Re-investigating the Effect of the Vergence-Accommodation Conflict on 3D Pointing

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ABSTRACT

The vergence-accommodation conflict (VAC) limits user performance in current Virtual Reality (VR) systems. In this paper, we investigate the effects of the VAC in a single-focal VR system using three experimental conditions: with no VAC, with a constant VAC, and with a varying VAC. Previous work in this area had yielded conflicting results, so we decided to re-investigate this issue. Eighteen participants performed an ISO 9241:411 task in a study that closely replicates previous work, except that the angle of the task space was rotated 20 degrees downward, to make the task less fatiguing to perform, which addresses a potential confound in previous work. We found that the varying VAC condition had worse performance than the other conditions, which indicates that the contrasting results in previous work were very likely due to biomechanical factors. We hope that our work contributes to the understanding of the influence of the VAC in VR systems and potential strategies for improving user experience and performance in immersive virtual environments.

CCS CONCEPTS

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

KEYWORDS

3D pointing, Fitts' Law, VR, vergence-accommodation conflict

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1 INTRODUCTION

In the last couple of years, companies like Meta, Varjo, and HTC[1] have released high-definition Virtual Reality (VR) and Augmented Reality (AR) Head-Mounted Displays (HMDs). Despite the associated technological advances such as a reasonable field-of-view (FOV), high resolution, and low latency, these devices still suffer from the vergence-accommodation conflict (VAC). The VAC is caused by how the technology underlying modern HMDs renders content in stereo. Stereo displays show two different images to the users' eyes from viewpoints that correspond to the eye positions in a human head. Each image is displayed at a fixed plane by the HMD (as determined by the lens system). When displaying 3D content that is not at the same visual depth as such fixed plane, the user is exposed to a mismatch between focusing on the display plane (accommodation) and rotating the eyes to see the object at its correct visual depth (vergence). This problem does not happen with targets in the real world, and previous work has identified that the VAC affects depth perception [21, 23], visual fatigue [3, 29], the overall performance of the visual system [26, 30, 55] and the cognitive load of the user [19].

Further, the VAC also affects interaction when pointing at 3D targets in peri-personal space, i.e., within arm's reach, usually less than 1 m away from the user [6, 7, 11]. This previous work identified that the VAC affects depth movements in both large stereo displays [4, 6] and VR/AR HMDs [11]. This effect is also present for other types of pointing, such as pointing at distal targets [9]. Yet, previous work that aimed to verify if the VAC affects pointing movements with virtual hands at targets within arms' reach did not reach the same conclusion [10]. In contrast to all other results in this domain, this study [10] found that a condition with a constant VAC (i.e., where the targets were not positioned at the focal point of the display system) exhibited a better user performance than conditions either without the VAC (i.e., with targets positioned at the focal plane of the display system) or with a varying VAC (i.e., where targets alternate between the focal plane of the display system and away from it). Based on these inconsistent outcomes of previous work on 3D pointing in peripersonal space, we realized a necessity to investigate some of the potential confounds that could affect interaction and their relationship with the VAC further.

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[1] https://www.meta.com, https://varjo.com, https://www.htc.com

When comparing the results of Batmaz et al. [10] to previous work, we identified four main factors that might have affected the user performance and caused the different results compared to the previous findings in the literature: *task, display system, input device, and grip style.* For an overview of this comparison, see Table 1. First, the experiments used different tasks, i.e., left-right and back-forward movements versus multi-directional selection. Second, they use different display systems, i.e., custom-built laboratory displays versus commercial displays. Third, they use different input devices, i.e., a HTC Vive controller versus a custom-made wand. Finally, the participants used different grip styles, i.e., a power grip versus a precision grip. One common thread among these factors is that the mechanics of the 3D pointing movements and different devices can affect user performance. Yet, the relationship between these factors and the VAC is under-explored, as most previous work has focused on either one of the topics in isolation.

The main motivation of this study is to investigate the interaction between the VAC conditions and movement biomechanics. We focus on two issues: 1) the effect of target distance to the user, as previous work found that hard-to-reach targets decrease user performance [2], and 2) the position where the controller is held, as previous work found that both the spatial position of the controller with respect to the user body and the hand grip style affect interaction [12, 35]. To investigate this, we conducted an experiment with 18 participants based on Fitts' law, where we closely replicated a previous study [10], yet rotated the target configuration downwards relative to the line of sight, to make further targets easier to reach [36]. Our results identify that biomechanics and/or fatigue are the most likely explanations for the contrasting results in said previous study [10]. Our results thus replicate and extend previous work [7–9], but also critically identify that their findings are influenced by the biomechanics of the reaching motions and the way the participant held the controller. In this paper, our main contribution is **for targets within arm's reach, demonstrating the interaction of the VAC and human bio-mechanical limitations in VR HMDs, for both virtual hand and raycasting interaction.**

2 PREVIOUS WORK

This section discusses ways to measure human performance for 3D selection. Then we review the effect of the VAC and biomechanics on 3D pointing.

2.1 3D pointing

We focus on 3D pointing, where the user points to a target in space before they select it, e.g., by pressing a button or making a gesture. Previous work found that Fitts' Law [25] predicts the 3D pointing movement time (MT), i.e., the time between the start of a movement and the (successful) selection of a target. Yet, due to the different hand movements used in different interaction techniques, different formulations of Fitts' Law apply [34]. Here we present the formulations relevant to the virtual hand and raycasting techniques.

Shannon Formulation of Fitts' Law: The *virtual hand technique* enables users to point at a virtual target by intersecting it with an input device or their bare hand. Thus, this technique is only useful for nearby targets, i.e., within arms' reach. As there is no consensus around 3D Fitts' Law formulations [5, 15, 16, 41], we use the Shannon Formulation [37] to calculate MT, motivated by previous work [52, 53]. See Equation 1 for the Shannon Formulation[37]:

$$MT = a + b \cdot \log_2\left(\frac{D}{W} + 1\right) = a + b \cdot ID \tag{1}$$

In Equation 1 the logarithmic term, known as the index of difficulty (*ID*), indicates the overall pointing task difficulty. The *ID* is calculated from D and W, which are the target distance and size, respectively, while a and b are empirically derived via linear regression. We also use throughput (THP) based on effective measures as defined in the ISO 9241-411:2015 document [32] (Equation 2):

$$THP = \frac{EffectiveIndexOfDifficulty}{MovementTime} = \frac{ID_e}{MT} \tag{2}$$

Equation 3 below defines the effective index of difficulty (ID_e), where A_e is the movement amplitude and W_e the effective target width. W_e is determined from the standard deviation between the selected position and the target center (SD_x) and characterizes the accuracy of the task performance [38, 39]:

$$ID_e = \log_2\left(\frac{A_e}{W_e} + 1\right) = \log_2\left(\frac{A_e}{(4.133 \cdot SD_x)} + 1\right) \tag{3}$$

Angular Version of Fitts' Law: The *raycasting technique* allows users to point at a target by intersecting the object with a virtual ray extending from the input device. Thus, users typically only rotate their wrists to select a target. Due to these rotational control movements, we use the angular version of Fitts' Law [34], see Equation 4. To calculate the angular ID (ID_A), α defines the angular distance between targets, and ω the angular target width. The constant k is a relative weight [34], typically set to 1:

$$MT = a + b \cdot \log_2\left(\frac{\alpha}{\omega^k} + 1\right) = a + b \cdot ID_A \tag{4}$$

We define THP for angular movements also based on effective measures. See Equation 5, where α_e represents the effective angular distance, i.e., the actual angular movement distance to the target, and ω_e the effective angular target width, the distribution of the angular selection coordinates, calculated as $\omega_e = 4.133 \times SD_x$.

$$ID_e = \log_2\left(\frac{\alpha_e}{\omega_e^k} + 1\right) = \log_2\left(\frac{\alpha_e}{(4.133 \cdot SD_x)^k} + 1\right) \tag{5}$$

2.2 Effect of VAC on 3D pointing

While the 3D selection of targets benefits from stereo displays [34, 53], pointing THP is lower relative to 2D tasks [48, 52, 53].

In stereo display systems, a potential reason for this lower performance is a change in the visual depth between targets when selecting such 3D targets in peri-personal space. Previous work has shown that with the virtual hand technique, execution time and THP are lower for movements in visual depth compared to lateral movements on a large stereo display [5], and they confirmed this observation through a comparison with a real-world setup, which yielded an opposite result. Batmaz et al. [11] verified the existence of this effect in modern AR and VR HMDs. There does not seem

Table 1: Overview of previous 3D pointing experiments focusing on the VAC and biomechanics.

Publication	Movement Direction	Display Device	Input Device	Grip Style	Focus	Main Findings	Open Issues
Lubos et al. [36]	7 directions 9 positions	Oculus Rift	Gestures	Power Grip	Biomechanics	Visual Perception causes errors in 3D selection	Is the VAC the cause of these errors?
Barrera and Stuerzlinger [4]	2 directions	3D TV	Custom Wand	Power Grip	VAC	Depth movements are slower than lateral ones	Does this occur in the real world, too?
Barrera and Stuerzlinger [5]	2 directions	3D TV Physical apparatus	Custom Wand	Power Grip	VAC	Stereo displays affect 3D pointing negatively	Generalization to other stereo displays
Batmaz et al. [11]	2 directions	HTC Vive Meta 2 (AR)	Custom Wand	Power Grip	VAC	Stereo in HMDs affects 3D pointing negatively	Cause of performance drop?
Batmaz et al. [12]	11 directions	HTC Vive 2	Logitech Pen Controller	Power Grip & Precision Grip	Biomechanics	Precision grip exhibits less errors	Effect of tracking difference between pen and controller
Babu et al. [2]	13 directions	HTC Vive	Gesture Controller	Power Grip	Biomechanics	Controller is better than Gestures, nearby targets are easy to reach	How does the VAC interact with target distance
Batmaz et al. [7]	2 directions	Singlefocal VR/AR bench Multifocal VR/AR bench	Custom Wand	Power Grip	VAC	VAC slightly affects 3D pointing with Virtual Hand	Effect of limited reachability of targets at 70 cm
Batmaz et al. [9]	11 directions	HTC Vive 2	Controller	Power Grip	VAC	VAC clearly affects 3D pointing with Raycasting	How about virtual hand?
Batmaz et al. [10]	11 directions	HTC Vive 2	Controller	Power Grip	VAC	Constant VAC does not substantially affect 3D pointing	Instructions to participants did not emphasize speed/accuracy, effect of inconsistent grip on device
Clark et al. [17]	5 directions 2 positions	Oculus Quest 2	Gestures	Power Grip	Biomechanics	Hand movement depends on movement direction, hand used, and side of the body where movement occurs.	How do virtual hand kinematics interact with the VAC?
Current work	**11 directions**	**HTC Vive 2**	**Controller**	**Power Grip & Precision Grip**	**VAC Biomechanics**	**Biomechanics reduce the VAC's effect for virtual hand pointing**	**What specific biomechanical factor is responsible for this effect?**

to be previous work on the effect of visual depth on raycasting at nearby targets, except Teather and Stuerzlinger [53] who showed that varying target depth affects performance. For distal targets between 110 and 330 cm, Janzen et al. [33] found that performance is affected and that the user's distance to the screen has an effect, which could indicate that the focal distance plays a role.

Humans use a variety of nonpictorial depth cues, such as stereopsis, motion parallax, convergence, and accommodation, when selecting targets [14, 22, 44, 45]. Here, we focus on the vergence-accommodation conflict (VAC), which is caused by the fixed focal distance of the stereo display systems used in VR HMDs to show 3D content. Problems caused by the VAC in the human ocular system include 1) depth perception issues [21, 23], 2) that the eyes converge closer than necessary [30, 31], and 3) visual fatigue due to focal and vergence differences [28]. All these issues affect the performance of the human visual system [26, 55] and increase the user's cognitive load [19]. Previous work [9] identified an effect of the VAC when selecting distal 3D targets with *raycasting*. Their results showed that for targets in the HMDs' focal plane, i.e., in a condition without the VAC, participants were able to perform better in terms of time, errors, and THP than with a constant or varying VAC. Yet, this work did not study targets within arms' reach. Other previous work by Batmaz et al. [8] identified for targets in peri-personal space that the VAC affects 3D selection with the *virtual hand* technique, but only for purely lateral or purely depth motions. In their work, they used a custom-made stereo display but did not investigate if the VAC affects the selection of nearby targets with raycasting.

2.3 Biomechanics of 3D pointing

Several biomechanical factors are known to affect 3D pointing. These include the hand muscles used to grab the controller with a specific grip style [24, 42], the arm/shoulder muscles used to move the arm [1, 18], and even the eye muscles used for the vergence system [31, 54]. Here we focus on the first two:

Arm/Shoulder Muscles: Previous work identified that the muscles for shoulder extension affect 3D pointing [1, 36, 50]. Another factor that affects 3D pointing is the position/orientation of the user's limbs, i.e., the arm, wrist, hand, and finger [18, 35, 47, 51, 57]. Finally, hand movements are more complex when they cross the vertical midline of the body [43, 46].

Grip Style Muscles: While interacting with VR controllers, humans generally use prehensile movements, where the hand grasps the object fully, securely, or partially [24]. Previous work showed that grip style impacts user performance in 3D pointing tasks [12, 20]. Pham and Stuerzlinger [20] found that a precision grip, where the controller is pinched between multiple fingertips and the opposing thumb, can match the performance of a 2D mouse for distal pointing. Batmaz et al. [12] compared the precision and power grip. They found no significant difference for movement time and THP for grip style for peripersonal target selection. Still, their experiment was subject to differences in the tracking system between the used devices, which might have affected their results.

We extend these previous works by analyzing the effect of the hand and arm biomechanics on 3D pointing and studying their relationship with the VAC.

3 MOTIVATION & HYPOTHESIS

A previous pointing study with targets within arms' reach in different VAC conditions showed that participants were faster and their THP increased in the CONSTANT VAC condition [10]. This result directly contradicts previous work on the VAC [8, 9], where participants were slower and had lower THP with the CONSTANT VAC condition. The authors speculated that biomechanical constraints might be one of the potential explanations for this result since the participants were asked to select targets with a Vive controller at 65 cm in the virtual hand condition or while holding the controller around the shoulder of their dominant hand with raycasting [10]. Both of these conditions can be challenging, as targets at 65 cm might be hard to reach for some users in the virtual hand condition or the pose around the shoulder is unusual. In contrast to that work, a preceding study with a multifocal display [8] used a small, lightweight input device, whereas another related study on distal pointing [9] used a controller held in a more comfortable hand pose for raycasting. In this paper, we hypothesize that target positions in space that are harder to reach for the user negatively affect user performance and thus can suppress some of the main effects of the VAC.

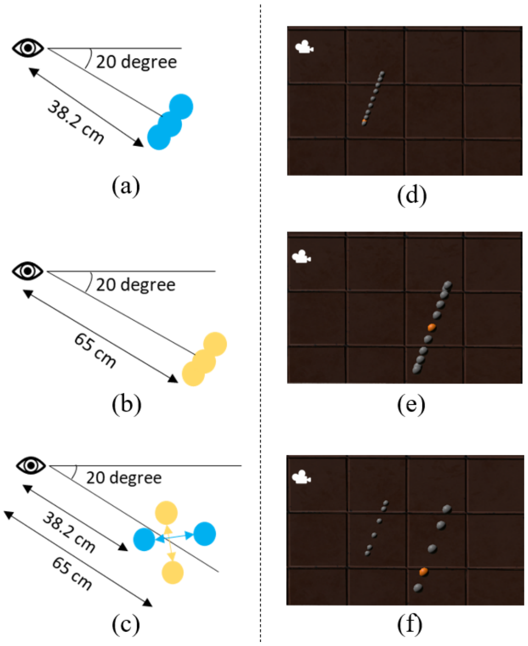
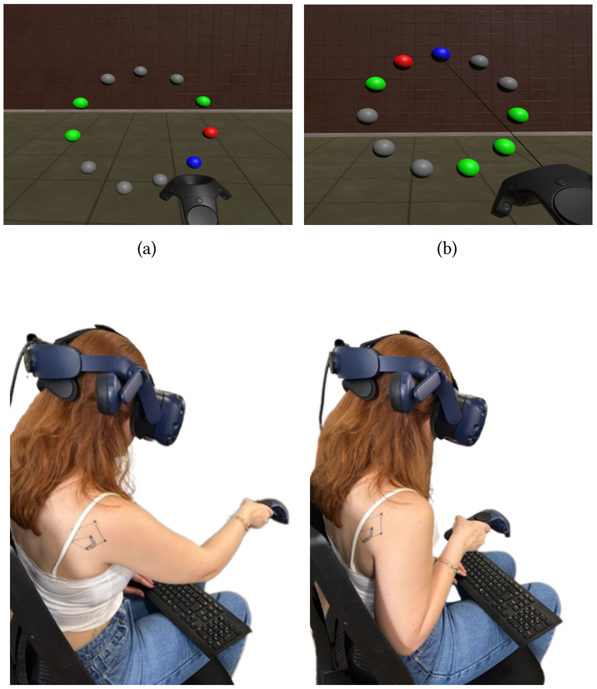


Figure 1: Side view for VAC conditions: (a) CONSTANT VAC where the targets are placed at 38.2 cm, represented with blue spheres, (b) NO VAC where the targets are placed at 65 cm, represented with yellow spheres, and (c) VARYING VAC where targets alternate between 38.2 and 65 cm. Side view for (d) CONSTANT VAC, (e) NO VAC, and (f) VARYING VAC. The camera icon represents the participants' head position.

4 PROCEDURE

Participants: We recruited 18 participants (11 male and 7 female), with ages ranging from 21 to 31 years (M = 22.27, SD = 2.3). 15 participants were right-handed, and the remaining 3 left-handed. 11 participants were right-eye dominant, and 7 left-eye dominant. 15 participants had normal vision, and the other 3 had corrected-to-normal vision. No one reported color vision deficiencies. Regarding their prior experience with VR, 5 participants had none, 5 1-5 times, and the remaining 8 had experienced it 5 or more times.

Apparatus: The experiment was conducted on a PC with an Intel(R) Core(TM) i7-11700F at 2.5 GHz, 32 GB RAM, and an NVIDIA GeForce RTX 3070 graphics card. We used two 2.0 Lighthouse base stations and a HTC VIVE Pro HMD with a single controller. Further, we designed and implemented the virtual environment using Unity3D version 2021.3.5f1.


(a) (b)

(c) (d)

Figure 2: User view for interaction techniques used during the experiment: a) Virtual hand and b) Raycasting. Participant holding the controller for (c) Virtual hand or (d) Raycasting. The space key of the keyboard on their lap is used to indicate the selection of the target aimed at.

User Study Procedure: Participants first filled out a pre-experiment questionnaire, where we asked for their consent to participate in the experiment voluntarily and their demographic information. Then, they were asked to sit on a chair, to put on the HMD, and were provided instructions on how to control the cursor with the controller held in their dominant hand, using either investigated interaction technique: raycasting or virtual hand. In the raycasting technique, participants positioned their hands roughly at chest level, and a virtual line was shown in the direction they pointed the controller. The cursor was at the end of the ray, at a distance appropriate for the current target plane. In the virtual hand technique, participants extended their hands, moving the controller to each target. The cursor in this technique was positioned 3 cm above the virtual controller. Based on lessons learned from pilot studies, we choose to rotate the target configuration 20° downwards to afford a comfortable hand position for the virtual hand condition while still allowing them to reach the targets without hitting their lap. To avoid the potential confound of a side view, the experimenter informed participants that they should not change their head position substantially during the experiment and ensured they conformed to this instruction.

At the beginning of each circle of targets, the target configuration was adjusted to appear at 20° below horizontal at the participant's initial head position at that time. Corresponding to the ISO 9241:411 multidirectional selection task 4.3, participants were presented with a circle of 11 gray spheres and were instructed to select the sphere shown in orange. According to the interaction technique, when they moved the virtual cursor within 0.5 cm of the sphere, the sphere's color changed from orange (or from gray if the sphere was not the target) to blue. Then, they made the selection by pressing the space key on the keyboard with their non-dominant hand. If the target was selected successfully, the blue sphere became green, otherwise red. Such an unsuccessful selection could happen in two ways: (1) another sphere was selected instead of the actual target, or (2) the virtual cursor did not hit any of the 11 spheres. The sequence then continued with the next target across the circular configuration, with that gray sphere turning orange and becoming the current target.

Similar to previous work [9, 10], we scaled targets depending on distance so that targets appeared to be the same size regardless of their distance from the user. Thus, participants could not use target size as a cue to how far the targets were away. While interacting with the virtual hand during the Varying VAC condition, the task configuration results in a diagonal movement where the movement distance is greater than the other VAC conditions. To compensate for this confound, we increased the size of the target spheres accordingly only for this condition – so that the Euclidean ID matches across all conditions.

4.1 Experimental Design

We performed a two-factor within-subjects user study with three different **VAC** conditions (3_{VAC} = No VAC, Constant VAC, and Varying VAC) and two **interaction techniques** (2_{IM} = Virtual hand and Raycasting), which resulted in an experimental design with ($3_{VAC} \times 2_{IM}$) 6 conditions. We measured task execution time (seconds), error rate (%), effective THP (bits/s), SD_x, and ID_e as dependent variables. We counterbalanced the VAC conditions and interaction techniques with a Latin Square across participants. To vary the task difficulty, we used 9 ID_As, using all combinations of three **angular target sizes** (3_{ATD}) and three **angular target distances** (3_{ATS}). In total, each participant performed $3_{VAC} \times 2_{IM} \times 9_{ID_A} \times$ 11 repetitions = 594 trials. The experiment took a total of 20 minutes for each individual.

5 RESULTS

The data were analyzed using Repeated Measures (RM) ANOVA on SPSS 24. We considered it to be normally distributed if Skewness (S) and Kurtosis (K) were within ±1 [27, 40]. Otherwise, we first tried log-transform, and if this still did not yield a normal distribution, we performed ART [56] on the original data before running the ANOVA using ARTool. ARTool automatically checks the correctness of the data set and we verified that all data is appropriate to be used with ART. We also checked that all the effects except for the effect for which the data were aligned were stripped out. For post-hoc analyses, we used the Bonferroni method and applied Huynh-Feldt correction when $\varepsilon < 0.75$. The figures show the mean in the graphs, and the error bars represent the standard error of the mean. After analyzing the outcomes of each interaction technique separately, we proceeded to conduct a two-way RM ANOVA, followed by a Fitts' law analysis and an analysis of the questionnaire results.

5.1 Detailed Analyses per Interaction Technique

Before analyzing the general results, we first investigated the individual outcomes for the virtual hand and raycasting interaction techniques. Figure 3 shows the results for the virtual hand and raycasting interaction techniques for all recorded measures.

5.1.1 *Virtual Hand.*

For the virtual hand interaction technique, THP (S = 0.11 and K = -0.04) and ID_e (S = 0.01 and K = 0.43) were normally distributed; time (S = 0.57. K = 0.53) and SD_x (S = -0.01, K = 0.02) only after log-transform. Error rate was not normally distributed even after log-transform, so we used ART.

Time: Participants were significantly slower when they selected the targets in the Varying VAC condition (F(2, 34)= 42.97, p< 0.001, η^2= 0.717, Figure 3(a)).

Error Rate: Participants made significantly more errors when they selected the targets in the Varying VAC condition (F(2, 34)= 12.347, p< 0.001, η^2= 0.421, Figure 3(c)).

THP:. Participants' THP significantly decreased when they selected targets in the Varying VAC condition (F(2, 34)= 19.2, p< 0.001, η^2= 0.528, Figure 3(e)).

SD_x: The standard deviation along the task axis was significantly higher for targets in the No VAC condition than in Varying VAC, which in turn was significantly higher than in the Constant VAC condition (F(2, 34)= 43.25, p< 0.001, η^2= 0.718, Figure 3(g)).

ID_e: ID_e results of the participants significantly increased when they selected targets in the Varying VAC condition (F(2, 34)= 18.245, p< 0.001, η^2= 0.518, Figure 3(i)).

5.1.2 *Raycasting.*

For raycasting THP (S = 0.37 and K = 0.05) and ID_e (S = 0.28 and K = 0.57) were normally distributed; Time (S = 0.41. K = 0.02) and SD_x (S = -0.16, K = 0.57) only after log-transform. We used ART on Error Rate, as it was not normally distributed even after log-transform.

Time: Participants were significantly faster when they selected targets in the No VAC condition than in Constant VAC, which was in turn significantly faster than in the Varying VAC condition (F(2,34)= 96.819, p< 0.001, η^2= 0.851, Figure 3(b)).

Error Rate: Participants made significantly fewer errors when they selected the targets in the No VAC condition (F(2,34)=3.127, p< 0.001, η^2= 0.155, Figure 3(d)).

THP:. Participants' THP was significantly higher when they selected targets in the No VAC condition than in Constant VAC, which in turn was significantly higher than in the Varying VAC condition (F(2,34)= 31.61, p< 0.001, η^2= 0.650, Figure 3(f)).

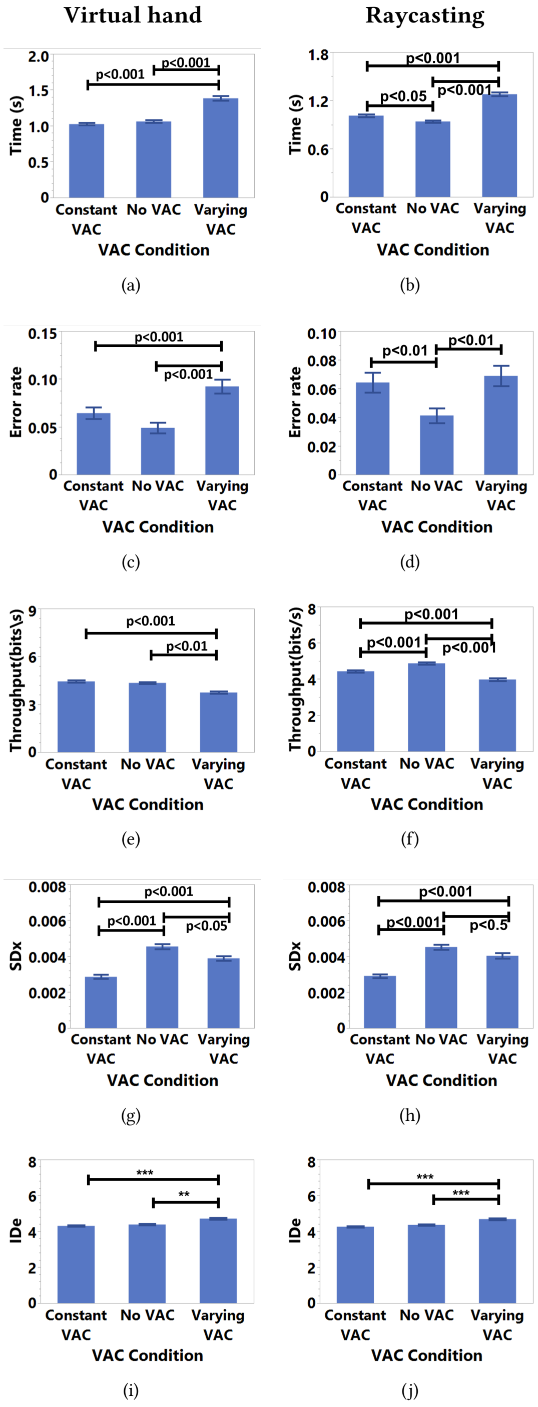


Figure 3: Virtual hand interaction technique results for (a) Time, (c) Error Rate, (e) THP, (g) SD_x, and (i) ID_e. Raycasting interaction technique results for (b) Time, (d) Error Rate, (f) THP, (h) SD_x, and (j) ID_e.

SD_x: SD_x was significantly higher when they selected targets in the No VAC condition than in Varying VAC, which in turn was significantly higher than with the Constant VAC condition (F(2,34)= 54.02, p< 0.001, η^2= 0.761, Figure 3(h)).

ID_e: ID_e results of the participants significantly increased when they selected targets in the Varying VAC condition (F(2,34)= 24.64, p< 0.001, η^2= 0.592, Figure 3(j)).

5.2 Two-way RM ANOVA

In the two-way RM ANOVA analysis, THP (S = 0.24, K = 0.07) and ID_e (S = 0.14, K = 0.48) were normally distributed; Time (S = 0.51. K = 0.38) and SD_x (S = -0.08, K = 0.029) only after log-transform. We again used ART for Error Rate, as it was not normally distributed even after log-transform. The results between interaction techniques are not presented in detail for *brevity* - except if there were notable.

Time: Overall, participants were significantly slower with Varying VAC compared to the other two conditions (F(2, 34)= 98.505, p< 0.001, η^2=0.853, Figure 4(a)).

Error Rate: Participants made significantly fewer errors with No VAC compared to the other two conditions (F(2, 34)= 10.7, p< 0.001, η^2= 0.387,Figure 4(b))

THP:. Participants' THP was significantly lower with Varying VAC compared to the other two conditions (F(2, 34)= 26.713, p< 0.001, η^2=0.611, Figure 4(c)).

SD_x: Participants' SD_x were significantly higher in the No VAC condition than in Varying VAC, which in turn was significantly higher than in the Constant VAC condition (F(1.4, 23.8)= 105.4, p< 0.001, η^2= 0.861, Figure 4(d))

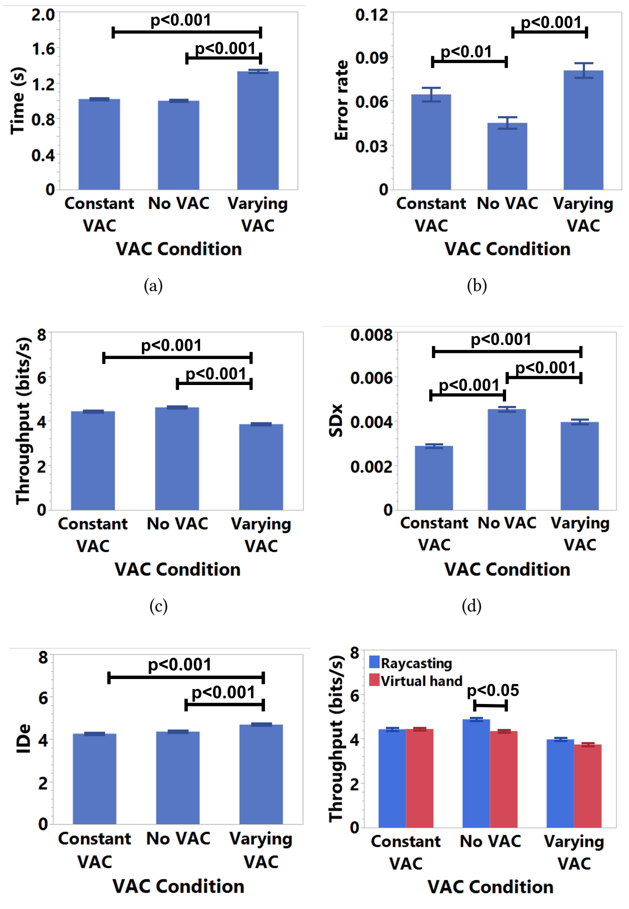
ID_e: Participants' ID_e was significantly higher with Varying VAC compared to the other two conditions (F(1.5, 24.5)= 47.9, p< 0.001, η^2=0.738, Figure 4(e))

Two-way Interaction Results: We only found a statistically significant difference between interaction techniques and VAC conditions for THP (F(2, 32) = 7.671, p < 0.01, η^2 = 0.311, Figure 4(f)). According to these results, participants had higher THP with raycasting in the No VAC condition (see Figure 4).

5.3 Detailed Varying VAC Condition Analysis

We analyzed the Varying VAC condition further and examined how user movement is affected when moving between the Constant VAC and No VAC target positions/planes. Thus, we ran an RM ANOVA with two **interaction techniques** (2_{IM} = virtual hand and raycasting) and two **target positions** (2_{TS} = No VAC and Constant VAC) for the Varying VAC condition as shown in ??. In this analysis, data were normal distributed for THP (S = 0.3, K = 0.07) and ID_e (S = 0.06, K = 0.22), and for Time (S = 0.52. K = 0.38) and SD_x (S = -0.12, K = 0.4) after log-transform. Error Rate was not normally distributed even after log-transform, so we used ART.

Time: Participants were significantly faster when they selected the targets in the No VAC positions (F(1, 17)= 26.408, p< 0.001, η^2=0.608, Figure 5(a)).



(a) (b)

(c) (d)

(e) (f)

Figure 4: Two-way RM ANOVA results for VAC conditions: (a) Time, (b) Error Rate, (c) THP, (d) SD_x, and (e) ID_e.

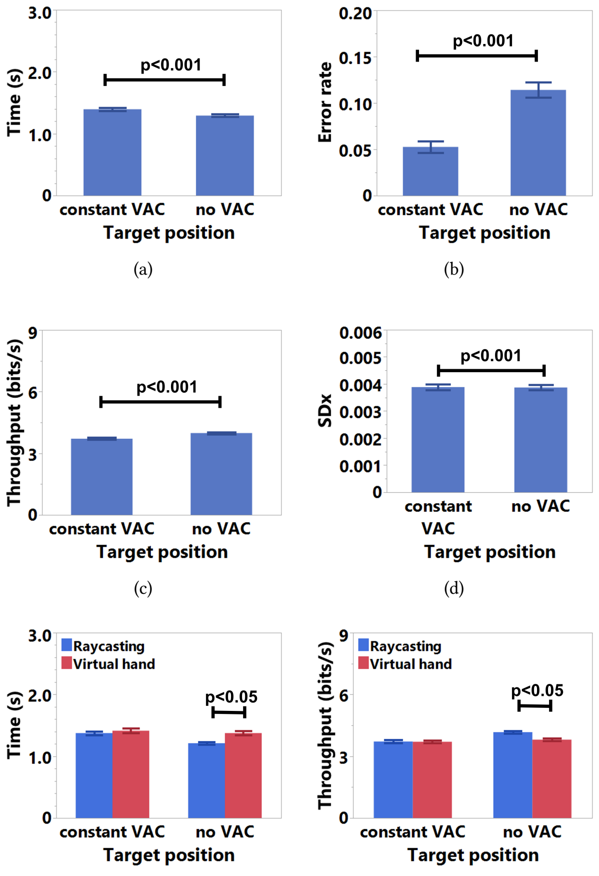
Error Rate: Participants made significantly more errors when they selected the targets in the No VAC positions (F(1, 17)= 28.47, p< 0.001, η^2=0.626, Figure 5(b)).

THP:. Participants' THP significantly increased when they selected targets in the No VAC positions (F(1, 17)= 44.21, p< 0.001, η^2=0.722, Figure 5(c))

SD_x: SD_x results of the participants significantly decreased when they selected targets in the No VAC positions (F(1, 17)= 5.78, p< 0.05, η^2=0.254, Figure 5(d)).

ID_e: We did not observe any significant interaction for ID_e (F(1, 17)= 0.162, p= 0.692, η^2=0.009).

Interactions: We found a significant interaction between target position and interaction technique for time (F(1,17) = 15.363, p < 0.001, η^2 = 0.475, Figure 5(e)) and THP (F(1,17) = 44.498, p < 0.001, η^2 = 0.59, Figure 5(f)). According to these results, participants were faster and exhibited higher THP with the raycasting interaction technique while they selected targets in the No VAC positions.



(a) (b)

(c) (d)

(e) (f)

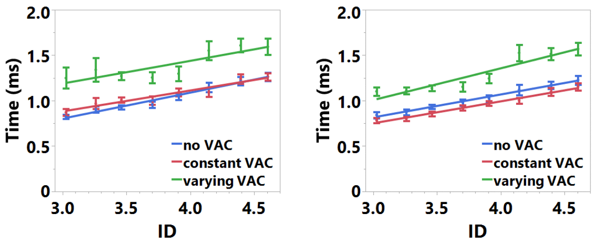
Figure 5: Detailed VARYING VAC condition results for (a) Time, (b) Error Rate, (c) THP, and (d) ID_e. Target position and interaction technique interaction results for (f) Time and (h) THP.

5.4 Fitts' Law

We also conducted Fitts' law analysis for both interaction techniques as shown in Figure 6 and Table 2. Our results indicate that the VARYING VAC condition exhibits different results than the other two conditions, with the lowest R^2 values, especially for the virtual hand technique.

Table 2: Fitts' Law Analysis Results

	Virtual hand	Raycasting
No VAC	MT = 0.17 + 0.23 × ID R^2 = 0.93	MT = 0.3 + 0.24 × ID R^2 = 0.98
CONSTANT VAC	MT = -0.04 + 0.28 × ID R^2 = 0.97	MT = -0.05 + 0.25 × ID R^2 = 0.98
VARYING VAC	MT = 0.45 + 0.24 × ID R^2 = 0.72	MT = -0.02 + 0.34 × ID R^2 = 0.86



(a) (b)

Figure 6: Fitts' law analysis results for (a) virtual hand and (b) raycasting.

5.5 Post-Study Questionnaire Results

At the end of the experiment, each participant completed a post-experiment questionnaire. We asked them first to report their preferred VAC condition and to explain their choice. Of all participants, 10 preferred the Constant VAC condition, 3 preferred the No VAC condition, and 5 preferred the Varying VAC condition. Participants who chose the Constant VAC condition mentioned that *"it required little effort to select the targets and did not tire my hands"* and *"it was easier to access the targets."* Those who preferred the No VAC condition stated *"I felt that I was more confident when targets are far away from me, especially in [...] raycasting"* and *"I think that the distance gave me freedom."* Lastly, participants who chose the Varying VAC condition mentioned that *"While using [Varying VAC], you can literally feel like you are in a 3D environment because of the depth"* and *"I perceived depth and made it easier to use."*

Finally, participants were asked to evaluate their physical and mental fatigue on a 7-point scale (1 = I don't feel physical/mental fatigue at all, 7 = I strongly feel physical/mental fatigue). According to the results, participants reported neither significant physical fatigue (M = 3.2, SD = 1.4, Mdn = 3) nor mental fatigue (M = 2.5, SD = 1.4, Mdn = 2) across all conditions.

6 DISCUSSION

We investigated the effect of VAC in an ISO 9241:411 task that was rotated 20° downwards relative to the view direction with two different interaction techniques: virtual hand and raycasting. Rotating the target configuration downwards makes the targets easier to reach in the virtual hand condition and allows participants to hold the controller in a more comfortable hand pose. This configuration allows us to investigate if user performance is affected by the difference in bio-mechanical constraints compared to a previous VAC study [10], whose results contradict other work [8, 9].

Our results show that participants exhibit worse performance in terms of time, errors, and THP in the Varying VAC condition. These results match the findings of previous studies [8, 9]; thus, we do not discuss them further here. However, our results contradict the findings of Batmaz et al.'s study [10]. To examine this in more detail, we investigated each interaction technique individually in a more detailed analysis. Our results show that participants were faster, made fewer errors, and had a higher THP in the No VAC condition for raycasting, which matches the results from the corresponding study for raycasting in previous work [9]. This is not surprising as the performance of raycasting (mainly) depends on the visual angle of targets and their angular distance, which should be (largely) insensitive to the position of the targets relative to the view direction.

Yet, our results do not match the results for the virtual hand condition in other previous work [10], whose experimental design we replicated here faithfully. The main difference with that study is that, in the study presented here, the targets were rotated downwards by 20° relative to the line of sight. In Batmaz et al. [10], the Constant VAC condition was superior in most measures to the other two, while in our current study, the Constant VAC and No VAC conditions perform overall similarly. We see this as an indication that the biomechanics of the pointing motion affect the results. Thus we confirm our hypothesis that *target positions in space that are harder to reach for the user negatively affect user performance, and thus can suppress some of the main effects of the VAC.*

After all, the lower position of the targets in the visual field makes targets that are further away (in the No VAC plane) easier to reach. We speculate that the results of previous studies related to VAC that used target configurations straight ahead of the user for virtual hand interaction [5, 8, 10] were confounded by the fact that targets in the No VAC position were more challenging to reach, which either slowed users down or caused additional fatigue.

These differences between our findings and the literature could also be caused by the input device that we used. Since previous work related to VAC [5, 8] used a lightweight wand to reach targets at arm's length (e.g., at 70 cm), it was easier and more comfortable for participants to select the given targets. In contrast, the HTC Vive controllers weigh 200 grams [49], which might have made it more challenging or fatiguing for the participants to (repeatedly) reach out for the targets at 65 cm in our experiment. Still, our results also match previous work that found that reaching for targets at 90% of the maximum arms' reach affects user performance [2]. After all, for most people, 65 cm is about 90% of their arms' reach.

We chose 20° of rotation based on our pilot studies. At 25° rotation, participants hit their laps with their hands with the virtual hand condition while they were comfortable with the raycasting condition. When we rotated the experimental setup to a smaller degree, participants exhibited discomfort holding the controller with the raycasting condition, similar to reports in previous work [10]. As the best available compromise for a seated posture, we thus used a rotation angle of 20° for this study. If participants were standing, we believe that a rotation angle of (say) 45° might be a more appropriate choice, but this needs to be verified in the future studies.

Another main outcome of this paper demonstrates how the biomechanics of pointing can affect the results of an interaction technique. Previous work on the VAC did not take participants' comfort into account [10] and asked participants to hold the controller in an awkward pose, which constitutes a potential explanation for participants' performance with the virtual hand deviating significantly compared to other previous work regarding the VAC [8]. Still, in our study and for the No VAC condition, user performance was significantly higher than in the Varying VAC condition with raycasting, which matches other previous work [9].

Another potential explanation of our results is the participants' task execution strategies. In this work, we asked participants to select targets as fast and as precise as possible, which is the recommended task execution strategy for the ISO9241:411 task. However, we did not find information regarding the participants' task execution strategy in Batmaz et al.'s corresponding study [10]. Still, previous work on different task execution strategies identified that user motor performance, in terms of Time, Error Rate, and THP, varies with different ISO 9241:411 task execution strategies in VR [13]. Thus, we believe that the impact of different task execution strategies should be investigated further with a more systematic user study.

6.1 Limitations

Our results are strictly only valid for a HTC Vive Pro in an ISO 9241-411:2015 task and our study should thus be replicated with other HMDs with a different focal length, such as the Oculus Quest 2, and also AR HMDs. Yet, based on previous work [7, 11] that showed no difference between AR and VR we do not expect a difference.

In this paper, our objective was not to investigate all biomechanics factors, such as body posture, since the previous work highlighted that the grip style could be a potential explanation for the contradictory results [10]. Moreover, we only investigated the precision and power grip, as defined in Napier's work based on prehensile movements [42]. Further, different body postures, such as pointing at virtual targets while standing, might influence the selection performance of the participants. Also, we did not vary the task space rotation and did not evaluate other rotation angles. We also did not vary the comfort of the task space. We focused only on the effect of the hand and arm biomechanics on 3D pointing using a fixed position for one single task.

Finally, and to increase comparability with previous studies [8, 9], we used a limited range of *ID*s in this experiment. We thus suggest extending our experimental design to a larger *ID* range. While it is possible that the trends between different VAC conditions, interaction techniques, and grip styles remain the same, a wider range of *ID*s might yield more detailed comparisons between them.

7 CONCLUSION & FUTURE WORK

In this paper, we investigated how the vergence-accommodation conflict (VAC) induced by single-focal stereo displays interacts with biomechanical factors. We closely replicated a previous study on the VAC [10] but used a more ergonomic target placement and controller holding styles. Matching other previous work [7, 9], our results showed that participants were faster, made fewer errors, and had a higher THP performance in the No VAC condition. Our results highlight the detrimental effects of biomechanic factors on studies of 3D pointing overall and the VAC in particular. Based on our results, we also recommend that designers, practitioners, and developers consider using lightweight controllers and comfortable holding positions to mitigate the effects of the VAC.

In the future, we are planning to investigate how specific individual biomechanical limitations, such as the grip style, affect user performance. Note also that even though the differences in terms of the VAC (which is governed by the visual depth as expressed in diopters) were the same across the virtual hand and raycasting in our study, our raycasting results match pointing at distal targets [9]. In this context, the fact that the No VAC condition was not significantly better than the CONSTANT VAC one with the virtual hand points out that there may still be other factors that need to be explored to explain pointing performance in peri-personal space fully.

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