Gaze-Contingent Ocular Parallax Rendering for Virtual Reality

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ABSTRACT

Current-generation virtual reality (VR) displays aim to generate perceptually realistic user experiences by accurately rendering many perceptually important effects including perspective, disparity, motion parallax, and other depth cues. We introduce ocular parallax rendering, a technology that renders small amounts of gaze-contingent parallax capable of further increasing perceptual realism in VR. Ocular parallax, small depth-dependent image shifts on the retina created as the eye rotates, occurs because the centers of rotation and projection of the eye are not the same. We study the perceptual implications of ocular parallax rendering by designing and conducting a series of user experiments. We estimate perceptual detection and discrimination thresholds for this effect and demonstrate that it is clearly visible in most VR applications. However, our studies also indicate that ocular parallax rendering does not significantly improve depth perception in VR.

CCS CONCEPTS

• **Computing methodologies** → **Mixed / augmented reality**; **Perception**; **Virtual reality**.

KEYWORDS

computational displays, virtual reality, augmented reality, eye tracking, gaze-contingent rendering

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1 INTRODUCTION

Immersive computer graphics systems, such as virtual reality (VR) displays, aim at synthesizing a perceptually realistic user experience. To achieve this goal, several components are required: interactive, photorealistic rendering; a high-resolution, low-persistence, stereoscopic display; and low-latency head tracking. Modern VR systems provide all of these capabilities and create experiences that support many, but not all, of the monocular and binocular depth cues of the human visual system, including occlusions, shading, binocular disparity, and motion parallax. The support of focus cues, i.e. accommodation and retinal blur, has also received attention in research and industry over the last few years. In this work, we study a depth cue of human vision that has not been discussed in the context of virtual reality and that may help further improve depth perception and perceptual realism: ocular parallax.

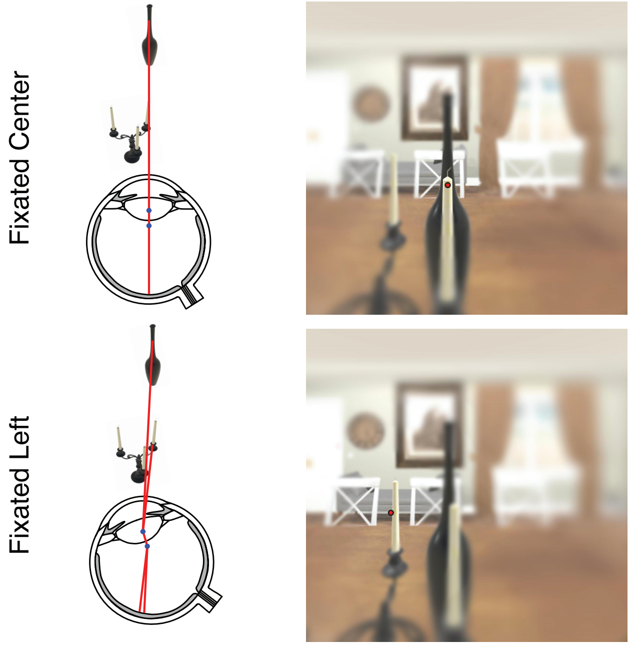

Figure 1: The centers of rotation and projection of the eyes are not the same; small amounts of parallax are created on the retina as we fixate on different objects. The nodal points of the eye, representing the center of projection, are shown as small blue circles on the left along with a ray diagram illustrating the optical mechanism of ocular parallax. Simulated retinal images accounting for the falloff of acuity in the periphery of the visual field are shown on the right. As a user fixates on the candle in the center of the scene (top, red circle indicates fixation point), the bottle is partly occluded by the candle. As their gaze moves to the left, ocular parallax reveals the bottle behind the candle in the center (bottom).

This monocular depth cue creates small amounts of depth-dependent image shifts on our retina (Figure 1) because the centers of rotation and projection in the human eye are not the same (Figure 2, top). They are separated by about 7.6 mm [Atchison 2017]. This depth cue was first described by Brewster [1845] and has been demonstrated to produce parallax that is well within the range of human visual acuity [Bingham 1993; Hadani et al. 1980; Kudo and Ohnishi 1998; Kudo et al. 1999; Mapp and Ono 1986]. Interestingly, species as diverse as the chameleon and the sandlance critically rely on this cue to judge distance [Land 1995; Pettigrew et al. 1999].

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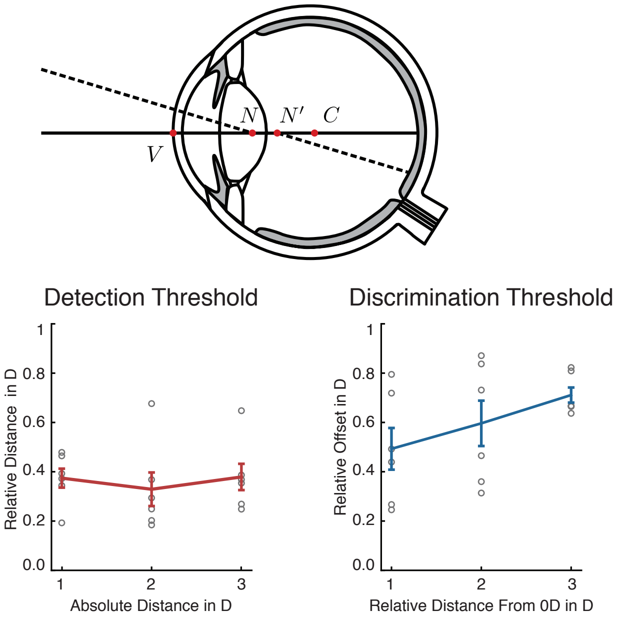

Figure 2: (Top) Illustration of a schematic eye, including the front and rear nodal points N, N', the center of rotation C, and the anterior vertex of the cornea V. The nodal points are two parameters of a thick lens model that refracts light rays as depicted. (Bottom) Detection and discrimination thresholds for ocular parallax in VR measured with two psychophysical experiments using an HTC Vive Pro head mounted display augmented with a Pupil Labs eye tracker.

2 OCULAR PARALLAX IN VR

Rendering ocular parallax into a VR experience requires eye tracking. Conveniently, many emerging display systems already integrate eye tracking, either to support foveated rendering [Guenter et al. 2012; Patney et al. 2016], accurate registration of physical and digital images in AR, or other gaze-contingent display modes [Padmanaban et al. 2017]. We introduce ocular parallax rendering as a new gaze-contingent rendering mode. The user's gaze determines each eye's nodal point which is then used to modify the view and projection matrices of the standard graphics pipeline. Ocular parallax rendering does not incur additional computational cost.

With ocular parallax rendering enabled, eye rotations induce tiny amounts of depth-dependent "micro parallax" into the retinal image. This gaze-induced parallax not only shifts objects but also affects occlusion, one of the strongest visual cues [Cutting and Vishton 1995], as structures may be revealed during eye rotation. However, the amount of depth-dependent motion induced by ocular parallax rendering increases in the periphery of the visual field, where visual acuity is lower than on the fovea. Moreover, the resolution offered by current-generation VR/AR displays is well below the visual acuity of human vision and it is not clear if this subtle effect is even perceptible in VR at all.

As such, we implement and evaluate ocular parallax rendering with a prototype virtual reality system: an HTC Vive Pro augmented with the open source binocular Pupil Labs eye tracker. We first perform two psychophysical experiments measuring the depth-dependent detection and discrimination thresholds for ocular parallax in VR (Figure 2, bottom), determining whether this effect is perceivable in current generation VR systems. For an eccentricity of 15°, we measured that users could detect ocular parallax between two objects spaced only 0.36 D (inverse meters) apart and found that this threshold was invariant to the absolute distance of the objects, consistent with Bingham [1993]. The measured discrimination thresholds, or the smallest amount of perceivable change, increases linearly with the amount of observed ocular parallax, consistent with Weber's law. The measured detection and discrimination thresholds are well within the range of the depths found in typical VR applications.

We further investigate whether ocular parallax rendering has the potential to serve as an additional depth cue in virtual scene understanding. Through an egocentric depth perception study and a subjective ranking evaluation of 3D scene understanding we find that this might not necessarily be case, suggesting that ocular parallax rendering may not improve depth perception in VR.

3 CONCLUSION

Virtual and augmented reality systems have focused on improving resolution, field of view, device form factor, and other characteristics. With the introduction of ocular parallax rendering, we hope to stimulate new directions for gaze-contingent rendering and improve perceptual realism with next-generation near-eye displays.

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