ChromaGazer: Unobtrusive Visual Modulation using Imperceptible Color Vibration for Visual Guidance

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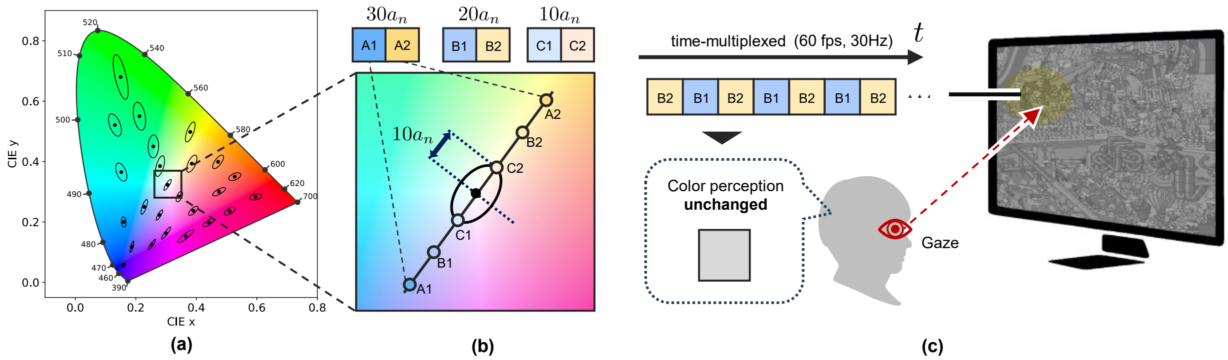

Fig. 1: Overview of our unobtrusive visual guidance (VG) using color vibrations. (a) The MacAdam ellipses [18] plotted on the xy chromaticity diagram represent regions where colors appear identical to the average human observer when placed adjacent to the central color of each ellipse. For illustration purposes, the ellipses are shown at 10 times their actual size. (b) We select color pairs by extending along the major axis a_n of each MacAdam ellipse by a factor r. Through empirical evaluation, we identified the optimal range of r suitable for unobtrusive VG. (c) By modulating regions of interest in an image with the r determined in (b), we implement VG without significantly altering the perceptual appearance of the image.

Abstract— Visual guidance (VG) plays an essential role in directing user attention in virtual reality (VR) and augmented reality (AR) environments. However, traditional approaches rely on explicit visual annotations, which often compromise visual clarity and increase user cognitive load. To address this issue, we propose an unobtrusive VG technique based on color vibration, a phenomenon in which rapidly alternating colors at frequencies above 25 Hz are perceived as a single intermediate color. Our work explores a perceptual state that exists between complete color fusion and visible flicker, where color differences remain detectable without conscious awareness of vibration. Through two experimental studies, we first identified the thresholds separating complete fusion, this intermediate perceptual state, and visible flicker by systematically varying color vibration parameters. Subsequently, we applied color vibrations with derived thresholds to natural image regions and validated their attention-guiding capabilities using eye-tracking measurements. The results demonstrate that controlled color vibration successfully directs user attention while maintaining low cognitive demand, providing an effective method for implementing unobtrusive VG in VR and AR systems.

Index Terms—visual guidance, imperceptible color vibration, color perception, augmented reality

1 Introduction

Visual guidance (VG) plays a fundamental role in directing user attention to specific areas of interest by overlaying information in both virtual and real environments. While initially developed for graphics and web design applications [24], VG has become increasingly important in virtual reality (VR) and augmented reality (AR) contexts, supporting virtual training [42], exploration assistance [21], and memory enhancement [37]. However, traditional VG approaches typically use explicit visual annotations such as arrows or circles [26, 27, 38], which often increase cognitive load and interfere with the visibility of target objects.

To address these challenges, researchers have explored *unobtrusive* VG techniques that preserve scene context while minimizing visual interference. One promising direction is to manipulate visual saliency [15]–the perceptual features that naturally attract gaze attention. Previous research has explored several saliency-based VG approaches to direct user gaze to regions of interest (ROI), including modifications of color and contrast [3, 20, 22, 35], as well as the strategic use of flicker effects [4, 21, 34]. While these saliency-based VG approaches avoid adding explicit graphical elements, they typically change the appearance of the scene, which can alter content interpretation, obscure critical information, and reduce real-world consistency in AR applications.

To overcome these limitations, we introduce ChromaGazer, a VG approach that guide user's gaze attention without changing the visual appearance of the content. Our approach builds on the phenomenon called imperceptible color vibrations, which alternating two colors of same luminance at frequencies above the critical color fusion frequency (CCFF, approximately 25 Hz) [5] are perceived as a single, fused color. In applying color vibration to VG, we hypothesized that by

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carefully selecting color pairs and adjusting their amplitude, it would be possible to create an intermediate perceptual state. We define this intermediate perceptual state as one in which the color vibration appears slightly different from a single fused color, but the apparent flicker is not perceived. We consider that if we could create this intermediate perceptual state, we could guide the user's gaze without the user being aware of the color vibration.

To assess the feasibility of using color vibration for VG, we conducted two experiments. In the first experiment, we systematically varied the vibration amplitude of color pairs based on the MacAdam ellipse [18] and asked participants to identify boundaries between three perceptual states between explicit flicker, intermediate states, and full color fusion. In the second experiment, we applied color vibrations with the parameters identified in the first experiment to specific regions within gray-scale natural images, and then evaluated their effectiveness in directing participants' gaze using eye-tracking data. The results confirm that this approach successfully redirected users' gaze patterns without their conscious awareness.

Our main contributions include:

- We propose ChromaGazer, a VG approach that uses imperceptible color vibrations without changing the appearance of the scene.
- We identify the optimal parameters for creating an intermediate perceptual state that balances the attention and visual integrity of content through a user study.
- We demonstrate the effectiveness of our color-vibration-based VG method in directing users' gaze to target regions within natural images through eye-tracking analysis and questionnaires.
- We explore the design considerations of our ChromaGazer approach and suggest future research directions.

2 Related Work

2.1 Visual Guidance

Visual guidance has been extensively studied due to its broad applications, such as navigating digital information [21, 24], assisting in industrial operations [30], and training system [37, 42, 43]. Research in this field recognizes two primary attention mechanisms: top-down and bottom-up [25]. Top-down attention responds to intentional cues such as arrows, icons, or text instructions, reflecting conscious cognitive processes. In contrast, bottom-up attention responds automatically to visual stimuli such as flickering, color changes, and motion.

Traditional visual guidance systems have predominantly employed top-down attention mechanisms, using geometric markers such as circular or rectangular frames [13, 14, 40] or arrows [29, 41, 43]. In contrast, considerable research has also explored bottom-up attention through saliency manipulation–the selective enhancement of visual elements to naturally attract attention. These approaches typically modify either color and contrast property [3, 20, 22, 35] or temporal properties through controlled flicker effects [4, 21, 34, 39].

Drawing on neuroscience, researchers have developed techniques based on saliency maps [15] to quantify and manipulate visual attention. For example, Kokui et al. [16] applied color shifts based on saliency maps. In addition, researchers have explored combining multiple parameters that influence saliency to achieve more effective gaze guidance. Examples include the simultaneous modulation of color and brightness [7, 31], the introduction of subtle blur effects to modulate visual saliency [9], and the application of genetic algorithms [23].

Recent research has investigated the combination of multiple saliency parameters to enhance the effectiveness of guidance. For example, Suzuki et al. proposed an approach that combines various parameters that affect visual saliency, such as blur, brightness, saturation, and contrast [36]. Similarly, Sutton et al. developed the VG method for real-world vision by modulating multiple visual salience parameters of the field of view with optical see-through head-mounted displays [35]. However, most existing saliency manipulation methods inevitably change the content appearance. Instead, this study aims to guide gaze by minimizing changing the content appearance by exploiting the phenomenon of imperceptible color vibration.

2.2 Imperceptible Color Vibration

The imperceptible color vibration is based on the visual phenomenon where rapid alternation between colors of the same luminance is perceived as a fused, intermediate color. This effect occurs above the CCFF of about 25 Hz [5], half the critical flicker fusion frequency (CFF) at which luminance flicker becomes imperceptible [19] for luminance alternation. Because this imperceptible color vibration can be used without the need for special high refresh rate displays, it can be implemented on standard displays with refresh rates above 60 Hz and finds applications in embedding information in video, such as camera-readable, invisible QR codes [1, 2].

Several studies have been conducted on efficient search methods for imperceptible color vibration pairs that can be detected by the color sensor [1, 10]. Recently, Hattori et al. [11] further improved the efficiency of color search by using MacAdam ellipses [18] as the basis for perceptual thresholds. They conducted user experiments to investigate the flicker perception threshold by varying the amplitude of the color vibration along ellipse major axes. Our approach extends their perceptual search for color vibration pairs to attention guidance applications.

2.3 Color Vibration and Bottom-up Attention

While color vibrations above the CCFF escape conscious perception, neuroscience research reveals differential processing across visual cortex regions [12]. While the ventral occipital (VO) cortex, which is responsible for advanced color processing, shows limited response, early visual areas (V1-V4) retain sensitivity to these vibrations. This finding suggests that color vibrations may influence bottom-up attention through early visual processing, even without conscious awareness. The results of this research are fundamental to our hypothesis. Although precise brain activity measurements are needed to test this hypothesis in detail and accurately, this study can be positioned as a first pilot test of this hypothesis with the user study.

3 Evaluation of Intermediate Perception in Color Vibration

Our ChromaGazer approach is based on a hypothesized intermediate perceptual state of color vibration in which the object appears to be subtly different from a fused, single color, but without a clearly perceptible flicker. In this section, we investigate both the existence and the precise amplitude parameters of such states before applying them to gaze guidance applications.

Building on the work of Hattori et al. [11] that established perceptual thresholds for color pair selection using the major axes of MacAdam ellipses, we conduct a detailed investigation of the intermediate perceptual state between complete color fusion and noticeable flicker.

Note that, in this paper, we focus on reproducing color vibration using only grayscale colors, as individual perception of color vibration differs depending on hue and saturation. Investigating the parameter for arbitrary colors will be the subject of future work.

3.1 Selection of Perceptual Color Vibration Pairs

To select suitable color vibration pairs for our experiments, we used MacAdam ellipses to account for the non-uniformity in human color perception.

Figure 1 (a) shows the distribution of MacAdam ellipses on the *xy* chromaticity diagram. Each ellipse represents a region where colors appear indistinguishable from a central reference color when viewed side by side, as determined experimentally. By using MacAdam ellipses, we can select color vibration pairs that take into account the varying sensitivity of the human visual system to different colors. For example, larger ellipses in green regions indicate reduced sensitivity to color differences within the *xy* chromaticity space compared to blue regions.

Each MacAdam ellipse $\mathscr{E}_n = \{\mathbf{c}_n, \theta_n, a_n, b_n\}$ $(n = 1 \cdots 25)$ is defined at 25 points on *xy* chromaticity diagram by its center coordinates $\mathbf{c}_n = [c_{nx}, c_{ny}]$, rotation angle θ_n, and major and minor axes lengths a_n and b_n. We select color pairs $\{\mathbf{p}_n^+(r), \mathbf{p}_n^-(r)\}$ by extending along each ellipse's major axis a_n by ratio r as color vibration pairs (Fig. 1 b), which denoted as

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

xy chromaticity diagram is calculated by normalizing the luminance $0 \leq Y \leq 1$ of the CIEXYZ color space. Therefore, when displaying colors based on the selected color pairs $\mathbf{p}_n^{\pm}(r)$, it is necessary to complement the luminance Y. As luminance Y approaches 0, both $\mathbf{p}_n^{\pm}(r)$ approach black and the vibration become nearly invisible. In contrast, as Y approaches 1, the brightness of the color pairs $\mathbf{p}_n^{\pm}(r)$ exceeds the sRGB range. Therefore, in this experiment, we set $Y = 0.4$ and converted xyY to XYZ as

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

Then, color pairs selected in CIEXYZ are converted to the sRGB color system for display:

$$\begin{bmatrix} R_{\text{linear}} \\ G_{\text{linear}} \\ B_{\text{linear}} \end{bmatrix} = \begin{bmatrix} 3.2406 & -1.5372 & -0.4986 \\ -0.9689 & 1.8758 & 0.0415 \\ 0.0557 & -0.2040 & 1.0570 \end{bmatrix} \begin{bmatrix} X \\ Y \\ Z \end{bmatrix} \quad (3)$$

The following gamma transformations were then applied to each channel $C \in \{R, G, B\}$:

$$C_{\text{srgb}} = \gamma(C_{\text{linear}}) \quad (4)$$

$$= \begin{cases} 1.055 \cdot C_{\text{linear}}^{1/2.4} - 0.055 & \text{if } c \geq 0.0031308, \\ 12.92 \cdot C_{\text{linear}} & \text{otherwise} \end{cases} \quad (5)$$

For implementation, we use the color-science library in Python [1]. The CIE 1931 2° observer function under D65 illumination is used for color conversion.

Previous research by Hattori et al. [11] found thresholds for color vibration perception by systematically varying the amplitude ratio r. Their results identified a threshold of $r = 24.4$ at which 50 % of participants detected the vibration, and r below this threshold were classified as imperceptible and applied to color vibration detection by cameras and sensors. Our study extends this work by investigating finer gradations of perceptual response, specifically the range of r values that produce an intermediate perceptual state where colors appear different from uniform colors but do not induce noticeable flicker.

3.2 Experiment Setup

Through the experiment, we systematically analyze how the parameters of vibration amplitude r, the stimulus distance from the center, and stimulus size affect the emergence of the intermediate perceptual state. This experiment setup is based on Waldin et al. [39] for flicker perception, and we have extended the setup to color vibrations.

3.2.1 Participants

17 participants (13 males, 4 females; age range 23–45 years, mean age 30.3 years) participated in the study. 9 participants used corrective lenses (glasses or contact lenses). All procedures were approved by Cluster, Inc. Research Ethics Committee (Protocol No. 2024-005).

3.2.2 Generation of Color Vibration Images

In this experiment, we varied three parameters: the amplitude ratio r, the diameter d of the image circle, and the display position of the image l. We presented various combinations of color vibrations to participants and measured human perceptual thresholds based on their responses. Participants were asked to choose one of the following three perceptual states:

1. **Uniform**: The image appears as a uniform color with no noticeable differences.
2. **Awareness**: The image appears slightly different from a solid color, but there is no noticeable flickering.

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

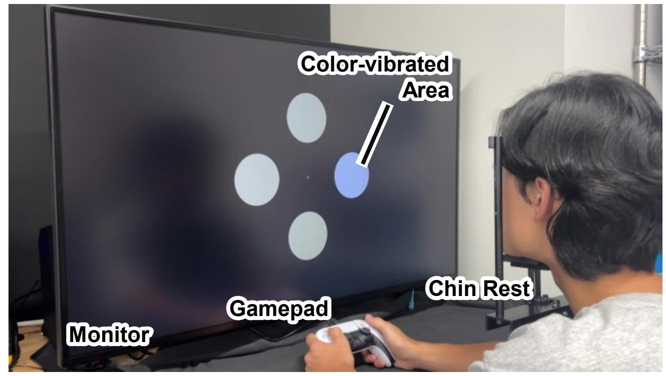


Fig. 2: Experimental setup for Sec. 3.

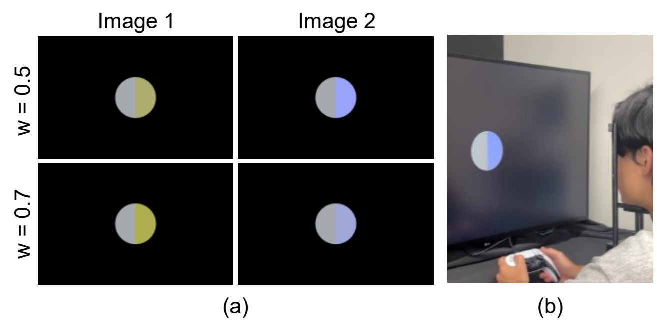


Fig. 3: (a) Image pairs to be presented during color vibration adjustment ($r = 50$) for each participant. The image pair at $w = 0.7$ has a stronger yellow saturation than the image pair at $w = 0.5$. (b) Color vibration adjustment. The participant adjusts the weight w so that the color appears perceptually the same as the gray of the left half.

3. **Discomfort**: The image has clearly noticeable flickering.

We selected the point $(x, y) = (0.305, 0.323)$ from the MacAdam ellipses in the xy chromaticity space as the base color for generating color vibration pairs. The luminance was set to $Y = 0.4$. This color is near the center of the xy chromaticity diagram and ensures that the color pairs remain within the sRGB gamut even as r increases. In the sRGB color space, this corresponds to $(R, G, B) = (0.640, 0.659, 0.678)$. We generated color pairs with r values ranging from 0 to 50 in increments of 5, resulting in 11 sets of color vibration pairs.

3.2.3 Apparatus

Participants were seated with their chins on a rest to stabilize head position, ensuring their eyes were level with the center of a 42.5-inch LCD display (43UN700-BAJP, LG Electronics) positioned 500 mm away. The display was calibrated to the sRGB color space using a monitor calibration tool (Spyder X Elite, Datacolor) and set to a luminance of 166 cd/m^2.

3.2.4 Experimental Conditions and Procedure

Figure 2 shows the experimental setup. Prior to the main experiment, we conducted a color adjustment procedure to account for individual differences in color perception. Participants viewed a centrally positioned circular stimulus (120 mm diameter) split vertically: the left half displaying a static color without vibration, and the right half showing a color-vibrating pattern at a specific r value. Using the left and right buttons of a gamepad, participants adjusted the weight parameter $0 \leq w \leq 1$ in increments of 0.02 until both halves appeared perceptually identical (Fig. 3).

In the main experiment, color pairs were calculated based on this adjusted weight w. Specifically, the ratio of the distance along the major axis of the MacAdam ellipse from the target color to the vibration colors

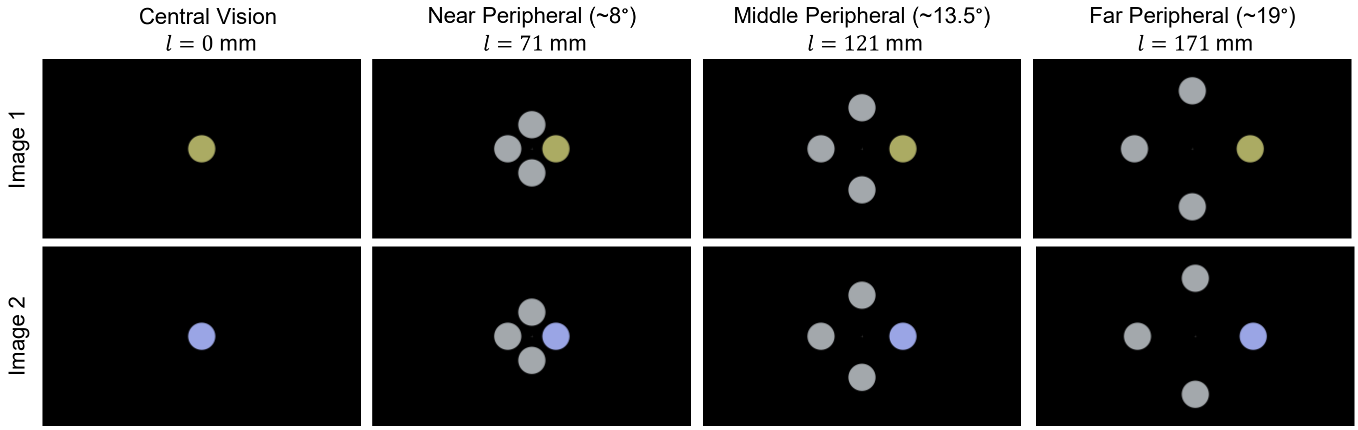
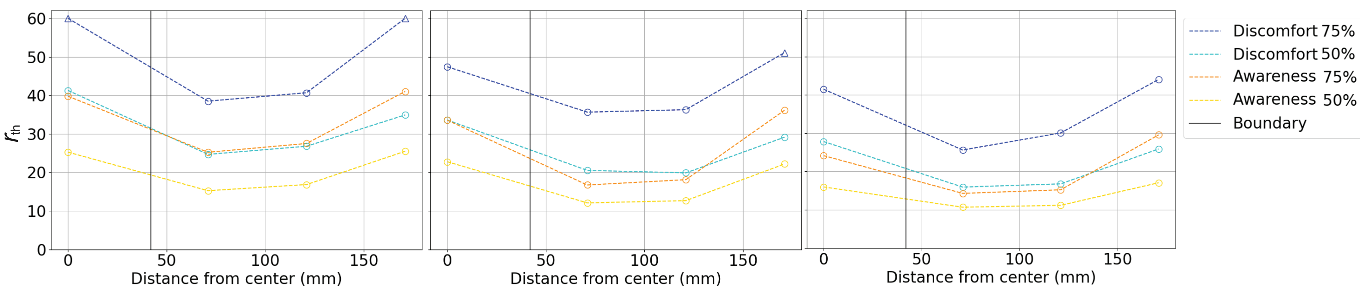


Fig. 4: An example of the color vibration image pairs presented in the experiment of Sec. 3. In the central visual field condition, we applied color vibration at a specified r and d to a single circle. In the peripheral visual field condition, we applied color vibration at the specified r and d to one of four circles. Participants were asked to indicate whether they perceived the color vibration.



(a) d = 60 mm (b) d = 80 mm (c) d = 100 mm

Fig. 5: Results of an experiment showing the thresholds r_{th} for the Awareness condition (participants recognized the color as different from the grayscale color) and the Discomfort condition (participants recognized it as a clear flicker) at each display position of the image circle l with 50 % and 75 % probability. From left to right, the results are shown for the conditions with image circle sizes of $d = 60$ mm, 80 mm, and 100 mm. The line indicates the boundary between central and peripheral vision.

(yellow and blue) was set to $w : 1-w$. Mathematically, the color pair corrected for individual as $\mathbf{p}^{\pm}_{\text{adj}}(r,w)$ can be calculated using w as

$$\begin{aligned} \mathbf{p}^{+}_{\text{adj}}(r,w) &= [c_x + 2wr \cdot a \sin\theta,\ c_y + 2wr \cdot a\cos\theta], \qquad (6)\\ \mathbf{p}^{-}_{\text{adj}}(r,w) &= [c_x - 2(1-w)r \cdot a \sin\theta,\ c_y - 2(1-w)r \cdot a\cos\theta]. \end{aligned}$$

When $w = 0.5$, these equations are the same as Eq. (1).

This adjustment procedure was repeated across five decreasing r values ($r = 50, 40, 30, 20, 10$) to establish familiarity with the range of color vibration and to help them understand the concept of "flicker." Between calibration trials, we displayed an inverted stimulus image for 100 ms to reduce afterimage effects, where the image circle turned black and the surrounding background remained the display color.

Figure 4 shows an example of the images presented in the main experiment. In the main experiment, we displayed circular color vibration stimuli with three diameters d: 60 mm (small), 80 mm (medium), or 100 mm (large). Stimulus positions also varied by the distance l from the display center: 0 mm (central vision, 0° visual angle), 71 mm (near periphery, $\sim 8°$), 121 mm (mid-periphery, $\sim 13.5°$), and 171 mm (far periphery, $\sim 19°$). For peripheral presentations, we displayed four symmetrically arranged circles around the center to eliminate directional bias.

Participants were displayed with a random sequence of the 132 combinations ($11 \times 3 \times 4$) of r, d, and l. On each trial, they used a gamepad (DualSense Wireless Controller, Sony Interactive Entertainment) to select one of the three perceptual states described above. In peripheral vision conditions, participants also indicated which circle they perceived as vibrating. An inverted stimulus was displayed after each response to prevent afterimages. Participants were given short breaks after every 10 trials to reduce fatigue.

3.3 Result and Discussion

We calculated the proportion of participants who reported each perceptual state at different r values for each condition. By fitting sigmoid functions to the data, we estimated the thresholds r_{th} at which participants had a 50 % and 75 % probability of perceiving the image as "different from a solid color" (Awareness) and "clearly flickering" (Discomfort). For peripheral vision trials, we counted responses as no detection when participants incorrectly identified the vibrating stimulus location.

Figure 5 shows the experiment result. The graph shows, from left to right, the r threshold at which subjects perceive a color as different from a single color with 50% and 75% probability, and the r threshold at which they aware an obvious flicker, for each display position of the image circle when $d = 60$ mm, 80 mm, 100 mm. As a result, we obtained 24 thresholds each at 50% and 75%.: 2 perception $\times$ 3 size $\times$ 4 distance.

3.3.1 Effect of Color Vibration Size

From Figure 5, we confirmed that there is an inverse correlation between the threshold of the color vibration amplitude r_{th} and the stimulus diameter d. For example, for $d = 60$, 80, and 100 mm at $l = 71$ mm, the threshold at which participants perceived the image as Discomfort with 50 % probability were $r_{\text{th}} = 25.22$, 16.73, and 14.29, and with 75 % probability were $r_{\text{th}} = 38.50$, 35.65, 25.61, respectively. Similarly, the thresholds for perceiving Awareness with 50 % probability were $r_{\text{th}} = 15.25$, 12.08, and 10.68, respectively, and with 75 % probability were $r_{\text{th}} = 25.22$, 16.73, and 14.29, respectively. This suggests that larger color vibration areas make it easier for participants to perceive color vibrations even at smaller r values.

3.3.2 Effect of Display Position

From Fig. 5, the thresholds r_{th} varied systematically with stimulus position for all d and perceptual states (Awareness/Discomfort). Central vision ($l = 0$) showed increased r_{th}, i.e., decreased sensitivity compared to near and mid-peripheral locations ($l = 71$, 121 mm). However, in the central viewing condition, since only one circle was displayed, it was not possible to compare the colors with the adjacent stimuli, which may have contributed to the high threshold observed.

In contrast, sensitivity decreased in far peripheral vision ($l = 171$ mm) relative to near and mid-peripheral locations. In general, the stimuli presented in the far periphery show increased sensitivity to flicker, but decreased sensitivity to chromatic differences. This experiment result suggests that the perception of the color vibration relies more on chromatic processing mechanisms than on temporal, flicker detection systems. This result is consistent with the well-known finding that the far periphery has a low number of cone cells, which perceive color, and a high number of rod cells, which perceive brightness.

3.3.3 Intermediate Perceptual State of Color Vibrations

For all d and l, there are consistent differences between the thresholds r for Awareness and Discomfort, which indicates that there is a range between the amplitude of perceived color difference from single colors and the amplitude of perceived noticeable flicker. Therefore, by choosing an appropriate r value that falls between the Awareness and Discomfort thresholds, depending on the position and size of the content being displayed, it is possible to design effective visual guidance that does not cause noticeable flicker.

4 Evaluation of Color Vibration Vision Guidance

Building on the results of Sec. 3, we investigated whether applying color vibration to ROI could effectively guide attention while preserving overall appearance of the image. Figure 7 shows the experimental setup. This experimental protocol was also approved by the Cluster, Inc. Research Ethics Committee.

4.1 Experiment Setup

4.1.1 Participants

30 participants (18 males and 12 females; age range 23-50 years, mean age 30.8 years), participated in this study. 4 participants corrected their vision with glasses and 15 used contact lenses.

4.1.2 Apparatus

Participants were seated with their chins resting on a chin rest placed in front of the same 42.5-inch LCD display used in Sec. 3.2. The display settings, viewing distance (500 mm), and ambient lighting conditions were the same as in the previous experiment. For 23 participants without glasses, we recorded gaze trajectories using the wearable eye tracker (Pupil Labs, Pupil Core). To map gaze data to display coordinates, ArUco markers of known dimensions were displayed at the four corners of the content images, allowing homography transformation using the eye tracker's cameras.

4.1.3 Stimuli Preparation

Figure 6 shows an example of the presentation image used in this experiment. We selected 8 images from "Pocket Edition NEW Where's Wally!" by Martin Handford [8], a picture book in which readers search for a specific character among many others. Note that, in this experiment, the character that the participants have to find is not necessarily Wally, as they are asked to look at objects in various positions on the screen. The selected images were scanned at 600 dpi using a scanner (ScanSnap iX1300, PFU) and cropped to 1200 px $\times$ 1200 px to adjust the difficulty level to ensure that participants could locate the target character within the 30 second display limit even in the unmodulated condition.

Since colors close to white or black are difficult to apply to color vibration, the image was converted to 8-bit grayscale and the pixel values were remapped from the original range of [0, 255] to [70, 185] to make it easier to apply color vibration to each pixel. These values are set so that the upper and lower limits of the grayscale values that can generate pairs of color vibrations within the sRGB range correspond to the maximum value of r_{th} in the obtrusive color vibration.

The ROI was defined as a circular area 80 mm in diameter sufficient to enclose a single character (not necessarily Wally), and the area of color vibration was also set as a circle 80 mm in diameter to match the size of the ROI. The positions of the ROIs were varied across images to avoid location bias.

We applied four variations of visual guidance to the images:

1. **Unmodified**: Original image without any modification.
2. **Unobtrusive Color Vibration**: ROI modulated with subtle color vibration using r_{th} corresponding to the "Awareness" condition.
3. **Obtrusive Color Vibration**: ROI modulated with noticeabl color vibration using r_{th} corresponding to the "Discomfort" condition.
4. **Explicit Guidance**: ROI marked with a 80 mm, black visible circle.

4.1.4 Determination of Color Vibration Parameters

The color vibration pairs were generated using the threshold values r_{th} corresponding to the diameter $d = 80$ mm of the stimuli area and the distance of the stimuli from the display center l, as obtained in the previous experiment. We chose the value of $r_{mathrmth}$ so that the subject would perceive a color vibration with a probability of 75 %. The reason for choosing 75 % is that, if we choose 50 %, half of the people will not be guided by gaze in principle, which is less appropriate for practical applications of VG.

For ROIs in central vision ($\leq 5^\circ$), we applied r_{th} values based on the result for $l = 0$ mm; for peripheral locations ($8^\circ - 19^\circ$, 71 mm $\leq l$), we linearly interpolated the r_{th} values based on the results for $l = 71$, 121, and 171 mm. We avoided placing ROIs outside of these ranges due to uncertainties in the applicability of linear interpolation.

Because the parameter r varied with distance from the center of the display, we adjusted the color-fitting parameter w accordingly for each participant, using linear interpolation based on the fitting results from the previous experiment.

4.1.5 Experiment Procedure

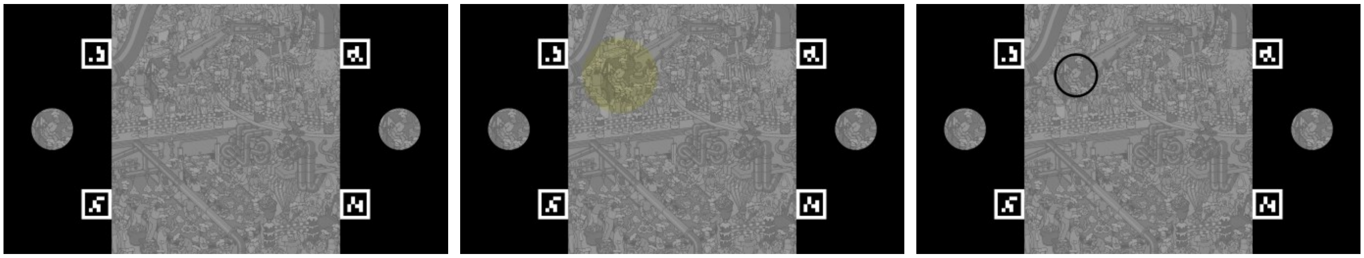
Participants gave informed consent and underwent the same color matching process as described in Sec. 3.2.4. They were then given definitions of the terms used in the Likert scale questionnaire. The eye tracker was calibrated before the start of the experiment.

During the experiment, participants were asked to keep their eyes fixed on the display by resting their chin on a chin rest. They were instructed to look at the display and select the target area in the content image with the mouse. The reference images for the search target were displayed on either side of the content image so that they could be referred to if necessary.

Each participant was presented with 8 images from 4 VG conditions in random order, for a total of 32 different stimuli. These were presented in a completely random order for each subject, while we set that the same image was never presented twice in a row.

The procedure for each trial consisted of:

1. **Fixation screen**: A black screen with a white cross in the center was displayed, and participants were instructed to fixate on the cross.
2. **Target presentation**: An image showing only the ROI (the target character) centered on the screen was presented to familiarize participants with the search target.
3. **Search task**: The content he assigned visual guidance was displayed. Participants searched for the target character and indicated their selection with a mouse click.
4. **Questionnaire**: After each image, participants rated the following on a 7-point Likert scale, following Sutton et al. [35]:



(a) Unmodulated (b) Guidance with color vibration (Unobtrusive / Obtrusive) (c) Explicit guidance

Fig. 6: Examples of images presented in Sec. 4. (a) The unmodulated image, i.e., the original image. (b) Images with color vibration applied to the ROI. (c) The "explicit" VG image with the ROI circled.

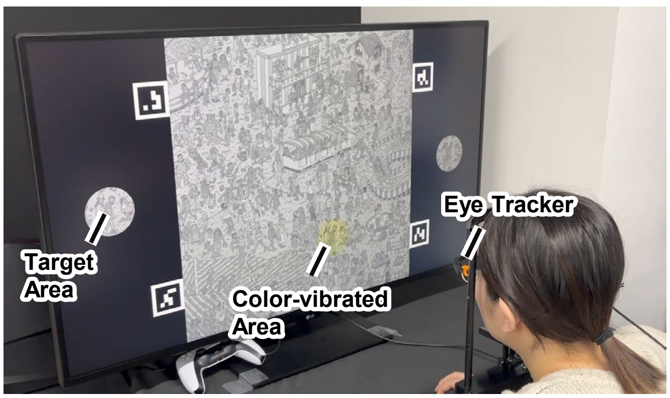


Fig. 7: Experimental setup for Sec. 4.

- **Naturalness**: The extent to which the image appeared unprocessed (1: very unnatural – 7: very natural).
- **Obtrusiveness**: The degree to which the image stood out undesirably (1: not at all obtrusive – 7: very obtrusive).

After every 8 images, participants took a short break and looked at a black screen to rest their eyes.

4.2 Results

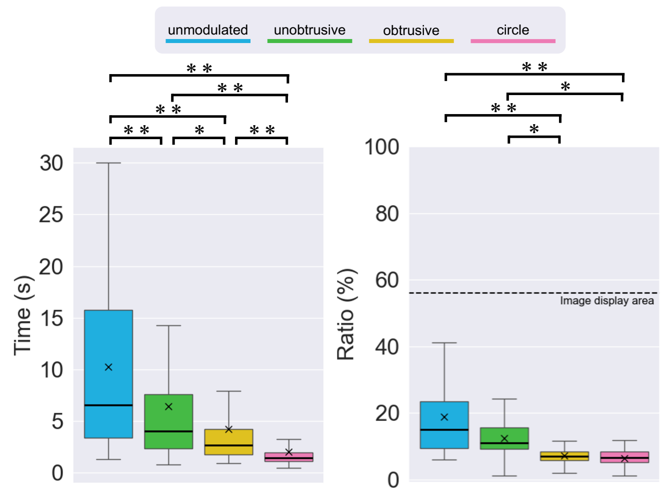
We evaluated the experiment from three perspectives: (1) task completion time (time to click on the correct search area), (2) proportion of the image explored by the gaze before task completion, and (3) scores from the user questionnaire.

4.2.1 Task Completion Time

Time was recorded based on participants' responses. Correct responses were assigned their respective completion times, while incorrect responses or timeouts (exceeding the 30-second limit) were assigned a 30-second time. Figure 8 (a) shows the task completion times for the four display conditions. As a result of conducting the Friedman test, the main effect of the display conditions on the evaluation score was significant ($\chi^2 = 327.278$, $p < .001$). Since the main effect was significant, the Wilcoxon signed-rank test was repeated under the Holm method as a sub-test. As a result, the task completion time of unmodulated condition was significantly higher than the unobtrusive condition ($p <$ .001, Cohen's $r = 0.357$), the obtrusive condition ($p < .001$, Cohen's r = 0.565), and the circle condition ($p < .001$, Cohen's $r = 0.829$). The unobtrusive condition was also significantly higher than the obtrusive condition ($p < .001$, Cohen's $r = 0.370$) and the circle condition ($p <$ .001, Cohen's $r = 0.771$). The obtrusive condition was also significantly higher than the circle condition ($p < .001$, Cohen's $r = 0.658$).

4.2.2 Proportion of Explored Area

We analyzed the proportion of the image explored through by fixations in the eye-tracking data using the Dispersion-Threshold Identification



(a) Completion Time (b) Image Exploration

Fig. 8: Results of (a) task completion time and (b) ratio of the area explored relative to the entire screen

(I-DT) algorithm [28]. This algorithm identifies fixations by detecting periods when the gaze remains relatively stable within a given specific spatial region for a minimum duration.

The algorithm first segments the raw gaze data into potential fixation groups based on the spatial dispersion of consecutive points. If the dispersion of these points remains below the threshold for longer than the minimum duration, the algorithm classifies this period as a fixation. This approach effectively filters out saccadic movements, providing a more accurate representation of the areas where participants were actually processing visual information. We set the duration threshold to 100 ms and the dispersion threshold to match the size of the central visual field (radius of 43.744 mm, within 5° of visual angle), as this represents the area where detailed visual processing occurs during stable fixation.

For each identified fixation point, we considered the area within the central visual field as the exploration area. These individual exploration areas were combined, and the total explored area was divided by the total image area to calculate the final proportion. Prior to this analysis, we transformed the eye coordinate data from the eye tracker camera space to the display coordinate system using homographic transformation based on the detected ArUco marker coordinates.

Figure 8 (b) shows the results. As a result of conducting the Friedman test, the main effect of the display conditions on the evaluation score was significant ($\chi^2 = 32.374$, $p < .001$). Since the main effect was significant, the Wilcoxon signed-rank test was repeated under the Holm method as a sub-test. As a result, the ratio of exploration area of unmodulated condition was significantly higher than the obtrusive condition ($p < .001$, Cohen's $r = 0.774$) and the circle condition ($p <$ .001, Cohen's $r = 0.805$). The unobtrusive condition was also signifi-

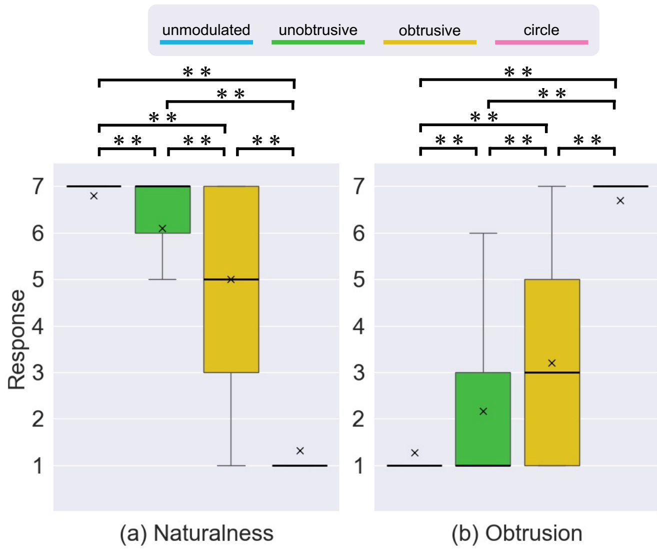


Fig. 9: Results of a user questionnaire on the four display conditions.

cantly higher than the obtrusive condition ($p = .002$, Cohen's $r = 0.672$) and the circle condition ($p = .002$, Cohen's $r = 0.691$). No significant differences were observed between the unmodulated and unobtrusive conditions ($p = .400$, Cohen's $r = 0.273$) and between the obtrusive and circle conditions ($p = .400$, Cohen's $r = 0.273$).

4.2.3 User Questionnaire

Figure 9 shows the questionnaire results for naturalness and obtrusiveness. As a result of conducting the Friedman test, the main effect of the display conditions on the evaluation score was significant for all categories of questions (Naturalness: $\chi^2 = 535.320$, $p < .001$; Obtrusion: $\chi^2 = 554.663$, $p < .001$). Since the main effect was significant, the Wilcoxon signed-rank test was repeated under the Holm method as a sub-test. The results are shown below:

- **Naturalness**: the score of unmodulated condition was significantly higher than the unobtrusive condition ($p < .001$, Cohen's $r = 0.816$), the obtrusive condition ($p < .001$, Cohen's $r = 0.812$), and the circle condition ($p < .001$, Cohen's $r = 0.867$). The score of the unobtrusive condition was also significantly higher than the obtrusive condition ($p < .001$, Cohen's $r = 0.776$) and the circle condition ($p < .001$, Cohen's $r = 0.856$). The score of the obtrusive condition was also significantly higher than the circle condition ($p < .001$, Cohen's $r = 0.837$).
- **Obtrusion**: the score of unmodulated condition was significantly lower than the unobtrusive condition ($p < .001$, Cohen's $r = 0.823$), the obtrusive condition ($p < .001$, Cohen's $r = 0.823$), and the circle condition ($p < .001$, Cohen's $r = 0.867$). The score of the unobtrusive condition was also significantly lower than the obtrusive condition ($p < .001$, Cohen's $r = 0.792$) and the circle condition ($p < .001$, Cohen's $r = 0.862$). The score of the obtrusive condition was also significantly lower than the circle condition ($p < .001$, Cohen's $r = 0.841$).

4.3 Discussion

Task Completion time The result of task completion times showed that there were significant differences between all four display conditions. This result indicates that unobtrusive gaze guidance using color vibration effectively directs users' attention and improves task performance without significantly altering the overall scene. Although its effectiveness is slightly lower than that of obtrusive color vibration and explicit guidance, it offers sufficient performance as a subtle gaze guidance method that avoids excessive interference with the user experience.

Proportion of Explored Area In the analysis of task completion times, there were significant differences except between the no modulation and unobtrusive color vibration conditions and between the obtrusive color vibration and explicit guidance conditions. In particular, it is interesting to note that there was a significant difference between the unobtrusive color vibration and the obtrusive color vibration conditions. This suggests that VG with obtrusive color vibration may strongly direct the gaze to a specific area, limiting the user's search, whereas VG with unobtrusive color vibration allows the user to naturally explore the entire area. With unobtrusive color vibration, the user can be subtly guided to important information while looking broadly at the entire area.

Questionnaire The results of the user questionnaire showed that there were significant differences in the ratings of naturalness and distraction for all display conditions. In particular, it was found that eye guidance using unobtrusive color vibration was more natural than eye guidance using obtrusive color vibration or explicit guidance. This confirms that unobtrusive VG can attract the user's attention without significantly changing the context of the scene. On the other hand, in terms of distraction, although all guidance methods were perceived as more distracting than the unmodulated condition, the unobtrusive color vibration achieved a good balance. It maintained a high level of salience that was sufficient to guide attention effectively while minimizing perceptual interference with the viewing experience.

These results suggest that unobtrusive gaze guidance using color vibration is an effective method that contributes to improving task completion speed and naturally supports users' search behavior. It is expected to have practical applications as it can improve access to necessary information without affecting the user's experience.

5 Application

This section explores three practical application scenarios of ChromaGazer: advertising enhancement, interactive picture books, and AR task assistance. Each application demonstrates how unobtrusive color vibration can guide visual attention while maintaining user immersion and a natural experience. Figure 10 illustrates these applications.

Advertising Enhancement (Fig. 10a) We applied color vibration to selected ROIs within advertisement images. This technique subtly draws the viewer's attention to specific products or information while maintaining the original design integrity of the advertisement. Unlike traditional attention-grabbing elements such as pop-ups or animated banners, this approach enhances advertising effectiveness without reducing viewer engagement with the content.

Interactive Picture Book (Fig. 10b) ChromaGazer synchronizes subtle visual cues within the images of a digital book with the flow of the narrative. By applying unobtrusive color vibrations to story-relevant elements, the system helps readers naturally track important characters and plot points. This integration of visual cues with storytelling facilitates reading comprehension while maintaining the immersive quality of the narrative experience.

AR Task Assistance (Fig. 10c) When implemented through AR glasses, ChromaGazer identifies task-relevant tools and components in real time and applies subtle color vibrations to guide the user's attention. This approach helps workers efficiently locate needed items without the visual interference typically associated with explicit overlays or markers, potentially reducing errors and improving task completion rates.

6 Limitation and Future Work

While this study establishes the feasibility of gaze guidance using unobtrusive color vibration, several areas require further investigation in order to generalize the perceptual parameters across different situations. We discuss the current limitations and potential directions for future work.

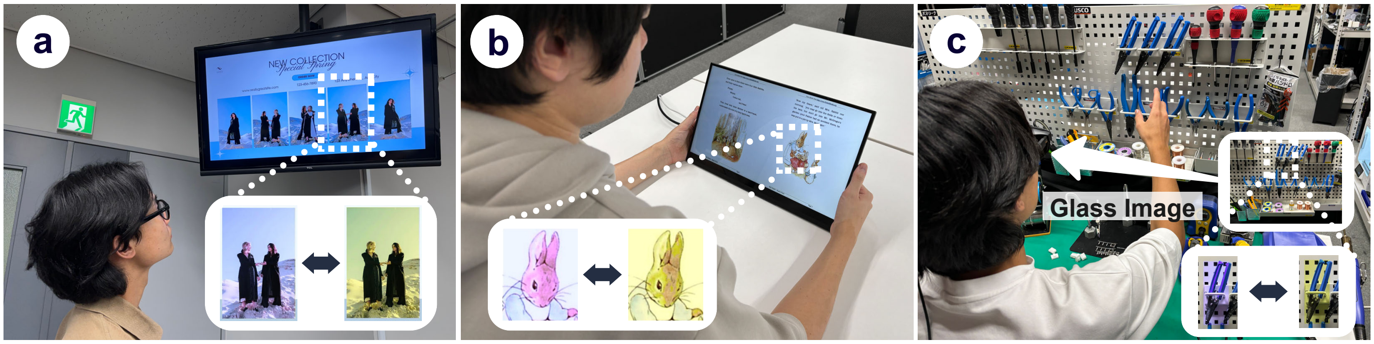


Fig. 10: Application scenarios utilizing unobtrusive color vibration for visual guidance: (a) Advertising: directing user attention to specific products or information within an advertisement without compromising design aesthetics; (b) Picture book: guiding readers' attention to important characters or key elements in a digital book while maintaining immersion; (c) Task assistance: helping users wearing AR glasses to identify necessary tools or parts during tasks by unobtrusively highlighting them, thereby improving work efficiency and reducing errors.

Relation Between Color Vibration Amplitude and Hue/Brightness Our initial investigation focused on grayscale color vibration to establish baseline effectiveness while controlling for visual variables. Having demonstrated the basic viability of this approach, future research should examine how different hues and saturation affect the perception and effectiveness of vibration.

In addition, the current implementation assumes a linear relationship between chromaticity amplitude and the major axis of the MacAdam ellipse. However, perceptual responses are likely to vary across color space. Future studies should develop more sophisticated models that account for the interaction between hue, brightness, and perceived chromaticity variation.

Experiments in different display environments Our current findings are based on tests with calibrated monitors under controlled lighting. Further research should examine how display characteristics and ambient lighting conditions affect color vibration perception. In addition, the application of this technique to displays specialized for VR and AR environments such as HMDs [6, 32, 34, 35] presents unique challenges that warrant dedicated investigation.

Generalized Saliency Model for Color Vibration The images used in this experiment are limited, and the effectiveness of this method should be verified in a variety of natural images. If an appropriate saliency model for color vibrations is provided, the VG effect of color vibrations can also be evaluated more generally. At present, however, no appropriate model has been proposed for the saliency model of color vibrations, and this is positioned as a direction for future research.

Expansion to Dynamic Content Our current knowledge is mainly based on still images. In dynamic content and natural scenes, the spatial relationships between elements are constantly changing, and the scene-specific saliency also changes, posing more complex problems arise. Future work will need to develop a computational saliency model that accounts for temporal dynamics and allows for more robust predictions of how color vibration affects attention in a variety of visual contexts.

Ethical Considerations in Subliminal Guidance The subliminal nature of color vibration-based guidance raises ethical considerations, particularly in commercial applications such as advertising, where subconscious influence may be a concern. Implementation of this technology should prioritize transparency and user consent, with clear disclosure protocols and user controls. These measures would help ensure that the technology enhances the user experience while respecting user autonomy and ethical design principles.

Neuroscientific Exploration of Color Vibration Consciousness As introduced in Sec. 2.3, the intermediate state of color vibration explored in this study was hypothesized based on neuroscientific findings. While this paper focused on user subjective evaluation and gaze analysis, estimating the intermediate state based on brain measurements such as fMRI is expected to deepen this method further.

Addressing Individual Differences in Color Perception The perceptual characteristics of color vibration depend on the individual, and experiments with larger numbers of participants are needed. Calibration and personalization of individual color vibration perception is considered a future research direction.

In particular, addressing accessibility for individuals with color vision deficiencies requires dedicated investigation [17]. Existing research has examined the effect of each characteristic of colorblindness on the *xy* chromaticity diagram. One possible approach is to select color vibration pairs on this *xy* chromaticity diagram are adapted for colorblindness [33]. Developing personalized calibration procedures has the potential to optimize the technique for different types of color blindness, but more in-depth research is needed, including how each individual perceives color vibration.

7 Conclusion

We presented ChromaGazer, a visual guidance technique that uses color vibration to direct user attention without perceptually altering the appearance of the image. Through user experiments, we determined thresholds for the intermediate perceptual state of color vibration, which informed the design of ChromaGazer. Evaluations with natural grayscale images demonstrated the effectiveness of the method in guiding gaze while preserving naturalness compared to existing approaches. We also evaluated the effect of color vibration amplitude on gaze guidance effectiveness, highlighting the need for optimal amplitude selection.

This study opens up possibilities for color vibration-based gaze guidance techniques. The generalization of our method requires further investigation into the perceptual characteristics of color vibration and the development of advanced gaze guidance strategies in diverse environments. We hope that this research will stimulate further exploration towards more sophisticated visual guidance systems.

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