Effect of Grip Style on Peripersonal Target Pointing in VR Head Mounted Displays

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ABSTRACT

When working in Virtual Reality (VR), the user's performance is affected by how the user holds the input device (e.g., controller), typically using either a precision or a power grip. Previous work examined these grip styles for 3D pointing at targets at different depths in peripersonal space and found that participants had a lower error rate with the precision grip but identified no difference in movement speed, throughput, or interaction with target depth. Yet, this previous experiment was potentially affected by tracking differences between devices. This paper reports an experiment that partially replicates and extends the previous study by evaluating the effect of grip style on the 3D selection of nearby targets with the same device. Furthermore, our experiment re-investigates the effect of the vergence-accommodation conflict (VAC) present in current stereo displays on 3D pointing in peripersonal space. Our results show that grip style significantly affects user performance. We hope that our results are useful for researchers and designers when creating virtual environments.

Index Terms: Human-centered computing—Human Computer Interaction (HCI); Human-centered computing—Virtual Reality; Human-centered computing—Pointing

1 INTRODUCTION

Industries ranging from education, engineering, the arts, and healthcare to entertainment have started to use Virtual Reality (VR) systems more broadly in the last few years. This trend leverages recent advances in Head Mounted Displays (HMDs), which are now capable of creating high-definition graphics while being self-contained, wireless, and lightweight. Modern VR HMDs are also affordable, which makes them accessible to a broad audience. For example, Meta has sold nearly 20 million VR HMDs [29]. In such VR systems (and in many application contexts), users must be able to interact quickly and accurately with virtual objects. Such interaction requires different hand movements depending on the movement and the object's characteristics. For example, holding a mug to drink coffee uses a power grip, while holding a pencil to write uses a precision grip. For interactions in VR to be successful, it is important to provide users with an appropriate controller or input device to support various tasks and the associated grip styles. Yet, most modern VR HMDs come with a standard controller, e.g., HTC Vive or Oculus Touch controllers, which are designed as multi-purpose solutions and do not provide the affordances needed for specific tasks, especially for those requiring precision.

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One by-product of a controller's shape, size, and weight is the grip style(s) it affords [19, 21], which refers to how the user grabs the controller. Grip style can also vary by a user preference or a specific task requirement, e.g., various table tennis shots require users to hold the paddle differently. Previous work identified that the grip style affects user performance [9, 19], but results were overall inconclusive: Pham and Stuerzlinger [19] found a positive effect of using pen-like controllers for distal pointing, but Batmaz et al. [9] did not find a significant difference between movement time and throughput for grip style.

Still, interaction in modern VR systems is not only affected by the controller grip style during virtual interactions. For example, HMDs use stereo displays to render virtual content. Such stereo displays display 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 focal plane by the HMD, and when displaying 3D content that is not at the same depth as said fixed plane, a user's eye 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). A recent study of the effects of the vergence-accommodation conflict (VAC) identified the grip style as a possible cause of their results [8]. It thus makes sense to include a re-investigation of the VAC in an experiment focusing on the effect of the hand grip on 3D pointing at targets in peripersonal space.

Consequently, the main motivation of this study is to analyze the interaction between grip style and the VAC. Based on the inconsistent outcomes of previous work on 3D pointing in peripersonal space, the core contribution of this paper is that we carefully (re-)examine if the user grip style enhances or diminishes user performance with nearby targets. For this, we conducted an experiment with 24 participants based on Fitts' law. We used the same experimental methodology as Batmaz et al. [7] to identify how the grip style affects performance and to ensure that our results are comparable with previous work. Our results show that grip style significantly affects user performance, for example, we found the highest user performance with the raycasting interaction technique and precision grip. Our results extend previous work by replicating previous studies ([5–7]) but critically identifying that their findings are not related to how participants hold the controller. Our results thus inform the future design of VR applications by asking designers to consider the controller available to the user and the type of grip style it is held with. It also informs work on future controllers.

In summary, our contributions are the following:

- We identify the effect of the grip style on 3D pointing performance in peripersonal space.
- We demonstrate the interaction of the VAC and grip style in a singlefocal display system for targets within arm's reach for both virtual hand and raycasting interaction.
- We quantify the effect of the VAC on the selection of targets in arm's reach with a precision grip within a commercial VR HMD system.

2 RELATED WORK

This section discusses the main interaction techniques for 3D pointing and different elements that affect them. We also discuss previous work on the effect of grip style and input device on 3D selection, along with the role of the VAC. Finally, we discuss the different approaches to measuring human performance for 3D selection.

2.1 3D Pointing in VR

3D pointing is a primary interaction method that plays a key role in selecting and manipulating virtual objects, as users need to first point to a target before they can select it, e.g., by pressing a button or making a gesture to inform the system of their choice. Despite its importance, 3D pointing is primarily affected by hardware and software limitations, including unintentional hand tremor and/or tracker pose variations caused by, e.g., jitter, thermal noise, and/or latency [10, 11, 13], and the input method [48, 49]. Previous work proposed novel interaction devices, methods, and techniques to improve 3D pointing performance [45]. The two most widely used selection methods are raycasting and virtual hand techniques.

The *raycasting technique* allows users to point at a target by intersecting the object with a virtual ray extending from the input device. This technique is useful for selecting distal targets directly, i.e., without the users having to move towards the target or without using proxy objects such as the options in a menu on the opposite hand. Still, targets very close to the user can require large angular movements [28]. Another limitation is that raycasting is susceptible to jitter, as the intersection area between the ray and the object is small [10, 25, 47]. On the other hand, the *virtual hand technique* allows users to point at a virtual target by intersecting it with an input device or their bare hand. Yet, the virtual hand can only select nearby targets, i.e., within arms' reach. It is also affected by the absence of haptic feedback when touching an object [48]. While these two pointing techniques have their individual challenges, they are both susceptible to depth perception issues in stereo displays, specifically the presence of the VAC [5, 7, 8].

Moreover, when comparing user performance between virtual hand and raycasting at targets within peripersonal space, Teather and Stuerzlinger [48] found that raycasting has worse performance than the virtual hand: a slower selection time, higher error rate, and smaller throughput. They hypothesized that raycasting is more susceptible to tracker jitter amplification but did not focus on other potential causes like different grip styles. In this work, we included the raycasting interaction technique since we wanted to explore how different grip styles affect user performance with common interaction techniques with nearby targets. Even though raycasting is typically used for farther targets, some raycasting variants can bring objects closer or work for both close and far targets, such as the HOMER technique [17]. Moreover, a subset of current VR applications, e.g., Tiltbrush, requires users to use raycasting to nearby objects by pointing toward a menu.

2.2 Biomechanics of 3D pointing

User performance during 3D pointing can be significantly affected by biomechanic factors, such as the muscles used by the shoulder extension [1, 32, 44] or the position/orientation of user's limbs (e.g., arm, wrist, hand, and fingers) [18, 31, 42, 46, 51]. For example, hand movements were found to be more complex when they cross the vertical midline of the body [39, 41]. Finally, the physical properties of the interacted object (e.g., size, shape, and weight) have a crucial impact on the ergonomy, grip strength, and hand pose [37, 43].

Grip style is another crucial biomechanical factor: different grip styles require different muscles to be activated, which ultimately affects user performance. While interacting with VR controllers, humans generally use prehensile movements, where the hand grasps the object (controllers) fully, securely, or partially [20]. Even though there are various prehensile movements, Napier [38] categorizes them anatomically and functionally into two major grip styles: precision grip and power grip. With the precision grip, the object is pinched between multiple fingertips and the opposing thumb tip – while the finger phalanges might or might not be involved, as shown in Fig. 2(a). With the power grip, the object is held between multiple finger phalanges and the opposing thumb phalanges in a clamp position – while the tips might or might not be involved, as shown in Fig. 2(b). For interacting with VR environments, VR standard VR controllers usually require a power grip, while VR pen/stylus devices afford a precision grip style.

Grip style has been shown to have an impact on user performance during 3D pointing interaction tasks. Pham and Stuerzlinger [19] demonstrated that interacting with a pen-like controller in VR increases user interaction performance to the same level as that of a 2D mouse for distal pointing. On the other hand, Batmaz et al. [14] identified a negative impact of grip style on interaction performance, albeit only in an experiment where the tracking system performed differently between input devices. In a follow-up study, Batmaz et al. [9] did not find a significant difference between movement time and throughput for grip style. They speculate that peripersonal space target selection was easier than distal target selection but also identified differences in the tracking system between the used devices, which might have again fundamentally affected their results.

2.3 Fitts' Law

In this paper, we use the Shannon Formulation [33] (Equation 1) to calculate MT for virtual hand interaction, as previous work identified that it applies to 3D movements [47, 48]:

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

The ID is calculated using 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 [26] (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 by the standard deviation between the selected position and the target center (SD_x), and characterizes the accuracy of the task performance [34, 35]:

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

We also use the angular version of Fitts' Law [28] to calculate MT for raycasting interaction, as angular distances determine performance (See Equation 4). The logarithmic term in its equation indicates the overall pointing task difficulty and is known as the index of difficulty (ID). In calculating the angular ID (ID_A), α is the angular distance between targets, and ω is the angular target width.

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

2.4 Vergence-Accomodation Conflict

Overall, previous work on the VAC yielded contradictory results [5, 8]: higher user performance was achieved either with the CONSTANT VAC conditions [8] or with the NO VAC condition [5]. We believe that the difference observed in previous work on the VAC might be due to the effect of biomechanics, i.e., due to the non-ergonomic holding style mentioned in Batmaz et al.'s work [8].

3 MOTIVATION & HYPOTHESES

Initial work by Pham and Stuerzlinger [19] identified that holding a pen in a precision grip is superior to holding the controller using a power grip. However, another study by Batmaz et al. [9] did not reveal significant differences between the two grip styles. Still, the authors used a VRInk to conduct their study, and in the limitations section, they acknowledged the high jitter in that controller. Thus, to understand how the grip style affects user performance, we decided to investigate the impact of grip style with an experimental approach that involves only a single controller with good tracking quality.

Due to the inconsistent results in previous work, a hypothesis that grip style will *always* affect performance might be inappropriate. Therefore, the first goal of this paper is to verify the effect of grip style on 3D pointing performance in peripersonal space. We hypothesize that **the grip style affects 3D selection performance for nearby targets (H1)**.

A secondary goal of this work is to re-investigate the effect of the VAC on 3D pointing performance for targets in peripersonal space. Given that previous work on the VAC might have been confounded by different grip styles for different VAC conditions, we aim to identify if the grip style interacts with the target depth by considering the effect of the VAC on the interaction. We thus also hypothesize that **the grip style interacts with the VAC to negatively affect 3D target selection (H2).**

4 USER STUDY

To test our hypotheses mentioned in Sect. 3, we performed a user study.

4.1 Participants

We conducted this study with 24 participants (13 male and 11 female, aged 18-38, M = 24.62, SD = 4.75), recruited from a variety of academic programs of the local university. 23 of them were right-handed, and 1 was left-handed. While nineteen participants reported the right eye as their dominant one, the remaining five reported their left eye to be the dominant one. All participants reported corrected-to-normal vision. When asked about how many times they had experienced VR previously, five participants reported never, seventeen reported 1-5 times, and two participants reported more than 5 times.

4.2 Apparatus

We used an 11th Gen Intel(R) Core(TM) i7-11700F at 2.5 GHz, 32 GB RAM desktop PC with an NVIDIA GeForce RTX 3070 graphics card. We used an HTC VIVE Pro HMD with one controller and two 2.0 Lighthouse base stations. To collect the controller motions as accurately as possible, one lighthouse was positioned 45° above the participants. We used Unity3D version 2021.3.5f1 to design and implement the virtual environment.

4.3 Procedure

Upon arrival, participants filled a consent form and an online demographic questionnaire. Then, the experimenter explained each interaction method (virtual hand and raycasting), demonstrated the procedure, and confirmed that the participants could use each grip style correctly and easily select targets at 65 cm [2]. The experimenter monitored participants to ensure that they did not change their grip style, but such correction was not necessary during the experiment. In addition, the experimenter also monitored participants' head movements to verify that they did not change their head pose while executing the task, i.e., that participants did not try to look at the targets from the side.

Participants were seated during the experiment and placed in a virtual environment depicting an empty room, with 11 gray spheres at their eye level for the ISO 9241:411 multidirectional selection task (Fig. 1). Out of the 11 spheres, one was selected as a target at any time and was highlighted in orange. Participants were asked to position a virtual cursor with a diameter of 0.5 cm inside the sphere for selection. When the cursor was positioned inside the sphere, we changed the color of the sphere to blue, either from gray (if the sphere was not the target) or orange (if the sphere was the target). To select such a blue sphere, participants were asked to use their non-dominant hand and press the space key on a keyboard placed on their lap (see Fig. 2), similar to previous work [9–11]. We asked participants to select the targets with the spacebar key on a keyboard to minimize unintentional motions of the pointing hand, which is also called the "Heisenberg effect" [16], i.e., the undesired re-positioning of the cursor when physical force is applied on the controller's trigger button. If the selected sphere was the target, the target's color became green; but if the sphere was not the target or the participants pressed the key when the cursor was out of the sphere, its color became red. Regardless of the correctness of the selection, the next target was then assigned diagonally across the circle of spheres and shown in orange. Additionally, we played a tone with 411 Hz as feedback when the selection was not successful [12]. Participants were instructed to rest when needed after completing a set of 11 repetitions of the selection task.

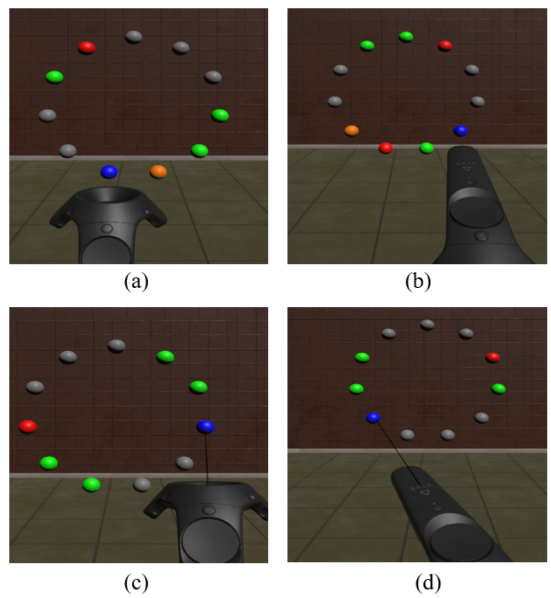


Figure 1: Cursor/ray representation in the virtual environment for virtual hand technique with (a) power grip or (b) precision grip, and raycasting technique with (c) power grip or (d) precision grip. These images were taken with target sizes ($TS = 3.5cm$) and target distances ($TD = 25cm$) appropriate for the CONSTANT VAC condition (targets were 38.2 cm away from the user). The green spheres represent targets selected when the cursor was inside of the target (i.e., "hit"), red spheres targets selected when the cursor was outside of the target (i.e., "miss"), the orange sphere the next target, and blue spheres indicate the cursor is inside of the sphere.

Participants were instructed to control the cursor through the controller held in their dominant hand with two interaction techniques: raycasting and virtual hand. In the *raycasting* technique, they kept their hands roughly at chest level (see Fig. 2) while we rendered a virtual line in the pointing direction of the controller, with the cursor placed at the tip of the ray, at a distance appropriate for the current target plane, see Fig. 1. For raycasting, we asked participants to keep their hand in (roughly) the same position without moving it (much), i.e., by mainly rotating their wrists to make selections. In the *virtual hand* technique, they reached out with their hand holding the controller towards the targets (Fig. 2), while the cursor was placed 3 cm above the virtual controller, see Fig. 1. For the virtual hand condition, participants moved their hands to make selections, so we used the Shannon-Formulation of Fitts' Law with Euclidean distances and IDs, not angular IDs.

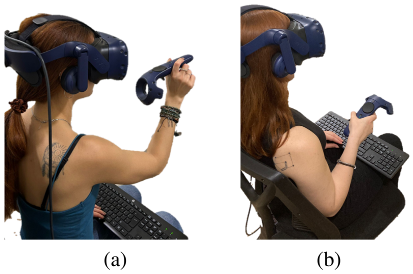


Figure 2: Participants holding the controller with a (a) precision grip and (b) power grip. The spacebar of the keyboard in the lap was used for selection.

In this study, and like previous related studies [9, 40], we also asked participants to select targets with two different **grip styles**: precision grip and power grip. For the precision grip, we asked participants to hold the controller like a pen; Fig. 2 (a) and for the power grip, like a stick; Fig. 2 (b)).

In addition to the interaction and grip techniques and in addition to the interaction and grip techniques, we also evaluated three different VAC conditions (3_{VAC}:) CONSTANT VAC, NO VAC, and VARYING VAC (Fig. 3). In the CONSTANT VAC condition, targets were placed at a constant 38.2 cm distance away from the participant; in the NO VAC condition at a constant 65 cm distance (which matches the focal distance of the used HMD); and in the VARYING VAC condition, targets were alternatingly placed at either 38.2 or 65 cm distance away from the participant. This pair of distances allowed us to vary target depth by (100/38.2-100/65=) 1.08 diopters.

Previous related work [5, 8] converted Euclidian measurements to angular ones and used the angular version of Fitts' law to analyze their results for both virtual hand and raycasting. In this study, we follow the same approach and use 9 unique angular **IDs** = 3.12 3.37, 3.55 3.59 4.02, 4.74, 3.8, 4.24, 4.5. Using the desired angular target size and target distances, we calculated Euclidean target size and target distance following Kopper et al.'s work [28]. This approach enables us to show targets with the same perceived size at both 38.2 and 65 cm depth distance while still maintaining comparability to previous work. We also used the same angular IDs as in previous work [5], where the participants were easily able to select targets at 38.2 and 65 cm with both virtual hand and raycasting conditions. As in previous studies [5, 8], we matched the ID range for the angular IDs and the Euclidean IDs to compare tasks with the same task difficulty across the two input conditions and previous studies.

As selection is a visually driven activity and apparent size could pose a confound, we used angular Fitts' law to guarantee the same perceived object sizes. Thus, the participants visually perceived the targets to have the same sizes but at different target depths (Fig. 4). This method was previously used by Batmaz et al. [5, 8], and we also used it in our study and verified that participants saw the objects with the same size (Fig. 5).

Even though participants perceived the same target sizes regardless of the distance of the target, the required physical motion varied with the interaction method in this work. With raycasting, participants needed to rotate their wrists, but with the virtual hand, they

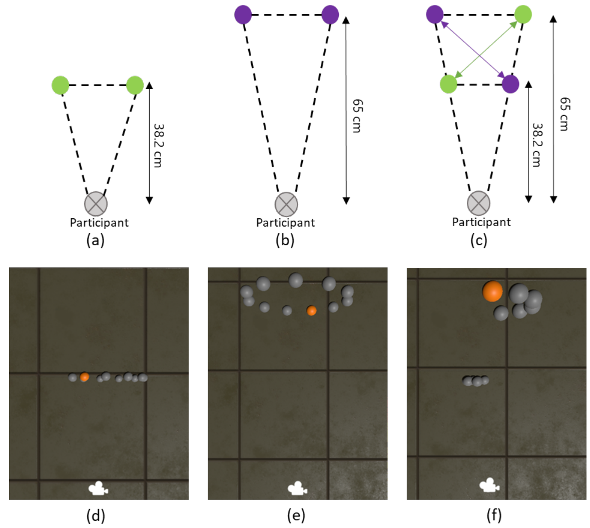


Figure 3: Top view illustration for VAC conditions: (a) CONSTANT VAC where the targets are placed at 38.2 cm, shown with green spheres, (b) NO VAC where the targets are placed at 65 cm, shown with purple spheres, (c) VARYING VAC where targets alternate between 38.2 and 65 cm. Top-down scene view for (d) CONSTANT VAC (e) NO VAC, and (f) VARYING VAC. The camera icon represents the participants' head position.

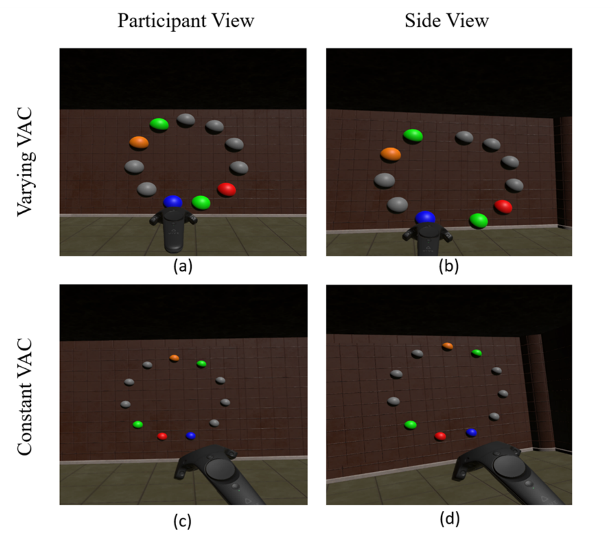
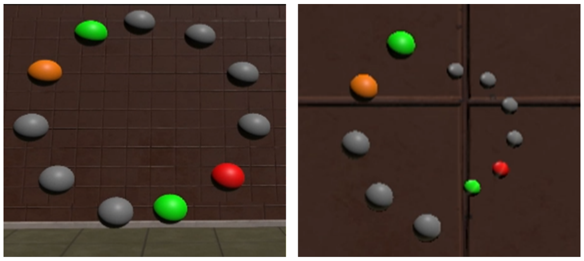


Figure 4: VAC condition differences in the ISO 9241:411 task: (a) VARYING VAC from a participant's perspective, (b) side view of VARYING VAC, (c) CONSTANT VAC from a participant's perspective, and (d) side view of CONSTANT VAC. Side view perspectives were not shown/available to the participants during the experiment and are only presented here for an illustration of the different VAC conditions.

had to move their hands to the correct location in space to select a target. For the virtual hand, this results in a diagonal movement, and thus, the distance covered was greater for the VARYING VAC condition. The increased diagonal distance between targets at 38.2 and 65 cm thus increased A_e, too. To compensate for this and to match the desired Euclidean ID, we increased the size of the target spheres accordingly in the VARYING VAC condition. This approach ensures that all conditions yield the same ID for participants.



(a) (b)

Figure 5: VARYING VAC condition: a) perspective view, where the participants perceived the targets at the same size, and b) orthographic view of the same scene from the same camera position.

4.4 Experimental Design

We conducted a three-factor within-subjects user study with three **VAC** conditions (3_{VAC} = NO VAC, CONSTANT VAC, and VARYING VAC), two **grip style** conditions (2_{GS} = power grip and precision grip), and two **interaction techniques** (2_{IM} = virtual hand and raycasting), yielding a ($3_{VAC} \times 2_{GS} \times 2_{IM}$) 12 condition ($12_{cond}$) design. We counterbalanced them across participants with a Latin Square. In total, we used 9 unique ID_As, based on three **angular target sizes** (3_{ATD}) and three **angular target distances** (3_{ATS}). Each participant performed $12_{cond} \times 9_{ID_A} \times 11$ repetitions = 1188 trials. As dependent variables, we measured task execution time (seconds), error rate (%), effective throughput (bits/s), SD_x, and ID_e.

5 RESULTS

Data was pre-processed and plotted through JMP and analyzed using three-way repeated measures (RM) ANOVA in SPSS 24. We considered data distributions to be normal when Skewness (S) and Kurtosis (K) were within ± 1 [24, 36]. Otherwise, we used log-transform before ANOVA. If the data was not normally distributed after the log transform, we used ART [50] on the original data before ANOVA. We used the Bonferroni method for post-hoc analyses and applied Huynh-Feldt correction when $\varepsilon < 0.75$. The graphs shown in the figures show the mean and the error bars show the standard deviation of the mean.

Here, we analyzed all conditions with a Repeated Measures (RM) ANOVA. We also analyzed our results for virtual hand and raycasting interaction techniques separately, but include this information only in the supplementary material.

ID_e (S = 0.2, K = 0.8) and throughput (S = 0.38, K = -0.06) were normally distributed, and time (S = 0.24, K = -0.1) and SD_x (S = 0.2, K = 0.66) after log transform. Error Rate was not normally distributed even after the log transform, so we used ART. The results are shown in Table 1 and Fig. 6.

Time: Participants were slower with the virtual hand compared to raycasting (Fig. 6(a)) and with VARYING VAC compared to CONSTANT VAC and NO VAC conditions (Fig. 6(d)). The interaction results between the interaction technique and VAC conditions revealed that they were faster with raycasting in the NO VAC condition compared to the CONSTANT VAC and VARYING VAC conditions (Fig. 6(i)). Moreover, we found a significant interaction between the interaction technique and grip style, indicating that participants were faster with the precision grip with raycasting (Fig. 6(n)).

Error Rate: Participants made fewer errors with raycasting compared to the virtual hand (Fig. 6(b)) and with NO VAC compared to the CONSTANT VAC and VARYING VAC conditions (Fig. 6(e)). Analysis between the interaction technique and VAC conditions revealed that they made fewer errors using raycasting with NO VAC compared to the CONSTANT VAC and VARYING VAC conditions (Fig. 6(j)). Moreover, we observed that they made more errors using the virtual hand technique with VARYING VAC compared to the NO VAC and CONSTANT VAC conditions.

Throughput: Participants exhibited higher throughput with raycasting compared to the virtual hand (Fig. 6(c)) and with NO VAC compared to the CONSTANT VAC and VARYING VAC conditions (Fig. 6(f)). The results revealed that virtual hand with VARYING VAC had lower throughput compared to the CONSTANT VAC and NO VAC conditions (Fig. 6(k)). Further, we found a significant interaction between interaction technique and grip style, identifying higher throughput with the precision grip with raycasting compared to the virtual hand (Fig. 6(o)).

SD_x: Participants had lower SD_x with CONSTANT VAC compared to NO VAC and VARYING VAC conditions (Fig. 6(g)). The results for the interaction technique and VAC conditions revealed a higher SD_x using raycasting with VARYING VAC compared to the NO VAC condition (Fig. 6(l)). In addition, we found a significant interaction between VAC conditions and grip style, indicating lower SD_x for the power grip with CONSTANT VAC compared to the NO VAC and VARYING VAC conditions (Fig. 6(r)).

ID_e: The results demonstrated lower ID_e with CONSTANT VAC compared to the NO VAC and VARYING VAC conditions (Fig. 6(h)). The results for the interaction technique and VAC conditions revealed that the virtual hand had lower ID_e with CONSTANT VAC compared to the NO VAC and VARYING VAC conditions (Fig. 6(m)). Analysis between grip style and interaction technique showed that a power grip with the virtual hand exhibited higher ID_e (Fig. 6(q)). Also, we saw lower ID_e results for the precision grip, but only in the NO VAC condition (Fig. 6(s)). Moreover, we identified a significant interaction between VAC conditions and grip style, indicating lower ID_e results for the precision grip in the NO VAC condition (Fig. 6(r)).

5.1 Fitts' law Analysis

We also conducted a Fitts' law analysis for both grip styles and VAC conditions, as shown in Fig. 7 and Table 2.

5.2 Questionnaire Results

Upon completion of the tasks, participants were asked to complete a post-experiment questionnaire. They were queried about their grip preference: fifteen participants preferred the power grip, while nine preferred the precision grip. Participants who preferred the power grip commented that "The heavier part of the controller is the upper part, which makes it harder to [hold] in a precision grip," and "I felt more comfortable with the power grip." On the other hand, participants who chose the precision grip stated that "I felt like I am holding a pen, and it gives me more control" and "Wrist movements were easier." We also asked participants if it was easy to select targets with each of the power and precision grips on a 1-7 Likert scale (1 = totally disagree, 7 = totally agree). Our results show that they found it easier to select targets with the power grip (Mean (M) = 5.58, Standard Deviation (SD) = 1.15, and Median (Mdn) = 6) compared to the precision grip (M = 4.62, SD = 1.67, and Mdn = 5). We also performed a Kruskal Wallis rank-based non-parametric test for these Likert scores, but did not find a significant difference between grip styles (p = 0.053) in terms of user scores.

We also asked their preference among VAC conditions: twelve participants preferred CONSTANT VAC, nine NO VAC, and three preferred VARYING VAC. Participants who preferred CONSTANT VAC commented that "It was easier to aim" and "It made me feel less tired." Those who preferred NO VAC stated that "VARYING VAC made me slower and CONSTANT VAC was too close" and "My aim was better when the targets were not close to me." Lastly, participants who chose VARYING VAC mentioned that "It kept my

Table 1: RM ANOVA Results, with significant results shown in bold.

Parameters	Interaction Technique	VAC	Grip Style	ID	Interaction Technique × VAC	Interaction Technique × Grip Style	VAC × Grip Style
Time(s)	**F(1,23)=47.13, p<0.001, η^2=0.67**	**F(2,46)=190, p<0.001, η^2=0.892**	F(1,23)=2.217, p=0.15, η^2=0.088	**F(8,184)=305.69 p<0.01 η^2=0.93**	**F(2,46)=4.41 p<0.05 η^2=0.161**	**F(2,46)=4.41 p<0.05 η^2=0.161**	F(2, 46)=0.025 p=0.975 η^2=0.01
Error rate	**F(1,23)=10.85, p<0.01, η^2=0.32**	**F(2,46)=17.65, p<0.001, η^2=0.434**	F(1,23)=0.229, p=0.636, η^2=0.01	**F(8,184)=24.054 p<0.001 η^2=0.511**	**F(2,46)=7.676 p<0.001 η^2=0.25**	F(2,46)=2.82 p=0.106 η^2=0.109	F(2, 46)=0.934 p=0.400 η^2=0.039
Throughput	**F(1,23)=59.72, p<0.001, η^2=0.722**	**F(2,46)=91.12 p<0.001, η^2=0.798**	F(1,23)=4.074, p=0.055, η^2=0.150	**F(8,184)=50.824 p<0.001 η^2=0.686**	**F(2,46)=12.23 p<0.001 η^2=0.35**	**F(2,46)=26.61 p<0.001 η^2=0.109**	F(2, 46)=0.980 p=0.383 η^2=0.041
SD_x	F(1,23)=0.99, p=0.34, η^2=0.04	**F(2,46)=221.778 p<0.001, η^2=0.906**	F(1,23)=1.113, p=0.302, η^2=0.046	**F(8,184)=96.83 p<0.001 η^2=0.808**	**F(2,46)=11.91 p<0.001 η^2=0.34**	**F(2,46)=11.12 p<0.05 η^2=0.326**	**F(2, 46)=3.492 p<0.05 η^2=0.132**
ID_e	F(1,23)=0.543, p=0.469, η^2=0.023	**F(2,46)=76.67 p<0.001, η^2=0.77**	F(1,23)=1.05, p=0.317, η^2=0.044	**F(8,184)=128.68 p<0.001 η^2=0.848**	**F(2,46)=14.221 p<0.001 η^2=0.38**	**F(2,46)=10.54 p<0.01 η^2=0.314**	**F(2, 46)=3.52 p<0.05 η^2=0.133**

Table 2: Fitts' Law Analysis Results

	Power Grip	Precision Grip
NO VAC	MT = -0.03 + 0.26 × ID R^2 = 0.98	MT = 0.03 + 0.24 × ID R^2 = 0.97
CONSTANT VAC	MT = -0.14 + 0.3 × ID R^2 = 0.98	MT = -0.18 + 0.3 × ID R^2 = 0.98
VARYING VAC	MT = 0.05 + 0.3 × ID R^2 = 0.92	MT = -0.05 + 0.33 × ID R^2 = 0.92

attention, and I was more focused during it" and "It was much easier for me to detect the orange sphere between different distances."

Finally, participants evaluated their physical and mental fatigue on a 1-7 scale (1 = I don't feel physical fatigue at all, 7 = I strongly feel physical fatigue). Participants did not indicate a strong feeling of physical fatigue (M = 4.12, SD = 1.64, and Mdn = 4.5) nor mental fatigue (M = 2.58, SD = 1.65, and Mdn = 2).

6 DISCUSSION

To analyze 3D pointing performance in peripersonal space, i.e., within arm's reach, we presented a user study and its results. There, we asked 24 participants to select targets in an ISO 9241-411:2015 multi-directional task with the two most frequently used interaction techniques: virtual hand and raycasting, with two grip styles and targets at a plane where NO VAC occurs, with a CONSTANT VAC, and with a VARYING VAC, where targets alternate in distance.

While we found no overall effect of grip style, we identified significant effects of grip style for *raycasting* in terms of time and throughput as well as an effect for SD_x and ID_e with the virtual hand. This supports our first hypothesis, **H1**, that the grip style affects 3D selection performance for nearby targets, albeit only for raycasting. Our results also confirm the previous findings of Pham and Stuerzlinger [19] and Batmaz et al. [9], where participants exhibited higher 3D pointing performance with the precision grip with raycasting. On the other hand, our results contradict the outcomes of Batmaz et al.'s most recent work [8] in terms of the influence of the VAC. We speculate that the reason for this discrepancy is how participants were asked to hold the controller in that study. In that study, participants were asked to hold the controller above their shoulder for the raycasting condition to be able to provide extra distance between the controller and the target locations so that they could interact more easily [8]. We believe that this uncommon hand pose and its effect on the grip style affected user performance, possibly creating fatigue and hindering some of their movements. Another possible explanation of this outcome might be related to task execution strategies. In our current study, we asked participants to select targets as fast and as precisely as possible. As a result, and aligned with other work [3,4,9,19], the average time was 1.05 seconds to select a target, while the average task execution time in Batmaz et al.'s study [8] was around 2 seconds. Further, we know from the previous literature that different task execution strategies can affect user motor performance [22,23], so it seems that task instructions might have been different in that previous study [8]. Thus, we invite researchers to study the effects of different task execution strategies while interacting with different VAC conditions.

In our results, we observe the fastest and highest throughput performance using raycasting and the precision grip. Even though most daily VR devices use the power grip with virtual hand interaction, we believe that the findings of our study should motivate designers to reconsider this option in future systems, not only for 3D pointing tasks but also for all interaction-based applications. Our qualitative results indicate that some participants were comfortable with holding the controller like a pen, while others were not. We believe that there might be some correlation with hand size and/or grip strength. Thus, lighter/more slender controllers that can be used in both a power and precision grip are worth looking at in the future.

Our current results strengthen not only previous findings [5,6,15] but also systematically and mathematically identify the interaction between the VAC and grip style on user performance. Still, our results must be extended and generalized to other HMD controllers, such as the Meta Quest ones. Distinct physical attributes inherent to a controller, such as its form factor, exterior material, weight, and weight distribution, might vary the findings here. Consequently, we recommend that the presented experiment be replicated with different input devices, thereby facilitating the generalization of results across a broader spectrum of controllers.

We did not observe difficulties or challenges with participants holding the controller in the precision grip style – all participants reported being comfortable with that grip style. Yet, the physical characteristics of users, such as larger hands having an easier time holding the Vive controllers, can be investigated as future work.

Our results on time, error rate, and throughput match those from previous work on the VAC [5]: in the presence of a VARYING VAC, participants were slower, made more errors, and had lower throughput for both raycasting and virtual hand interaction techniques.

We also found a significant interaction between grip style and VAC conditions. Our detailed analysis for raycasting revealed that the precision grip increases the accuracy and precision of the participants in the VARYING VAC. This supports our second hypothesis, **H2**, that the grip style interacts with the VAC for 3D target selec-

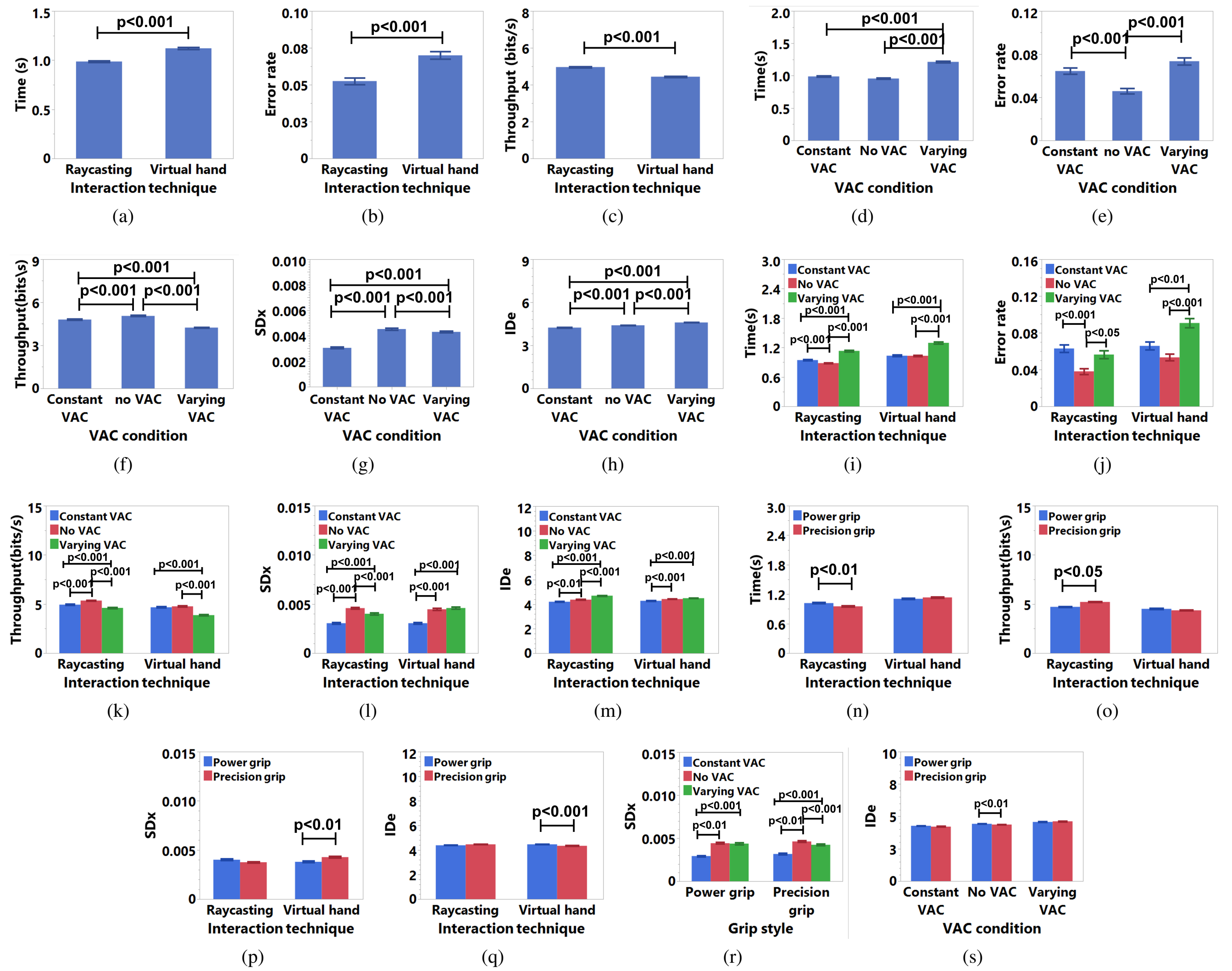


Figure 6: Results by interaction technique for (a) time, (b) error rate, and (c) throughput. Results by VAC condition for (d) time, (e) error rate, (f) throughput, (g) SD_x, and (h) ID_e. Results for interaction technique and VAC condition for (i) time, (j) error rate, (k) throughput, (l) SD_x, and (m) ID_e. Results for grip style and interaction technique for (n) time, (o) throughput, (p) SD_x, and (q) ID_e. Results for grip style and VAC condition for (r) SD_x and (s) ID_e.

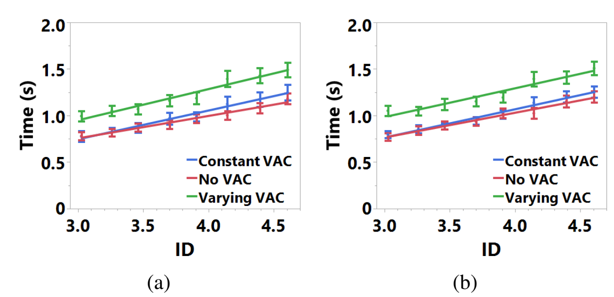


Figure 7: Fitts' law results for (a) precision grip and (b) power grip.

tion, again only for raycasting. We speculate that the perceptual challenges in the VARYING VAC condition cause this, where participants have to shift between targets at different depths continuously. Yet, the precision grip was not affected: participants had only lower performance with the power grip for the VARYING VAC. The need to switch visual depth seems to increase the task difficulty, which negatively affected user performance for the power grip.

After each 11 repetitions of the selection task, participants were instructed to rest when necessary. However, none of the participants preferred to take a break. The seated position used in our study affords a relatively relaxed pose, and we did not observe a strong need to force participants to rest their arms. Furthermore, participants did not report significant fatigue in the post-questionnaire. Thus, we believe that our results were not affected substantially by fatigue.

In this study, we asked participants to select targets using virtual hand and raycasting, the two most commonly used interaction techniques [30]. As our findings are consistent with previous work on this topic [9, 19], where participants reported being more precise with virtual hand, we did not analyze this further here.

6.1 Limitations

Our results are strictly only valid for HTC Vive Pro in an ISO 9241-411:2015 multidirectional selection task; therefore, our study should be replicated with other HMDs with different focal lengths – such as the Oculus Quest 2.

To keep the input devices and tracking performance across different conditions the same, we did not use a pen-like input device but used only an HTC Vive Pro controller to select targets in the VR, also with the precision grip. Previous work that used different input devices identified that physical properties such as the weight distribution of a controller might affect the user performance [19]. Even though Kern et al. [27] previously used a VR controller as a pen-like device and reported its feasibility, we recommend verifying our findings with a pen-like VR input device.

The weight distribution of the VR controller might be a limitation, affecting the results. Yet, the HTC Vive 2 controllers are reasonably light (220 gr) and still support a precision grip (albeit an admittedly non-ideal one). Still, to our knowledge, there is no existing VR controller that allows us to compare the two grips with a better balance between controller form and tracking accuracy. Yet, our results must be replicated with other VR and AR devices to generalize to the other controllers, such as the Meta Quest controllers.

We did not fix participants' head or hand positions during the experiment for ergonomic reasons, to maintain external validity, and to maintain comparability with previous work ([5, 8, 19]),. During the execution of the experiments, the experimenter made sure that there were no substantial head movements that would change the perspective to be a side view or large hand movements in the raycasting condition. However, small head movements caused by the lack of head restraint might still have affected our findings. Moreover, the uneven previous VR experience of the participants could also have impacted the user performance.

In this paper, we used Fitts' law to investigate our hypothesis since it enables a systematic comparison with previous VAC studies. However, we acknowledge that the results might vary with more complex tasks. Moreover, we used a limited range of *ID*s in this experiment, again to increase comparability with previous studies [6,7]. Still, we 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 insights into the differences between them.

7 Conclusion & Future Work

Here, we investigated the effect of two grip styles (precision grip and power grip) onto interaction with the two most frequently used interaction techniques (virtual hand and raycasting) in VR HMDs for pointing at targets in peripersonal space. Our results showed that different grip styles, thus biomechanics, have an effect on user performance. Participants were faster and had higher throughput for raycasting with the precision grip. Also, participants exhibited higher accuracy and precision with the precision grip in the VARYING VAC condition. Yet, grip styles did not statistically affect the adverse effects of VAC; participants still performed worse in the VARYING VAC condition. We also were able to reconfirm the effect of the VAC on pointing movements in peripersonal space [4, 6, 7].

Our future plans involve additional analysis of biomechanical factors and further studies of the impact of VAC in peripersonal space for other interaction techniques, larger depth differences, and different HMDs. Finally, we aim to repeat our experiment with a varifocal display and conduct further in-depth analysis of the VAC in stereo displays.

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SUPPLEMENTARY MATERIAL

Detailed Virtual Hand Analysis

For the Virtual Hand condition, throughput (S = 0.56 and K = 0.22) was normally distributed; and time (S = 0.14, K = -0.02) and SD_x (S = 0.2, K = 0.70) were normally distributed after log transform. Error Rate and ID_e were not normally distributed even after log transform, so we used ART on the original data. The results are shown in Table 3 and Fig. 8.

Time: Participants were slower in VARYING VAC compared to the CONSTANT VAC and NO VAC conditions (Fig. 8(k)).

Error rate: Participants made more errors in VARYING VAC compared to the CONSTANT VAC and NO VAC conditions (Fig. 8(l)).

Throughput: Participants had a lower throughput in VARYING VAC compared to the CONSTANT VAC and NO VAC conditions (Fig. 8(m)).

SD_x: Participants had lower SD_x with the power grip compared to the precision grip (Fig. 8(p)); and a lower SD_x in CONSTANT VAC compared to the NO VAC and VARYING VAC conditions (Fig. 8(n)).

ID_e: Participants had lower ID_e with the precision grip compared to the power grip (Fig. 8(q)); and a lower ID_e in CONSTANT VAC compared to the NO VAC and VARYING VAC conditions (Fig. 8(o)).

Table 3: Detailed RM ANOVA for Virtual hand. Significant results are shown in bold.

Parameters	VAC	Grip Style	ID
Time(s)	**F(2,46)=87.39, p<0.001, η^2=0.792**	F(1,23)=0.733, p=0.401, η^2=0.031	**F(4.48,111.31)=141.17, p<0.001, η^2=0.86**
Error rate	**F(2,46)=15.21, p<0.001, η^2=0.398**	F(1,23)=3.559, p=0.072, η^2=0.134	**F(6.255,143.86)=12.625, p<0.001, η^2=0.354**
Throughput	**F(2,46)=60.197, p<0.001, η^2=0.724**	F(1,23)=2.94, p=0.099, η^2=0.114	**F(8,184)=20.46, p<0.001, η^2=0.471**
SD_x	**F(2,46)=103.3, p<0.001, η^2=0.818**	**F(1,23)=12.758, p<0.01, η^2=0.357**	**F(8,184)=40.351, p<0.001 η^2=0.637**
ID_e	**F(2,46)=10.76, p<0.001, η^2=0.319**	**F(1,23)=13.011, p<0.01, η^2=0.361**	**F(8,184)=43.773, p<0.001 η^2=0.656**

Detailed Raycasting Analysis

For raycasting, ID_e (S = -0.06 and K = 0.6) and throughput (S = 0.33 and K = -0.09) were normally distributed, and time (S = 0.24, K = -0.22) and SD_x (S = 0.19, K = 0.59) was normally distributed after log transform. Error Rate was not normal even after log transform, so we used ART on the original data. The results are shown in Table 4 and Fig. 8.

Time: Participants were faster with the precision grip (Fig. 8(f)); and with NO VAC compared to the CONSTANT VAC and VARYING VAC conditions (Fig. 8(a)).

Error rate: Participants made fewer errors with NO VAC compared to the CONSTANT VAC and VARYING VAC conditions (Fig. 8(b)).

Throughput: Participants had higher throughput with the precision grip (Fig. 8(g)); and a higher throughput with the NO VAC condition than the CONSTANT VAC and VARYING VAC conditions (Fig. 8(c)). We also found a significant interaction between grip style and VAC conditions (F(2,46)= 4.662, p<0.05, η^2=0.169), indicating no significant difference for precision grip between CONSTANT VAC and NO VAC (Fig. 8(h)).

SD_x: Participants exhibited a higher SD_x with the NO VAC condition (Fig. 8(d)). We also found a significant interaction between grip style and VAC conditions (F(2,46)= 6.148, p<0.001, η^2=0.211), identifying a higher SD_x for the VARYING VAC with a power grip compared to the precision grip (Fig. 8(i)).

ID_e: Participants had a higher ID_e with the VARYING VAC compared to the CONSTANT VAC and NO VAC conditions (Fig. 8(e)). We also found a significant interaction between grip style and VAC conditions (F(2,46)= 6.276, p<0.01, η^2=0.214), with a higher ID_e for the VARYING VAC with the precision grip compared to the power grip (Fig. 8(j)).

Table 4: Detailed RM ANOVA for Raycasting. Significant results are shown in bold.

Parameters	VAC	Grip Style	ID
Time(s)	**F(2,46)=179.92, p<0.001, η^2=0.887**	**F(1,23)=12.810, p<0.01, η^2=0.358**	**F(4.86,111.92)=224.13, p<0.001, η^2=0.93**
Error rate	**F(2,46)=9,85, p<0.001, η^2=0.300**	F(1,23)=0.556, p=0.463, η^2=0.024	**F(8,184)=14,057, p<0.001, η^2=0.379**
Throughput	**F(2,46)=57.82, p<0.001, η^2=0.715**	**F(1,23)=22,77, p<0.001, η^2=0.498**	**F(8,184)=31.595, p<0.001, η^2=0.579**
SD_x	**F(2,46)=125.02, p<0.001, η^2=0.845**	F(1,23)=1.958, p=0.175, η^2=0.078	**F(8,184)=57.517, p<0.001 η^2=0.714**
ID_e	**F(2,46)=101.14, p<0.001, η^2=0.813**	F(1,23)=1.91, p=0.18, η^2=0.077	**F(8,184)=6.276, p<0.01 η^2=0.214**

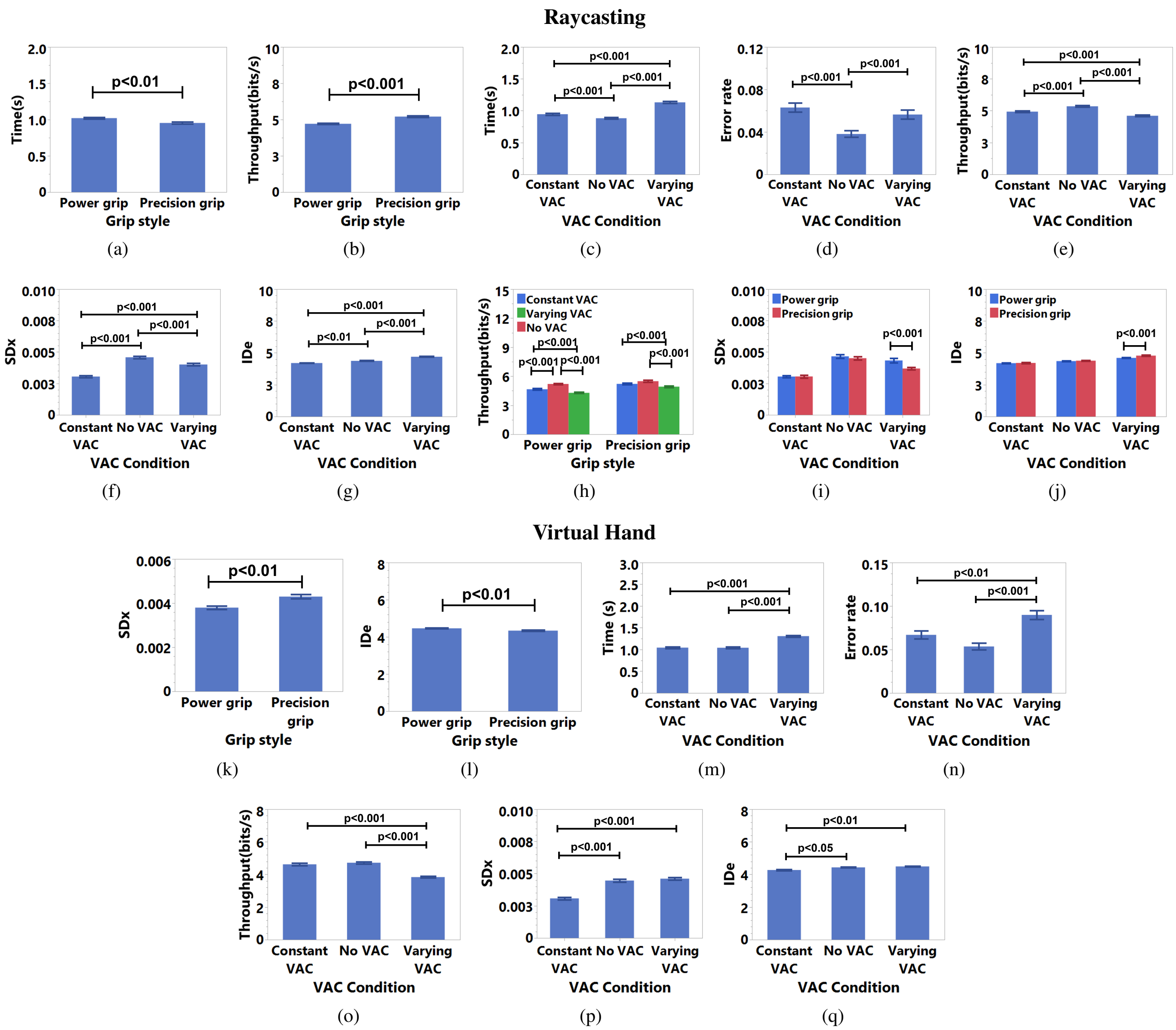

Figure 8: Detailed results for raycasting by Grip style for (a) time and (b) throughput. VAC condition results for (c) time, (d) error rate, (e) throughput, (f) SD_x, and (g) ID_e. Interaction between grip style and VAC condition for (h) throughput, (i) SD_x, and (j) ID_e. Detailed results for the virtual hand technique by grip style for (k) SD_x and (l) ID_e. VAC condition results for (m) time, (n) error rate, (o) throughput, (p) SD_x, and (q) ID_e.