# Perceptually Calibrated Foveated Chroma Attenuation for Gaze-Contingent VR Displays

Category: Research

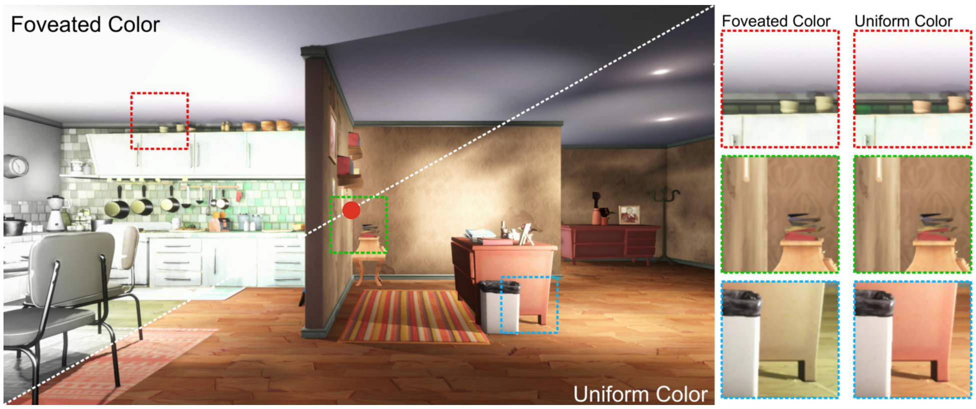



Figure 1: Side-by-side comparison of Stylized House Interior with uniform color and our foveated chroma attenuation model. The gaze point is at the image center (marked with a red dot).


## Abstract

We introduce a foveated chroma attenuation strategy for gaze-contingent virtual reality (VR) displays. Conventional stereo rendering maintains uniform color fidelity across the visual field, disregarding its perceptual non-uniformity at increasing retinal eccentricities. To exploit this perceptual asymmetry, we propose an adaptive chroma modulation technique that preserves full chroma at the fovea and progressively attenuates saturation toward the visual periphery. This strategy is evaluated in real-time rendering with diverse virtual scenes. Through perceptual calibration experiments, we found the color degradation weights [0.70,0.85] for the blue-yellow and [0.35,0.55] for the red-green channel. Within these bounds, theoretical analyses indicate a potential chroma bandwidth reduction of 31–37%.


**Index Terms:** Foveated Color Rendering, Foveated Chroma Attenuation.

## 1 Introduction

Color is the fundamental component of visual perception. However, color sensation is subjective and eccentricity-dependent, and often influenced by different parameters, such as scene brightness and contrast. The neurophysiological evidence indicates the mechanism of color perception degradation as a function of eccentricity. Recent advances in wide-angle VR displays with eye trackers make it possible to exploit this color perception degradation. This opens up some interesting applications for increasing rendering efficiency, reducing bandwidth requirements for wireless transmission, and lowering the power consumption of VR displays [5, 3, 2].

In this study, we present an eccentricity-dependent chroma attentuation model and evaluated whether, with significant degradation weights, the foveated color manipulations are unperceivable compared to uniform color representations (Fig. 1). The primary goal of our study is to bridge the gap in perception-driven color rendering literature by investigating the relationship between perceivable chroma and eccentricity under photopic illumination and natural viewing conditions.

## 2 Background & Related Work

The color signal processing is primarily driven by cone distribution. The cone density is maximum at the fovea, decreases steeply up to 3°, for 3–10° the decrease is less, and in 10°–80° it is very slow [7]. Nonetheless, three cone types are not equally distributed, and the human periphery is comparatively more blue sensitive than red [1].

A large body of work has explored gaze-contingent adaptation to accelerate rendering in VR, predominantly by reducing spatial resolution in the visual periphery [6, 8]. Similar strategies have been investigated for video compression and remote VR streaming, where peripheral detail is reduced to save bandwidth and computation [4]. Nevertheless, these approaches largely ignore eccentricity-dependent color fidelity. More recently, several studies have begun to exploit eccentricity-dependent perception to reduce on-device power consumption, for example by adapting color rendering as a function of retinal eccentricity [5, 2]. To this end, Chen et al. [2] present a systematic comparison of multiple color degradation functions. These efforts, however, focus on power consumption of displays. Extending such perceptually calibrated chroma attenuation to interactive, real-time rendering in VR remains underexplored.

## 3 Methodology

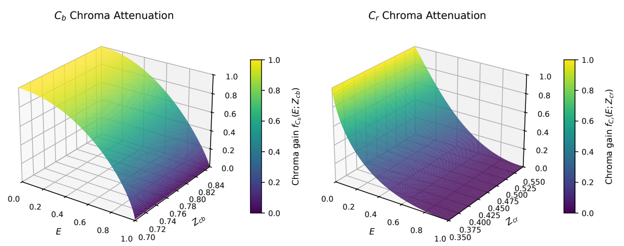
In our chroma attenuation model, eccentricity is mapped to a normalized space, $\hat{E} \in [0,1)$, followed by color-space conversion $I_{RGB}$ to $I_{YC_bC_r}$ to process color opponent channels. Luminance ($Y$) is preserved at high resolution over the entire visual field. The eccentricity dependent chroma attenuation is modelled with a Tukey biweight function (Eq. 1) to the $C_b$ (blue-yellow) and raised cosine function (Eq. 2) to the $C_r$ (red-green) channel.

$$f_{C_b}(\hat{E};Z_{cb}) = (1-\hat{E}^2)^{Z_{cb}}, \qquad 0 \leq \hat{E} < 1. \tag{1}$$

$$f_{C_r}(\hat{E};Z_{cr}) = \frac{1}{2}(1+\cos(\pi\hat{E}^{Z_{cr}})), \qquad 0 \leq \hat{E} < 1. \tag{2}$$

Here, the $Z_{cb}$ and $Z_{cr}$ are the degradation weights. Finally, we convert the modified $YC_b^{\star}C_r^{\star}$ back to $I'_{RGB}$ color-space. In summary:

$$\underbrace{I_{RGB} \rightarrow I_{YC_bC_r}}_{\text{color conversion}} \xrightarrow{(1)(2)} \underbrace{YC_b^{\star}C_r^{\star}}_{\text{foveated chroma attenuation}} \rightarrow \underbrace{I'_{RGB}}_{\text{color conversion}}$$




(a) (b)

Figure 2: Estimated chroma gain with the Eqs. 1 and 2: (Fig. 2(a)), $Z_{cb} \in [0.70, 0.85]$ and (Fig. 2(b)), $Z_{cr} \in [0.35, 0.55]$.

Throughout the user studies (Sec. 4), we determined the degradation weights as $Z_{cb} \in [0.70, 0.85]$ and $Z_{cr} \in [0.35, 0.55]$. With these bounds, we estimate that a theoretical average chroma gain of 31–37% (Fig. 2) is achievable within the identified degradation ranges.

## 4 User Study Design

In order to find degradation weights for our model, we conducted one survey of experts study and two within-subject pilot studies in a controlled laboratory environment. The survey of experts study and *Pilot Study 01* followed a bidirectional Method of Adjustment (MoA) procedure. The *Pilot Study 02* followed a Method of Constant Stimuli (MoCS) procedure. Two participants ($M28$, $M33$) took part in the survey of experts study. Nine participants ($6M, 3F$, age 23-47 years ($\mu$ 31.1, $\sigma$ 7.8)) participated in the pilot studies.

Stimuli. We evaluated six diverse virtual scenes with plausible lighting conditions (Fig. 3).

Software & Apparatus. All experiments were implemented in Unity 6000.0.53f1. During the user study, VIVE Pro Eye VR headset, retrofitted Tobii eye tracker, Intel Core i9 12900Ks processor, and NVIDIA GeForce RTX 3090 GPU were used.

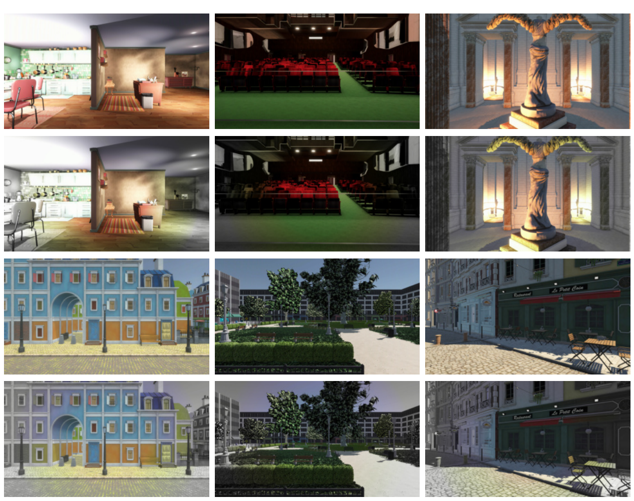


Figure 3: (Left to right) Row 1: Stylized House Interior, Gwangju Theater, Sun Temple with uniform rendering; Row 2: foveated chroma attenuation. Row 3: Modular Victorian City, Emerald Square, Lumberyard Amazon Bistro with uniform rendering; Row 4: foveated chroma attenuation.

Results & Discussion. We analyzed both pilot studies with appropriate descriptive and inferential statistics. Across the pilot studies, participants exhibited substantial tolerance to peripheral chroma attenuation. Nonetheless, the tolerance was chroma channel and content-dependent. In the *Pilot Study 01*, participants converged to stable scene-agnostic central tendencies, with a higher median for $Z_{cb} = 0.70$ than for $Z_{cr} = 0.35$. *Pilot Study 02* showed a similar trend with mean $Z_{cb} = 0.85$ and $Z_{cr} = 0.55$. Additionally, the inferential statistics from both studies signify a tolerance range $Z_{cb} \in [0.70, 0.85]$ and $Z_{cr} \in [0.35, 0.45]$, indicating that participants preserved more blue-yellow color than red-green (Fig. 2). Fig. 3 exhibits a visual comparison between uniform and foveated chroma attenuation.

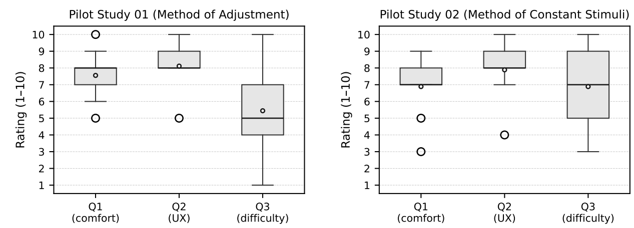



Figure 4: Distribution of questionnaires ratings (Q1=comfort, Q2=UX, Q3=difficulty) for the two pilot studies, following two different adjustment procedures.

At the end of each pilot study, participants completed a post-study questionnaire rating Q1: visual comfort, Q2: user experience, and Q3: experiment difficulty on a 10-point ordinary differential scale. Here, the results show no significant differences between the pilot studies. (Fig. 4).

## 5 Conclusion

Gaze-contingent color rendering offers a powerful but under-exploited opportunity for efficiency gains in VR. Based on the viewer's gaze position, our foveated chroma attenuation dynamically adjusts color fidelity without compromising visual quality. The findings are red-green chroma degradation is steeper than the blue-yellow towards periphery. Moreover, the degradation is mostly scene-dependent.

## References

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