modulated with subtle color vibration using r_{th} corresponding to the "Discomfort" condition and with complementary presentation.
- **Explicit Guidance (EG)**: ROI marked with a black visible circle.

The region of color vibration was defined as a circular area with a diameter of 100 mm centered on the ROI. Black circles used for explicit guidance matched the ROI size (44-mm diameter).

5.1.4 Experiment Procedure. Color vibration pairs were generated using threshold r_{th} based on the target's distance l from the display center. Since r depends on the distance from the image center, r was adjusted based on distances derived from previous experiments.

For ROIs within the central vision (l < 44 mm), the corresponding r_{th} was applied. For ROIs in the peripheral vision ($l = 71 \sim 364$ mm), r_{th} were linearly interpolated. ROIs were not placed in the range $l = 44 \sim 71$ mm) due to uncertainties regarding the applicability of linear interpolation.

Individual differences in color perception were addressed by adjusting the vibration center during the preparation phase. Participant-specific parameters w were determined for each r, and untested values of w were calculated via linear interpolation, as in the previous section.

The experiment consisted of 60 trials, with each trial comprising the following 4 steps:

(1) **Fixtation**: Participants fixated on a central white cross displayed in the center of a black screen.
(2) **Target Presentation**: A cropped image of the ROI was shown to familiarize participants with the search target.
(3) **Search Task**: One of the 6 VG methods was applied to an image, and participants were instructed to locate and click the ROI as quickly as possible (Figure 6b).
(4) **Questionnaire**: After each image, participants rated the image on a 7-point Likert scale based on the following criteria:
  (a) **Naturalness**: The extent to which the image appeared unprocessed (1: very unnatural - 7: very natural)
  (b) **Obtrusion**: The degree to which the image stood out undesirably (1: not at all obtrusive - 7: very obtrusive)

In the questionnaire, following Sutton et al. [22], we assessed the presented images in terms of naturalness and obtrusion using the definitions: "having undergone little or no processing" for naturalness and "noticeable or prominent in an unwelcome or unwanted way" for obtrusion.

10 different images were used, with each guidance method applied once per image, resulting in 60 trials. To prevent participants from recognizing targets too easily due to repeated exposure, the same image was not shown consecutively, with at least two different images presented in between. After every 6 images, participants were given a rest period, viewing a black screen.

The images were fixed at a 500 mm distance in front of the participants' viewpoint, independent of HMD positional tracking. During the search task, participants could refer to the ROI by holding down the right mouse button. Trials automatically advanced to the questionnaire phase if participants failed to click within 30 seconds.

5.2 Results

We evaluated the experiment from three perspectives as follows: (1) task completion time (time to click on the correct ROI), (2) proportion of the image explored by the gaze before task completion, and (3) scores from the user questionnaire. The results are shown in Figure 8 and Table 1.

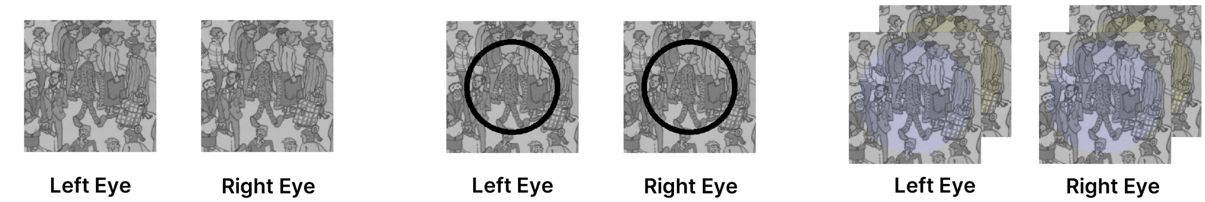
5.2.1 Task Completion Time. For the time required for the search, the completion time was recorded if the correct ROI was selected. However, if an incorrect ROI was chosen or the 30-second time limit was exceeded, a time of 30 seconds was assigned.

A Friedman test showed a significant main effect of the VG methods on the evaluation score (χ^2 (X) = 434.209, $p < .001$). Then, we conducted Wilcoxon signed-rank tests (Holm-corrected), and the results are shown in Table 1a.

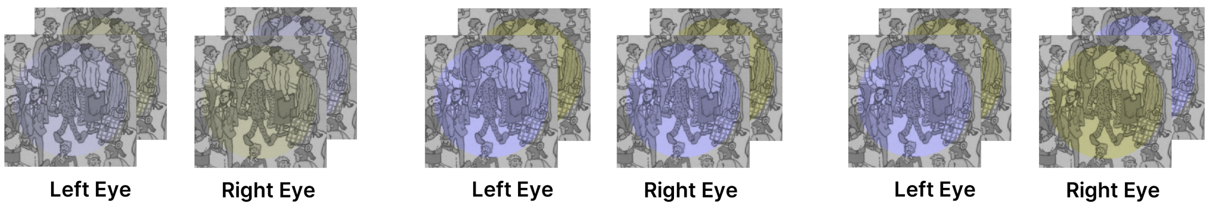
5.2.2 Proportion of Explored Area. Using gaze data, we calculated the proportion of the explored area relative to the entire image. The region within the central visual field (5°) at any gaze position was considered as the explored area.

A Friedman test showed a significant main effect of the VG methods on the evaluation score (χ^2 (X) = 249.687, $p < .001$). Then, we conducted Wilcoxon signed-rank tests (Holm-corrected), and the results are shown in Table 1b.

5.2.3 User Questionnarie. Friedman tests showed a significant main effect of the VG methods on the naturalness score (χ^2 (X) = 801.476, $p < .001$) and obtrusion score (χ^2 (X) = 776.349, $p < .001$).



(a) No Guindance (NG) **(b) Explicit Guidance (EG)** **(c) Unobtrusive Synchronous color vibration (US)**



(d) Unobtrusive Complementary color vibration (UC) **(e) Obtrusive Synchronous color vibration (OS)** **(f) Obtrusive Complementary color vibration (OC)**

Figure 7: Examples of images presented in the experiment of Sec. 4. The original image is shown in (a), where (b), (c), and (e) present the same stimulus on both sides, while (d) and (f) display different stimuli on each side.

Then, we conducted Wilcoxon signed-rank tests (Holm-corrected), and the results are shown in Table 1c, 1d.

5.3 Disucussions

5.3.1 Task Completion Time. All five VG conditions showed a significant difference compared to the no guidance condition, demonstrating that color vibration can effectively guide attention without altering the entire image. A significant difference was found between obtrusive and unobtrusive conditions, with unobtrusive taking longer, though still performing significantly better than no guidance. For unobtrusive conditions, a significant difference was found between complementary and synchronous presentations, with complementary taking longer. No significant differences were found between complementary and synchronous presentations in obtrusive conditions, and their highly similar statistical distributions suggest equivalent performance levels.

5.3.2 Proportion of Explored Area. All five VG conditions showed a significant difference compared to the explicit guidance condition. Unlike explicit guidance, which restricts exploration, color vibration allowed users to naturally explore while being subtly guided. No significant differences were observed between complementary and synchronous presentations in either obtrusive or unobtrusive conditions, with their similar statistical distributions indicating equivalent levels of information gathering.

5.3.3 User Questionnaire. Significant differences in naturalness ratings were found across all conditions. Unobtrusive color vibration was rated significantly higher in naturalness compared to both obtrusive vibration and explicit guidance. For both obtrusive and unobtrusive conditions, complementary color vibration was rated significantly higher in naturalness than synchronous vibration.

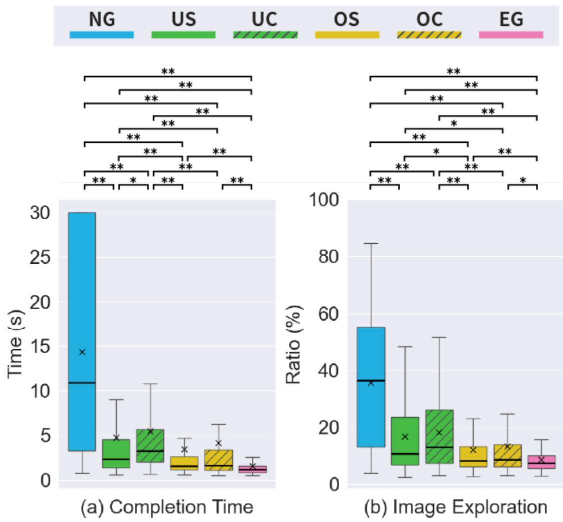
Regarding obtrusiveness, significant differences were found across all conditions except between complementary and synchronous presentations at the same intensity. Notably, unobtrusive color vibration was found to be significantly less forceful than obtrusive color vibration or explicit guidance, suggesting a smaller negative impact on the content's context. While obtrusive color vibration may force users to focus on specific areas and potentially undermine overall content comprehension, unobtrusive color vibration can guide attention to necessary information while aligning with users' natural gaze movements.

5.3.4 Comparison Between HMD and Standard Displays. Search tasks took approximately twice as long in our HMD environment compared to the original ChromaGazer study on standard displays [25]. This difference may be attributed to our larger visual field coverage (28° vs 18°) and the characteristics of the Vive Pro Eye's Fresnel lenses, which can introduce distortion and chromatic aberration at peripheral angles.

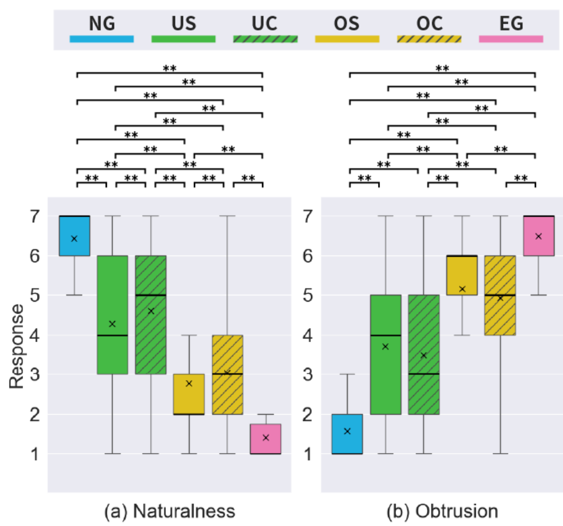
5.3.5 Summary. These results show that VG using unobtrusive color vibration, which induces intermediate perception, contributes to faster task completion in exploratory behavior and is an effective and natural method for aiding users. Furthermore, complementary color vibration was found to be more natural than synchronous color vibration, suggesting that VG using complementary color vibration can draw attention to necessary information without disrupting the user's experience.

6 Application Scenarios

Here are three application scenarios of the ChromaGazer-HMD. Each example leverages color vibration to subtly guide user attention without disrupting immersion, as illustrated in Figure 9.



(a) Results of task completion time and ratio of the area explored relative to the image



(b) Results of naturalness score and obtrusion score

Figure 8: Results of the evaluation of the six VG methods ($p < .05^{*}$, $p < .01^{**}$)

VR Game (Fig. 9a). In VR games where users can freely explore their surroundings, important clues can often be overlooked. To address this, the proposed method directs attention to hard-to-notice objects while preserving immersion, enabling users to become aware of critical information. This feature can be implemented as a hint system aimed at novice players, reducing frustration from being stuck and enhancing overall satisfaction with the game experience.

360° Video (Fig. 9b). In 360°videos, users may miss critical scenes if they are not looking in the intended direction. By applying color vibration to highlight objects the creator wants the audience to notice, ChromaGazer-HMD can guide attention without compromising the natural appearance of the video. While this approach can not effectively direct attention to objects entirely outside the user's field of view, it can draw focus to objects in peripheral vision, enhancing the viewer's experience with 360°content.

Task Assistance (Fig. 9c). Video-see-through HMDs, such as the Meta Quest 3 and Apple Vision Pro, dynamically process and augment real-world visuals. This capability provides significant advantages in precisely controlling visual presentations in real-world environments. By incorporating ChromaGazer-HMD into these systems, subtle VG can be implemented to support real-world tasks without causing unnecessary distractions.

Table 1: Cohen's r for two conditions in the Wilcoxon signed-rank test. Cohen's r show the absolute values.

(a) Completion Time

	NG	US	UC	OS	OC
US	0.609^{**}				
UC	0.579^{**}	0.164^{*}			
OS	0.753^{**}	0.277^{**}	0.486^{**}		
OC	0.660^{**}	0.232^{**}	0.351^{**}	0.421^{**}	
EG	0.857^{**}	0.630^{**}	0.768^{**}	0.074	0.545^{**}

(b) Image Exploration

	NG	US	UC	OS	OC
US	0.551^{**}				
UC	0.523^{**}	0.009			
OS	0.690^{**}	0.152^{*}	0.376^{**}		
OC	0.663^{**}	0.189^{*}	0.270^{**}	0.039	
EG	0.845^{**}	0.461^{**}	0.548^{**}	0.247^{**}	0.164^{*}

(c) Naturalness

	NG	US	UC	OS	OC
US	0.835^{**}				
UC	0.800^{**}	0.525^{**}			
OS	0.856^{**}	0.774^{**}	0.796^{**}		
OC	0.858^{**}	0.717^{**}	0.746^{**}	0.604^{**}	
EG	0.867^{**}	0.826^{**}	0.844^{**}	0.770^{**}	0.784^{**}

(d) Obtrusion

	NG	US	UC	OS	OC
US	0.820^{**}				
UC	0.793^{**}	0.503			
OS	0.855^{**}	0.731^{**}	0.763^{**}		
OC	0.855^{**}	0.702^{**}	0.733^{**}	0.533	
EG	0.865^{**}	0.827^{**}	0.854^{**}	0.756^{**}	0.766^{**}

$p < .05^{*}$, $p < .01^{**}$

7 Limitation and Future Work

7.1 Color Vibration Beyond Grayscale

The perception of color vibration varies depending on hue and saturation, and is also subject to individual differences. Thus, this study focused solely on color vibration within grayscale. However, for the results to be applicable more generally, further research is needed in diverse environments that include a range of colors beyond grayscale. This extension is promising as Hattori et al. [9] have demonstrated that imperceptible color vibrations for eight

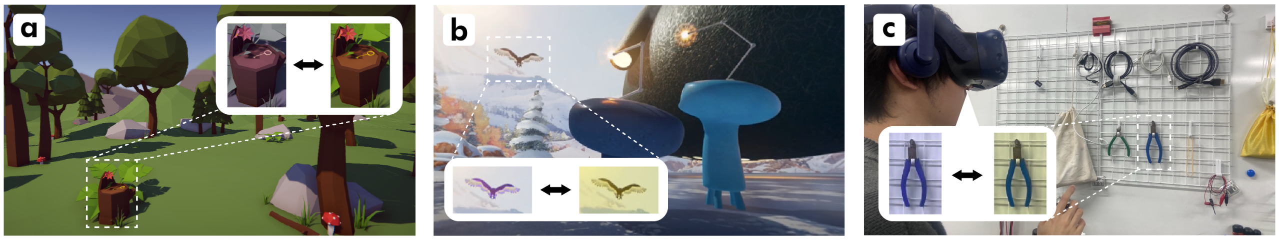


Figure 9: Application scenarios utilizing unobtrusive color vibration for VG: (a) VR Game: directing attention to less noticeable objects ensures that important information is not overlooked; (b) 360°Video [20]: guiding attention to the areas the video creator wants the viewer to focus on, important scenes can be highlighted without compromising immersion; (c) Task Assistance: by applying ChromaGazer-HMD to video see-through HMDs, it becomes possible to support tasks in the real world.

representative colors can be designed using similar approaches based on MacAdam ellipses.

7.2 Dynamic Modulation

Color vibration in the peripheral vision has a larger amplitude ratio r than when it is presented in the central vision. This can cause stimuli that were not noticeable before VG to become apparent after the gaze is directed. As a result, it may perceptually alter the content, leading to lower naturalness and higher perceived forcefulness. Other VG methods [3, 29] have addressed this issue by using eye-tracking to detect the gaze position and dynamically adjusting or removing the modulation as the gaze approaches the ROI. Thus, dynamically modulating the stimuli using eye-tracking could potentially result in less noticeable VG.

7.3 Simulating Color Vibration to Adapt to Frequency

In this study, we used 45 Hz and 22.5 Hz color vibrations instead of the typical 30 Hz due to the 90 Hz refresh rate of the HMD. The 22.5 Hz color vibration was especially effective, but it falls below the typical Critical Color Fusion Frequency (CCFF) of 25 Hz. As a result, it may be harder to achieve intermediate or full perception compared to color vibrations at or above 25 Hz.

To address this, we could explore methods for simulating 30 Hz color vibration in environments with a 90 Hz refresh rate. This could be done by introducing the original image as a third stimulus between the two modulated color stimuli. The perceptual effects and potential for effective VG using this simulated color vibration remain untested, but it could provide a way to achieve more unobtrusive VG.

7.4 VG in Contexts Beyond Exploratory Behavior

This study demonstrated the effectiveness of color vibration for VG in the context of supporting exploratory behavior when searching for a target. However, in many VR environments, such as 360-degree videos and VR games, users are often unaware of the areas or objects creators want them to focus on. The effectiveness of the proposed method in contexts other than exploratory behavior remains unclear and should be tested using other evaluation methods.

8 Conclusion

We proposed ChromaGazer-HMD, an adaptation of the ChromaGazer system, which utilizes color vibration based on MacAdam ellipses for gaze guidance in HMD environments. Through systematic evaluation, we revealed several key findings. First, while 45 Hz color vibration proved challenging for achieving intermediate and full perception in HMD conditions, 22.5 Hz color vibration demonstrated significant effectiveness in supporting exploratory behavior. Our investigation showed that color vibration at 22.5 Hz successfully reduced search times and areas compared to conditions without guidance, while maintaining the naturalness of the content.

Furthermore, our study introduced complementary color vibration, where opposite-phase vibrations are presented to each eye. Our experiments suggested that this approach may preserve naturalness better than conventional synchronous color vibration while maintaining equivalent performance levels. This finding opens up new possibilities for gaze guidance techniques specifically designed for HMD platforms.

ChromaGazer-HMD opens up new possibilities for unobtrusive gaze guidance in various HMD applications, from immersive VR experiences to task assistance in augmented reality. Moving forward, this research sets the foundation for exploring more sophisticated gaze guidance techniques that take full advantage of the binocular nature of HMD displays.

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