All But Static: Exploring Dynamic Eye Dominance for Foveated Rendering

Franziska Prummer [*]
Lancaster University
Florian Weidner [†]
Lancaster University
Hans Gellersen [‡]
Lancaster University, Aarhus University

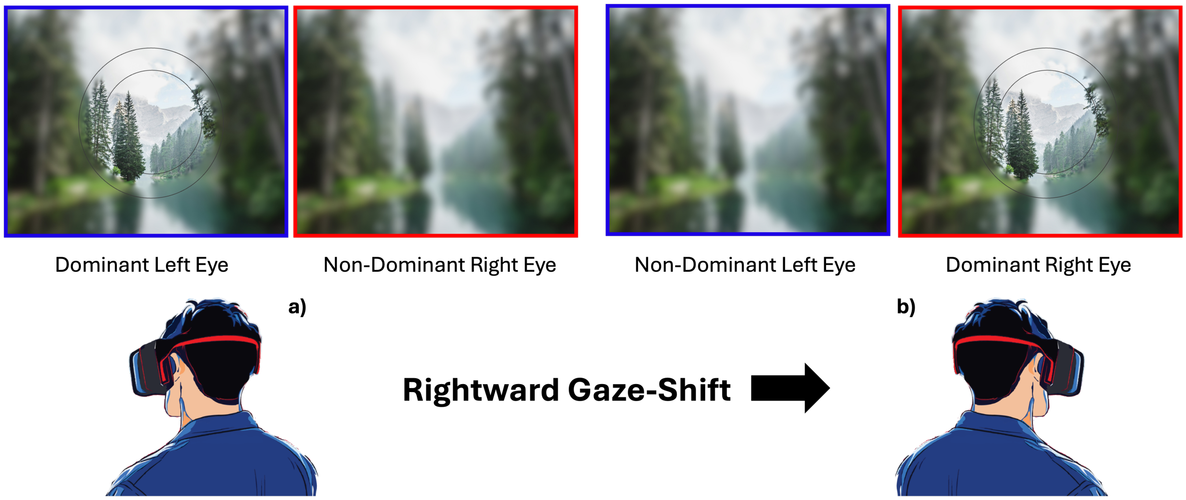

Figure 1: Conceptual illustration of dynamic eye dominance-guided foveated rendering. a) Depicts both eyes' views with the left eye as dominant, rendered at a lower foveation level. b) Shows the shift in eye dominance following a rightward gaze shift, with foveated rendering adjusting to the newly dominant eye.

ABSTRACT

Foveated rendering is a promising technology in virtual and augmented reality (VR/AR), leveraging eye tracking to optimize computational load by rendering high-quality imagery only in the user's gaze direction. Recent advancements have explored using eye dominance, a user's subconscious preference for one eye, to enhance efficiency. So far, methods have treated eye dominance as a fixed trait. Evidence from vision science and psychology suggests it is dynamic and context-dependent. This paper reviews existing research on eye dominance behaviour and its variability, highlighting its implications for VR/AR rendering. Building on these insights, we propose refinements to foveated rendering, incorporating calibration and real-time prediction mechanisms to account for eye dominance variability. By embracing the dynamic nature of eye dominance, these advancements aim to optimize computational performance while maintaining a seamless and personalized user experience in VR/AR applications.

Index Terms: foveated rendering, eye dominance, eye-tracking, AR, VR

1 INTRODUCTION

Today's virtual and augmented reality is predominantly consumed via head-mounted displays (HMDs), and the visual stimulation of both eyes is often the primary means of content display. Research has spent years developing and optimising high-quality and efficient stereo-rendering techniques. Foveated rendering is a technology that reduces the computational load to render images, allowing VR/AR devices to run with higher frame rates, have less powerful components, and lead to prolonged battery life [6, 28]. It relies on eye tracking and, knowing the direction in which the users look, the rendering algorithm computes only a small portion of the visual field in high quality. In contrast, the rest is rendered in lower quality (cf. Figure 1). This is — if done correctly — unnoticeable by the user [28].

Research has optimized foveated rendering by utilizing eye dominance [17, 29]. Eye dominance is the subconscious preference for one eye over the other [20]. Based on research stating that 71% of the population is right-eye dominant and 29% is left-eye dominant [19], computer graphics and HCI research frequently treats eye dominance as a fixed trait analogous to handedness, overlooking its potential variability [17, 24]. In contrast, recent findings from vision science and psychology indicate that eye dominance can exhibit a more dynamic or fluctuating nature, shaped by factors such as handedness [13] or the angle of visual stimulation [23, 15].

Exploiting eye dominance, Meng et al. [17] have shown that rendering content with a lower foveation level and higher detail for the dominant eye significantly enhances rendering efficiency without affecting the user's experience. Thus, observing how eye dominance contributes to rendering efficiency gains is promising. In their work, they once determined the participant's dominant eye and did not change this throughout the experience. However, previous research (especially from psychology and HCI) suggests that eye dominance is not static [13]. Rather, it can change based on various parameters, such as the eye-in-head angle [23].

This dynamic nature of eye dominance may have implications for eye-dominance-guided foveated rendering. On the one hand, treating it as static while it is not might lead to users noticing the low quality of the pre-determined non-dominant eye after a switch. On the other hand, being overly sensitive to switches might also lead to repeated quality switches between the left and right eye, irritating users.

This work discusses how dynamic eye dominance can be imple-

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[*] e-mail: f.prummer@lancaster.ac.uk
[†] e-mail: f.weidner@lancaster.ac.uk
[‡] e-mail: h.gellersen@lancaster.ac.uk

mented into foveated rendering to further optimize eye dominance-guided foveated rendering. We review the existing literature to understand previous findings on how eye dominance behaves and explore how eye dominance can be influenced. Building on these insights, we suggest refining eye dominance-guided foveated rendering, incorporating eye dominance's dynamic and context-dependent nature. We propose three research areas (other factors influencing eye dominance, calibration algorithms, and real-time prediction) and the importance of transition areas.

Our work is relevant in the context of foveated rendering, as optimizing rendering efficiency through precise eye-tracking promises substantial performance improvements and extended battery life — key factors in accelerating the adoption of HMDs. By revisiting the assumptions and implementation of eye dominance, we offer further opportunities for enhancing device performance, adaptability, and user experience. We contribute to a deeper understanding of eye dominance and its implications for advancing gaze-based interactions and optimizing the next generation of HMDs.

2 RELATED WORK

This section outlines the existing body of work. We review studies related to eye dominance, contributions to foveated rendering, and examine the dynamic characteristics of eye dominance.

2.1 Eye Dominance

Eye dominance is the subconscious preference for one eye over another and is fundamental to human perception [3]. It influences our daily interactions: when pointing, we align our finger with the dominant eye; we naturally tilt our head toward it; and it influences horizontal saccades during reading [15, 9, 26]. Typically, eye dominance is determined with tests such as the Miles- or Hole-in-Card test, each dependent on the participant indicating what they see [18, 2]. Furthermore, perceptual differences between the dominant- and non-dominant eye have been documented [21]. Objects are perceived as larger and sharper with the dominant eye, which also exhibits greater contrast sensitivity, with significantly lower contrast thresholds compared to the non-dominant eye [4, 22, 8]. Other studies indicate a higher performance of the dominant eye during various perceptual tasks, such as detecting "the odd element" during visual search [25]. When applying a higher blur towards the non-dominant eye, no perceptual difference was noted [31, 27, 7]. With that, prior research highlights the importance of eye dominance because the non-dominant eye tolerates blurry images, pointing towards the applicability of foveated rendering.

2.2 Foveated Rendering

We perceive high detail only within an approximation of 5° circle at the centre of our visual field [10]. Foveated rendering takes advantage of this aspect of human vision to improve rendering efficiency for VR and AR devices and is undetectable by users [30]. The peripheral vision is rendered at a lower resolution, and the higher resolution is maintained only within the foveal (central) vision [28] (cf. Figure 1). This imperceptible optimization saves computational power and improves hardware performance [30].

Recent advances, like eye-dominance-guided foveated rendering, have further improved computational efficiency [17, 29]. By prioritizing content in the dominant eye, rendering in the non-dominant eye was reduced without compromising the user experience. Using the Miles test [18], Meng et al. [17] and Wang et al. [29] identified the participants' dominant eye before the study. The participants then completed two tests. First, they used a slider to identify the lowest foveation parameter that visually matched a non-foveated reference image. This was done with five scenes, each tested under two conditions: symmetric foveated rendering applied equally to both eyes and asymmetrical foveation adjusted for the non-dominant eye only. In the second test, participants rated the perceptual difference of the foveated rendering between two scenes on a 5-point Likert scale. The authors concluded that the disparity in visual acuity between the dominant and non-dominant eye is significantly different for users, showing that this visual imbalance can effectively be leveraged to optimize rendering. Furthermore, acceptable perceptual quality was achieved with the measured rendering parameters. Finally, eye-dominance-guided foveated rendering found an average speedup of 1.35× compared to original kernel foveated rendering. While not tested in real applications, their results show the benefit of integrating eye dominance into foveated rendering algorithms.

2.3 Factors Influencing Which Eye Is Dominant

Although work by Meng et al. [17] considers eye dominance a static phenomenon, other studies from vision research show that eye dominance shifts can occur, challenging the traditional view of a static dominant eye.

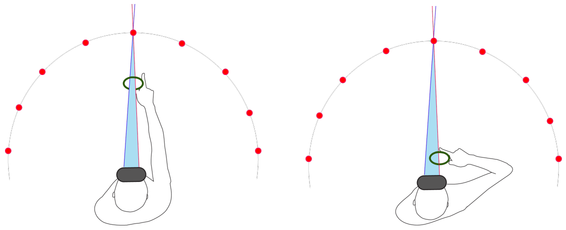
The three factors discussed in the studies are viewing angle, viewing distance, and the hand used in motor movement during classification. Regarding the hand used, three studies demonstrated a possible dependence of eye dominance on the hand engaged in motor movement for classification or pointing, which is independent of the individual's preferred hand [1, 13, 5]. Further, Johansson et al. observed a switch in some participants' eye dominance between near and far testing distances [12]. In addition, recent research demonstrated that a greater viewing distance results in a greater magnitude of sighting dominance [11]. Khan and Crawford investigated the influence of horizontal viewing angles on eye dominance [15, 13]. Changes in eye dominance were observed in participants, depending on where targets were located. On average, switches occurred at a horizontal viewing angle of 15.5°, showing that eye dominance tends to differ at eccentric angles [13]. This does not conform with previous assumptions of an unchanging dominant eye within participants. Here, Prummer et al. [23] confirmed the dynamic nature of eye dominance in a VR setting. Their study replicated the work of Khan and Crawford [16], requiring participants to manually align a virtual cursor with a virtual target at various horizontal viewing angles. This suggests that the assumption that eye-dominance-guided foveated rendering might suffer when the dominant eye changes.

3 SHOWCASING THE DYNAMIC NATURE OF EYE DOMINANCE

Using viewing angle as an example, we highlight idiosyncratic changes in eye dominance in VR. We used data from a previous study by Prummer et al. [23] to showcase participants' dominant eye and dynamic behaviour. Eye dominance was determined using an explicit manual alignment task in a controlled setting by 20 participants (11 male, 8 female, 1 preferred not to indicate gender, M= 31.2 SD= 6.68 years).

In a VR setup, participants used a handheld controller to align a virtual ring with a circular virtual target measuring 3.2423° (Figure 2a). Once aligned, participants moved the controller towards their face while maintaining fixation on the target through the ring. This ultimately resulted in the placement of the ring in front of the dominant eye for the respective trial (Figure 2b). The virtual target was placed 1 meter away from the participants and appeared at pseudo-randomized horizontal angles, ranging from -40° to 40°, at 10° increments. A distance-based classification was used to determine which eye was dominant. The distances between the final ring position and each eye were compared. The shorter distance indicated the placement of the cursor over the dominant eye.

Figure 3 shows data for three individual participants from their dataset. At the outermost angles, participants shifted their dominant eye to achieve a clearer view of those positions. Participant 1 shows right-eye dominance throughout most trials, except at -40°, -30°,



(a) Start of movement.

(b) Final position at the end of alignment task.

Figure 2: Movement stages in the alignment task. (a): Participants fixate on the target and align the ring. (b): The participant moves the ring towards their face while continuing to fixate on the target through the ring.

and -20°, where the left eye dominated. Participant 2 displays a similar behaviour, yet transitioning to right-eye dominance at 0°. Participant 3 shows a tendency for left-eye dominance, shifting to right-eye dominance starting at 20°. These three examples indicate the variability in eye dominance between users and the changes that occur at different horizontal viewing angles.

4 EYE DOMINANCE IN FOVEATED RENDERING

Prior research shows that eye dominance can be leveraged to improve foveated rendering [17]. However, research also shows that assuming a simple static dominant eye does not align with findings that investigate the dominant eye — these works show that the dominant eye changes [13, 23]. This suggests that treating eye dominance as static overlooks opportunities to enhance performance in foveated rendering for AR/VR. However, transferring previous findings into foveated rendering is not trivial, as eye dominance is still an elusive phenomenon influenced by various known and unknown factors. Furthermore, to ensure the effectiveness of foveated rendering techniques, its overhead costs must be justified by the performance benefits it generates. Incorporating eye dominance may cost computing time, which must be carefully managed to maintain overall efficiency.

While it might be enticing to integrate findings from viewing angle into current foveated rendering algorithms, it is, for example, unclear if the target behaviour (e.g., a smooth movement of a target from the far left to the far right) leads to similar eye dominance behaviour than a random switch from any angle on the left hemisphere to any angle of the right hemisphere or if vertical viewing angle is a relevant factor.

Thus, we propose exploring the following research areas:

1. Exploring other factors influencing eye dominance. (subsection 4.1)
2. Development of one-off calibration algorithms and procedures for individual eye dominance. (subsection 4.2)
3. Development real-time eye dominance prediction algorithms for dynamic adaptation of foveated rendering. (subsection 4.3)
4. Integration of transition areas and patterns for eye-dominance-guided foveated rendering. (subsection 4.4)

1.–3. are strategies proposing gathering knowledge about eye dominance to integrate it into foveated rendering algorithms. 4. deals with situations on transitioning foveated rendering when the dominant eye switches or the currently dominant eye is unknown.

4.1 Other Factors Influencing Eye Dominance?

A thorough understanding of eye dominance is necessary to fully integrate eye dominance into foveated rendering algorithms. Otherwise, fully utilizing its potential for the best performance enhancements is impossible. Here, research on other factors leading to switches in eye dominance is necessary. Isolating factors in experimental laboratory studies (e.g., disparity, vertical viewing angle, eye movements) and testing which eye is dominant can provide further insights into eye dominance (similar to previous work such as Prummer et al. [23] or Khan et al. [13, 15]). These findings can then be translated and integrated into eye-dominance-guided foveated rendering.

4.2 One-off Calibration

Prior research has shown that (horizontal) viewing angle is a promising factor influencing eye dominance [23, 14]. Leveraging this, a calibration procedure determining at which angle the dominant eye switches for a user could be a valid basis for user-specific eye-dominance-guided foveated rendering algorithms. This calibration could be performed in addition to the regular eye-tracking calibration during setup. In addition, it could also include other factors, such as target movement or targets at vertical viewing angles.

4.3 Real-time Prediction

Dynamic eye-dominance-guided foveated rendering should, at best, adapt to changes in eye dominance by continuously detecting the users' current dominant eye. Here, a key challenge in developing a dynamic foveated rendering model is detecting the shift from one eye to another. This is not trivial, as there is not yet a detection algorithm for the dominant eye independent of user or context factors. Given the current knowledge, one could build a model that respects one or several factors (e.g., by combining findings about horizontal viewing angle). However, other factors might invalidate these findings (e.g., individual preferences or user-specific acuity differences between both eyes). Thus, having a model that detects the current dominant eye independent of such factors would be ideal. For example, by exploring differences in movements between the two eyes, such an algorithm might be derived, providing input for dynamic eye-dominance-guided foveated rendering.

4.4 Transition Areas

The elegance of foveated rendering is that it is not noticeable to users. Integrating eye dominance might disrupt this. Users might notice the lower quality when the eye the algorithm considers an eye as dominant while it is not the dominant eye (and vice versa). One way to prevent this is to keep the compression level so low that it cannot be detected by the dominant eye. However, this would decrease the efficiency of foveated rendering. Another way is to have transition areas. For example, a prediction algorithm could offer a confidence score. If the confidence is too low, both eyes could see images from regular foveated rendering algorithms. Similarly, a calibration procedure or simple heuristics could define transition areas where the calibration or heuristics cannot accurately determine a dominant eye. With that, foveated rendering algorithms could rely on eye dominance in certain areas, increasing performance. In contrast, regular foveated rendering takes over in areas where the dominant eye is unknown or ambiguous.

5 CONCLUSION

This work examined the role of dynamic eye dominance in optimizing foveated rendering for VR/AR applications. Although current approaches often treat eye dominance as static, research indicates it varies with factors such as viewing angles and handedness. Ignoring this variability risks disruptions to user experience, while overreacting to shifts may lead to unnecessary rendering adjustments.

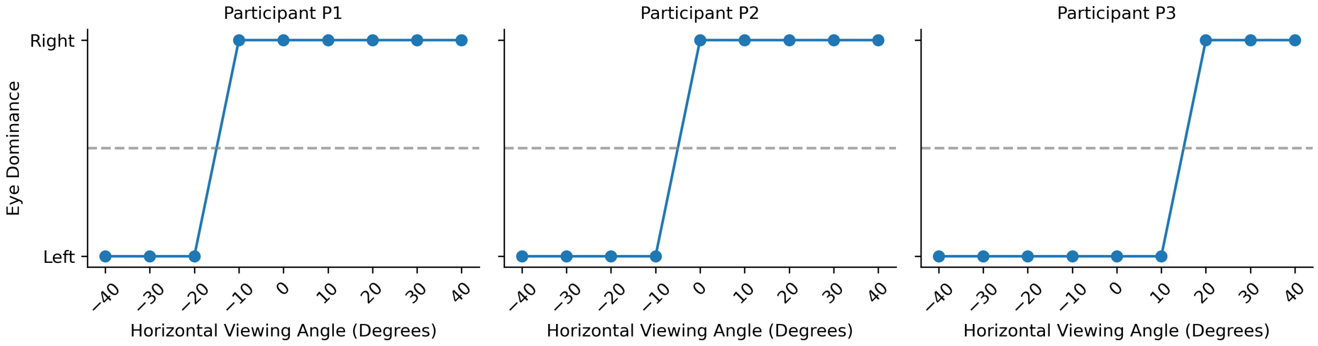


Figure 3: Individual participants' data showing changes in eye dominance from left to right and vice versa at different horizontal viewing angles.

To address these challenges, we proposed three key directions for future research: exploring factors influencing eye dominance, developing user-specific calibration methods, and implementing real-time prediction mechanisms. By integrating these elements, foveated rendering can achieve greater adaptability, improving computational efficiency while maintaining seamless visual experiences. This approach promises to enhance rendering systems and opens pathways to more personalized and context-sensitive VR/AR technologies.

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