Effects of Visual Depth on Vergence–Accommodation Conflict in Gaze- and Controller-Based Selection in Virtual Reality

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Abstract

The vergence–accommodation conflict (VAC) in stereoscopic head-mounted displays is known to affect depth perception and interaction performance. Prior studies have examined its impact on a controller, but it remains unclear how the VAC affects gaze pointing in Virtual Reality. Here, we investigate Gaze- and Controller-based 3D target selection under varying depth conditions. Results show that Gaze is more prone to depth variation, exhibiting longer movement times, higher variability along the task axis, and lower throughput than Controller-based interaction. Fitts' law modeling with a "*Variation in Diopter*" term further indicates greater depth-dependent variability for gaze input. Despite these differences, perceived usability and workload were comparable. These findings suggest that the VAC affects pointing modalities differently, which should be considered when designing gaze-enabled 3D interfaces.

CCS Concepts

• **Human-centered computing → Pointing**; **Virtual reality**; **Human computer interaction (HCI)**.

Keywords

Virtual Reality, Vergence-Accommodation Conflict, Stereo Deficiencies, Distal Pointing, Fitts' Law, Gaze Interaction

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1 Introduction

Selection is a fundamental interaction task in Virtual Reality (VR) [30] which often requires users to judge the distance of objects from oneself, and act upon the corresponding spatial relationships. Thus, selection performance is closely tied to how depth is represented by the display and perceived by the user [29, 50], potentially subject to depth cue conflicts.

A well-known limitation of modern VR head-mounted displays (HMDs) is the vergence–accommodation conflict (VAC) [1, 42]. For humans, vergence and accommodation are coupled in the real world: the eyes rotate to and focus at the same physical distance. In contrast, most current VR systems use stereoscopic displays at a fixed focal plane to present virtual objects at varying depths. This mismatch forces users to accommodate to the display plane while (con-)verging to different virtual depths, introducing the VAC [4, 47, 55]. Prior work has shown that the VAC can impair depth perception, increase visual discomfort and fatigue [25, 32, 37], and, in turn, degrade 3D selection performance [7, 9].

However, existing work on VAC and interaction has almost exclusively studied the effect of the VAC on hand-based selection techniques, e.g., with controllers or virtual hand [6, 9, 13]. Yet, this overlooks an important aspect of selection: users implicitly *visually* fixate on a target before selecting it [32, 40, 41]. In other words, gaze plays a crucial role in target acquisition, even with controller-based input, and it remains unclear whether the VAC's effects translate into gaze-based selection performance. Thus, we investigate the related open question: *how does the vergence–accommodation conflict affect selection performance when gaze is used as the primary pointing modality?*

To address this question, we present a user study in VR where participants performed a 3D target selection task under various depth conditions using two pointing modalities: controller-based raycasting and gaze-based pointing. Our main contribution here is to investigate the selection performance across input modalities and depths, to better understand how VAC-related effects interact

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with pointing techniques and to inform the design of gaze-based 3D interfaces.

2 Related Work

Human depth perception relies on a combination of pictorial and non-pictorial cues, including binocular disparity, motion parallax, vergence, and accommodation [20]. In natural viewing, vergence and accommodation are tightly coupled: as the eyes rotate to fixate objects at different depths, they simultaneously adjust focus to bring the objects into clear view. Most stereoscopic HMDs, however, present virtual content at a fixed focal distance while simulating depth via binocular disparity [55], thereby decoupling the two and producing the VAC [29]. The VAC can impair depth perception and visual stability [9, 25], leading to reduced depth discrimination accuracy, increased visual discomfort [19, 45], and altered vergence dynamics such as increased latency and overshoot [9, 51].

Several studies have shown that the VAC not only affects perception but also degrades 3D interaction performance, particularly in 3D pointing tasks [7, 9, 22]. Barrera and Stuerzlinger [6] demonstrated that pointing movements involving depth changes are significantly slower than lateral movements when using stereoscopic displays, suggesting that limitations in depth perception directly impact interaction [5]. Subsequent studies extended these findings by confirming that depth-axis movements yield lower throughput and increased correction behavior compared to lateral ones [11, 13]. Other works on ray-based pointing techniques similarly found that changes in target depth negatively affect selection performance [7, 11, 13]. Importantly, most of these studies evaluate interaction using manual pointing techniques, such as raycasting or virtual hand interaction [7], where VAC-related effects manifest primarily through changes in manual motor behaviour, including longer ballistic phases and increased corrective movements [52].

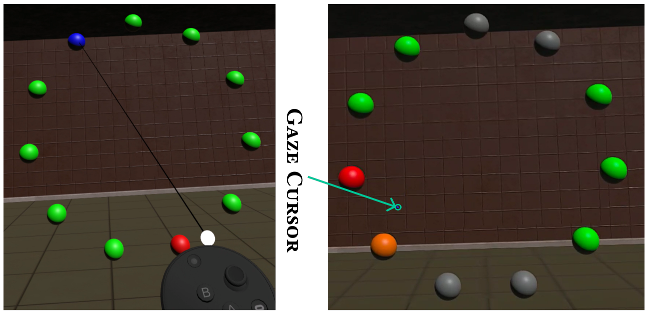
One area that has not been studied regarding the effect of the VAC on interaction is gaze-based target selection. Gaze-based pointing has recently gained attention in 3D and immersive environments [39, 43, 44], as it offers potential advantages over controller-based pointing, including reduced physical effort, faster target acquisition, and more direct alignment between attention and selection [41, 48, 54]. In gaze-based interaction, eye fixation is used to indicate a target, while selection is typically confirmed through dwell or a physical action such as a button press or pinch gesture [38, 41]. While vision research has examined how the VAC affects vergence stability and eye movement behaviour [4, 25], gaze is typically treated as a dependent measure rather than as an input modality for interaction. Yet, the VAC has also been shown to cause unstable or oscillatory eye movements when users fixate objects at depths far from the focal plane [21, 49]. Consequently, it remains unclear how the VAC influences gaze-based target selection performance, or how such effects compare to those observed with manual, controller-based pointing techniques.

3 User Study

Participants and Apparatus: We recruited 24 participants (12 female, 12 male), aged 23-32 years ($\mu = 26, \sigma = 2.06$), following established guidelines [3, 14]. Except for three, all were right-handed. 17 had normal vision, while others had corrected-to-normal vision. Nine participants had never used VR, three 1–5 times, and twelve more than five times. Only three had experience with gaze pointing. Participation was voluntary, and no compensation was provided.

The experiment was run on an Intel® i9-13900KF (3.0 GHz), 32 GB RAM, and NVIDIA GeForce RTX 4070 GPU PC. We used an Oculus Quest Pro HMD (focal distance: 1.3 m [18]) with a 106° horizontal × 96° vertical field of view. The virtual environment was created in Unity and displayed via Meta Quest Link.

Procedure: Following consent, participants completed a demographics questionnaire. An experimenter then explained the procedure and assisted participants with donning the VR HMD and eye tracking calibration. For the controller condition, they were instructed to hold the controller with their dominant hand and to avoid overly extending their arm to facilitate comfortable selection of nearby targets. A spherical cursor (0.5 cm diameter) was displayed at the intersection point with the scene geometry in both conditions. In the controller condition, the cursor followed a virtual ray rendered from the tip of the controller, while in the gaze condition, it followed the user's gaze direction (Figure 1). With the controller, participants confirmed selections by pressing the space bar using their non-dominant hand on the keyboard placed in front of them, which avoids the "Heisenberg effect" [15]. For gaze, participants confirmed selections using a dominant-hand pinch gesture. Prior work had shown that pinch and click confirmation yields comparable performance and typically outperforms dwell [41]. Thus, the confirmation methods were chosen to minimize motor interference while maintaining comparable selection performance across modalities.



(a) (b)

Figure 1: The view inside the headset during the task. (a) User pointing with the controller. (b) User pointing using gaze. The gaze cursor appears smaller and less visible in this captured image due to rendering and capture differences, but in the virtual environment, it was clearly visible.

Following prior work [7, 10, 13], we employed a multidirectional selection task based on ISO 9241-411 [26]. The indices of difficulty, selection procedure, and used feedback followed Bashar et al. [7]. Targets were scaled to maintain a constant visual angle across depth conditions, with minor adjustments for the Quest Pro's focal plane. Participants were seated throughout the study, and the targets always appeared directly in front of them. The seated posture increased comfort, and no noticeable arm fatigue was observed. Still, participants were offered breaks between rounds, but none chose to

Table 1: Repeated Measures ANOVA Results.

	Depth	ID	Depth * ID
Movement Time	**$F(3, 69) = 8.527$, $p < .001, \eta_p^2 = .270$**	**$F(2.14, 49.31) = 173.653$, $p < .001, \eta_p^2 = .883$**	$F(10.14, 233.21) = 0.818$, $p = .613, \eta_p^2 = .034$
Error Rate	$F(3, 69) = 0.285$, $p = .836, \eta_p^2 = .012$	**$F(3.83, 88.11) = 34.778$, $p < .001, \eta_p^2 = .602$**	$F(10.14, 233.21) = 0.818$, $p = .613, \eta_p^2 = .034$
Throughput	**$F(3, 69) = 6.152$, $p < .001, \eta_p^2 = .211$**	**$F(4.86, 111.89) = 43.900$, $p < .001, \eta_p^2 = .656$**	F(9.86,226.88) = 1.366, $p = .129, \eta_p^2 = .056$
SD_x	**$F(3, 69) = 80.805$, $p < .001, \eta_p^2 = .778$**	**$F(4.02, 92.47) = 17.650$, $p < .001, \eta_p^2 = .434$**	$F(9.49, 218.32) = 1.527$, $p = .135, \eta_p^2 = .062$

take one. After completing the task, participants filled out the System Usability Scale (SUS) [16] and NASA-TLX [24] questionnaires. The experiment lasted about 25–30 minutes in total.

Experimental Design: We employed a within-subjects experimental design with two independent variables: *Pointing Modality* (Controller and Gaze) and *Depth*, expressed in diopters (0.75 D, 1.0 D, 1.25 D, and 1.5 D), corresponding to viewing distances of 1.33 m, 1.00 m, 0.80 m, and 0.66 m, respectively, given the focal distance of the HMD [7]. Targets were presented at four virtual distances centered around the VR HMD's fixed focal plane, selected to investigate the depth variation while maintaining stable gaze tracking and interaction conditions. This reduced depth range allowed us to focus on conditions where VAC effects and gaze stability are most pronounced (closer to the focal plane) [6]. Condition order was counterbalanced across participants. Dependent variables followed those used in prior depth-aware pointing studies [7].

4 Results

We analyzed the data using two-way repeated measures ANOVA. Normality was assessed using skewness and kurtosis (±1 threshold) [23, 36]. For dependent variables violating normality, data were log-transformed; if normality was still not met, that dependent variable was analyzed using an Aligned Rank Transform (ART) prior to ANOVA [31, 53]. Post-hoc comparisons used the Bonferroni method. Figures illustrate the mean in the graphs, and error bars represent the standard error of the mean. For *brevity*, only significant results (Table 1) are reported.

Movement Time (MT): Movement time differed significantly between pointing modalities across all *Depth* conditions, $F(3, 69) = 8.527$, $p < .001$, $\eta_p^2 = .27$. Gaze resulted in significantly longer movement times than Controller at every depth, see Figure 2a. For Gaze, movement time decreased monotonically as targets were presented at closer depths (higher diopter values). In contrast, Controller showed comparatively smaller variations across depth. Post-hoc results showed selection was significantly slower at the focal plane (0.75 diopter) than all the other depths, especially for Gaze, indicating a strong VAC effect. Additionally, the Index of Difficulty (**ID**) had a significant effect: tasks with higher ID values took more time, consistent with Fitts' law.

Throughput: Throughput was consistently higher for Controller than Gaze across all *Depth* conditions, $F(3, 69) = 6.152$, $p < .001$, $\eta_p^2 = .211$. Controller throughput remained relatively stable across depths (Figure 2b). In contrast, Gaze throughput was lowest at farther depths (lower diopter values) and increased as targets moved closer to the user, reaching its highest values at the nearest *Depth* condition. Significant differences were observed between modalities at all depths, as well as between *Depth* conditions for Gaze. The ID results were also significant, where lower throughput was observed for a higher ID.

SD_x: We observed a similar trend in participants' selection accuracy along the task axis. Gaze exhibited significantly higher SD_x than Controller at all depths, $F(3, 69) = 80.805$, $p < .001$, $\eta_p^2 = .778$ indicating reduced pointing stability. For both modalities, SD_x was highest at farther depths (lower diopter values) and decreased as targets were presented closer to the user (higher diopter values). This reduction was substantially larger for Gaze than Controller. Multiple significant differences were observed both across *Depth* conditions and between pointing modalities (Figure 2c). The interaction between *Depth* and ID was also significant, suggesting that the effect of depth on SD_x depends on the *ID*.

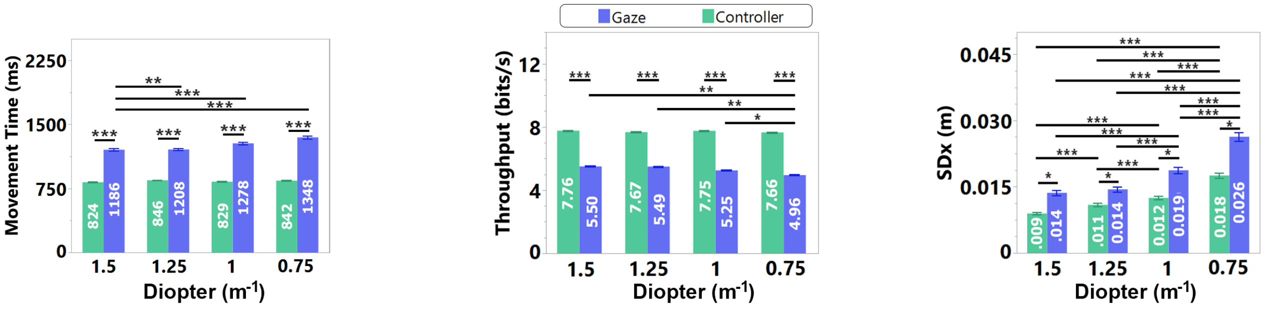
Fitts' law: The results of a Fitts' law [33] linear regression (with the Shannon formulation using angular sizes [3, 28]) showed a strong fit for Controller across all depths individually and mixed ($R^2 > 0.97$). In contrast, the model fit for Gaze degraded, particularly in the mixed-depth analysis, as shown in Figure 3 and Table 2. To further examine this, we applied Bashar et al.'s [7] "*Variation in Diopters*" (*ViD*) model. The results showed a substantially improved model fit using the *ViD* model compared to the Shannon formulation ($\Delta AIC > 10$) [2, 17, 27] across both individual and mixed-depth conditions for both Gaze and Controller.

SUS and NASA-TLX: Participants reported comparable usability and workload for both interaction techniques. Mean SUS scores were **80.31** ($\sigma = 11.92$) for Controller and **74.69** ($\sigma = 18.61$) for Gaze; a Wilcoxon test indicated no significant difference ($Z = -0.853$, $p = .394$). Similarly, overall NASA-TLX and its subscales showed no significant differences between Controller and Gaze ($Z = -0.543$, $p = .587$).

5 Discussion, Limitations, and Future Work

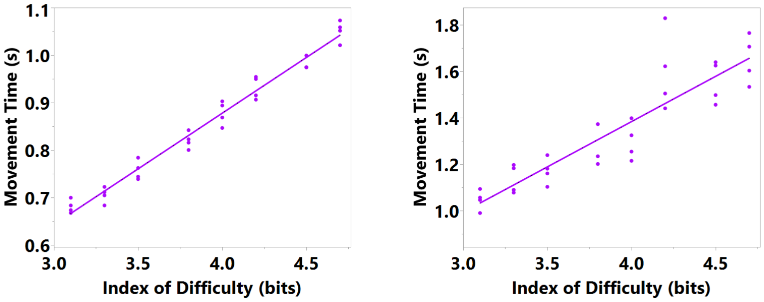
In this paper, we investigated how the vergence–accommodation conflict (VAC) affects 3D target selection with Gaze as the pointing modality, and compared it against Controller pointing using raycasting. Using a multidirectional selection task, we evaluated performance across multiple *Depth* conditions and analyzed both behavioral measures and depth-aware Fitts' law models.

Our results show that Gaze pointing is more sensitive to depth variations than Controller pointing. Across movement time, pointing precision and stability along the primary task axis (SD_x), and



(a) (b) (c)

Figure 2: Effects of target depth (expressed in diopters, i.e., 1/depth) and pointing modality on (a) movement time, (b) throughput, and (c) selection accuracy along task axis (SD_x). Results are shown for Gaze (blue) and Controller (green) pointing. Horizontal bars denote significant pairwise comparisons ($^{*}p < .05$, $^{**}p < .01$, $^{***}p < .001$).



(a) (b)

Figure 3: Fitts' law linear regression [34] for a) Controller and b) Gaze pointing across all *Depth* conditions in a mixed manner.

Table 2: Model fit results for Gaze and Controller across all *Depth* conditions in a mixed manner.

Model	Interaction	parameters	R^2	AIC
$MT = a + b \cdot ID$ [33]	Gaze	$a = -0.175$, $b = 0.389$	0.79	-48.94
	Controller	$a = -0.061$, $b = 0.234$	0.97	-155.62
$MT = a + b \cdot ID + c \cdot e^{f * \lvert ViD \rvert}$ [7]	Gaze	$a = -0.257$, $b = 0.389$, $c = 0.186$, $f = -3.029$	0.91	**-153.65**
	Controller	$a = -0.686$, $b = 0.234$, $c = 0.628$, $f = -0.014$	0.98	**-244.31**

throughput performance varied more strongly with depth for Gaze, whereas Controller remained comparatively stable. More specifically, gaze-based selection exhibited longer movement times, higher SD_x values (indicating reduced pointing precision and stability), and lower throughput, with pronounced improvements as targets were presented at closer depths. These effects were also reflected in the *ViD* [7] modeling results, where Controller was well described by a single parameterization across depths, while Gaze showed greater variability, with higher Akaike Information Criterion (AIC) [2] and Bayesian Information Criterion (BIC) [46] values.

These findings suggest that the VAC manifests differently depending on the input modality. For Controller interaction, depth-related perceptual uncertainty may be partially compensated by motor control and online corrective movements [6, 12]. In contrast, when Gaze is used for pointing, VAC-related oculomotor instability–such as reduced fixation precision or increased variability in eye movements–directly impacts pointing precision along the task axis, leading to higher SD_x and longer movement times. Prior work has shown that gaze-based interaction exhibits a learning effect, with performance improving as users adapt to the unfamiliar (and noisy) interaction technique [35, 39]. Limited familiarity with gaze interaction among our participants may therefore lead to increased selection variability due to less stable fixations and suboptimal coordination between gaze and confirmation actions. Also, the VAC is known to affect vergence stability and accommodation dynamics, particularly for inexperienced users who may require longer adaptation periods. Limited gaze experience, combined with VAC-related oculomotor demands, thus likely also amplified performance variability in gaze-based pointing, contributing to increased movement time and SD_x in our study. Still, despite these objective differences, participants reported comparable usability and workload for gaze-based and controller-based interaction.

In addition to the behavioral measures, our modeling results provide further insight into how depth and VAC affect different pointing modalities. Using the widely adopted Shannon formulation of Fitts' law [3, 33], we observed a strong fit for CONTROLLER pointing but a degraded fit for GAZE pointing, particularly when data were pooled across multiple depth conditions. This suggests that a depth-agnostic formulation is insufficient to capture gaze-based performance when targets span different virtual depths, where VAC-related effects vary systematically [6, 7, 9]. By contrast, applying the "*Variation in Diopters*" (*ViD*) model [7] yielded substantially improved fits for both CONTROLLER and GAZE condition, as reflected by lower AIC and BIC values. These results indicate that explicitly modeling depth in diopters allows the *ViD* formulation to account for VAC-related challenges that influence selection performance. In particular, the *ViD* model captures how changes in visual depth modulate the speed–accuracy relationship, making it more suitable than traditional Fitts' law formulations for analyzing 3D pointing tasks under depth variation [3, 8]. Together, these findings suggest that depth-aware models, such as *ViD*, are better suited for future studies of 3D interaction in VR, especially when gaze-based input is involved, and VAC-related effects cannot be overlooked.

Our findings also have direct implications for gaze-based interaction design in immersive environments. Because gaze pointing performance varies significantly with depth, selectable interface elements should be placed within a narrow depth band to minimize VAC-related variability. Designers should also be cautious when using gaze for distal interaction, since gaze-based pointing is more sensitive to depth-induced visual changes than with the controller, which is comparatively stable and may be better suited for tasks spanning varied distances. Finally, the better fit of depth-aware formulations such as the *ViD* model highlights the importance of incorporating explicit depth parameters when evaluating or predicting gaze-based interaction performance in 3D environments.

Limitations include the use of a single fixed-focus VR headset, and thus, the results may not generalize to display technologies that mitigate the VAC, such as varifocal or multifocal systems. Also, we focused on a controlled multidirectional target selection task, which enables comparison with prior work but may not fully reflect more complex, real-world gaze-based interactions. Finally, although our depth range was chosen to maintain controlled and reliable gaze interaction, broader depth ranges and longer exposure times may reveal additional effects related to adaptation and fatigue. Although the investigated depth range may seem relatively near, it reflects typical placement distances for floating menus and workspace elements in modern VR, which are often positioned around the focal point of HMDs for better visibility and comfort. Because VAC-related effects are already evident within this moderate range, future work should examine further targets and multi-plane environments to determine how gaze and controller pointing scale under larger depth separations.

While gaze-based pointing consistently exhibited degraded performance compared to controller-based pointing, results do not necessarily imply fundamental limitations of gaze input. Instead, they highlight an important gap in our understanding of how gaze-based interaction evolves with experience and adaptation under VAC. Future work should investigate gaze-based pointing with extended training periods and repeated sessions to assess learning effects, oculomotor adaptation, and improvements in gaze–confirmation coordination. Such studies are necessary to determine whether the observed performance costs persist with expertise or diminish as users become more proficient with gaze interaction.

6 Conclusion

We examined how vergence-accommodation conflict influences 3D target selection with gaze versus controller pointing. Our results show that gaze pointing is more sensitive to depth variation, with degraded movement time, pointing precision, and throughput. Depth-aware Fitts' law modeling further indicates that traditional formulations are insufficient across mixed depths, while the *ViD* model better captures depth-dependent performance. These findings highlight that the VAC affects pointing modalities differently, and also emphasize the importance of considering depth-aware modeling when designing gaze-enabled 3D interfaces.

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