Toward a More Standardized Multi-directional Tapping Task in VR: The Effect of Target Depth

Haejun Kim[*] KAIST

Yuhwa Hong[†] KAIST

Jihae Yu[‡] Kangwon National University

Shuping Xiong[§] KAIST

Woojoo Kim[¶] Kangwon National University

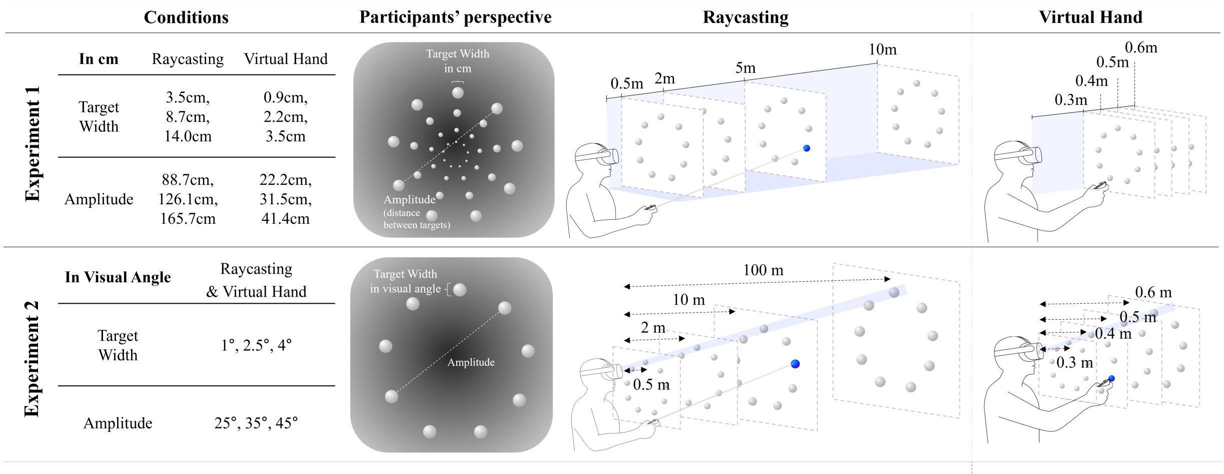

Figure 1: Experimental design for two selection techniques: Raycasting and Virtual Hand. Experiment 1 maintains consistent physical target width across depths, while Experiment 2 maintains consistent visual angles. Although these variables create different indices of difficulty, their main effects are not the primary focus of this study.

Abstract

The multi-directional tapping task has long served as a foundational tool for evaluating pointing performance in human-computer interaction research. However, its transition from 2D interfaces to virtual reality (VR) raises challenges, especially in standardizing target depth. This study explores how target depth influences performance in VR, focusing on two common techniques: Raycasting and Virtual Hand. We conducted two controlled experiments (each with n = 20) to isolate depth effects. In Experiment 1, fixed target size led to visual angle (VA) shifts across depths, affecting performance. Both techniques performed best when VA was between 1–4°; Raycasting peaked at 2 m, Virtual Hand at 0.4–0.5 m. In Experiment 2, we controlled VA to isolate depth itself. Raycasting remained stable beyond 2 m but degraded at close range due to biomechanical limits. Virtual Hand remained sensitive to depth despite fixed VA, but differences were smaller, with throughput unaffected. These results suggest VA should be the primary parameter for standardizing the task in VR. Depth-specific evaluation remains necessary, except for Raycasting beyond 2 m. We provide depth-aware guidelines to improve standardization and comparability while aligning with ISO protocols.

Index Terms: Virtual reality, multi-directional tapping task, target selection, target depth, Fitts' law.

[*]e-mail: vedonefor@kaist.ac.kr
[†]e-mail: yuhwahong@kaist.ac.kr
[‡]e-mail: vievanitas@kangwon.ac.kr
[§]e-mail: shupingx@kaist.ac.kr; corresponding author
[¶]e-mail: woojoo.kim@kangwon.ac.kr; corresponding author

1 Introduction

Standardized evaluation techniques have long been essential for human-computer interaction (HCI) research. Among them, the multi-directional tapping task—formalized in ISO/TS 9241-411 [21] (formerly ISO 9241-9 [20]) and also known as the 2D Fitts' law task [48]—has been widely used to assess pointing performance in graphical interfaces [14, 59, 47]. As virtual reality (VR) becomes prevalent, researchers increasingly adapt this task for 3D environments [60]. However, this 2D-to-3D shift introduces challenges, especially in configuring target depth consistently.

A key difficulty arises when incorporating depth in VR tapping experiments. While viewing distance affects 2D performance [19], it is usually fixed. In VR, however, depth varies and must be explicitly controlled. Originally designed for 2D, the multi-directional tapping task lacks clear guidelines for managing depth in VR. Consequently, researchers have used varied approaches, placing targets from arm's reach to several meters away [11]. Such variation hinders cross-study comparison due to methodological inconsistency. This is particularly problematic for techniques like Raycasting and Virtual Hand [41, 13].

The issue becomes more complex when considering depth-size interplay. Unlike 2D targets, those in VR appear smaller with distance due to perspective. Researchers either fix physical size or maintain constant VA–the angular size perceived at varying depths (see Sec. 2.2). Yet most 3D Fitts' law studies do not explicitly treat depth as a variable [1], leading to inconsistencies and impeding cumulative insights.

This study addresses these standardization issues by examining the role of target depth. We test two hypotheses: (H1) depth affects performance, and (H2) this effect persists even with constant VA. Two experiments were conducted. Experiment 1 varied depth (and thus VA) while fixing physical size and amplitude. Experiment 2 held VA constant across depths to isolate depth's effect. Both used

Raycasting and Virtual Hand to evaluate metrics such as movement time, error rate, and throughput. Our findings offer empirical guidelines for configuring target depth and VA, supporting standardized task design and enhancing cross-study comparability aligned with ISO/TS 9241-411.

2 Related Work

2.1 Fitts' law and the multi-directional tapping task

Fitts' law has been a fundamental principle in HCI research since its introduction in 1954. Though initially developed for 1D tasks, researchers have effectively expanded its application to 2D interfaces, contributing to major advancements in evaluating input devices and designing interfaces [38, 55]. This mathematical model has been especially useful in standardizing performance measurements across various input devices and interaction techniques, with its incorporation into the ISO/TS 9241-411 standard representing a significant achievement in HCI research methodology. The standard multi-directional tapping task has become a commonly used method for evaluating pointing devices, providing researchers with a systematic approach to measuring user performance.

This Fitts' law-based task has undergone continuous refinement through key changes in methodology, particularly regarding the calculation and interpretation of performance metrics. Researchers have developed sophisticated approaches to measuring effective target width (W_e) and effective target amplitude (A_e), which consider the actual distribution of movement endpoints rather than nominal target parameters [55, 36]. These improvements have enhanced the task's sensitivity to subtle variations in user performance, resulting in more reliable and comparable results across studies. The standardized nature of the task has enabled comprehensive evaluations of various input devices, ranging from conventional mice and touchpads to emerging technologies such as eye-tracking and gesture-based interfaces [62, 58].

Recent adaptations of the multi-directional tapping task have extended beyond traditional interface evaluations. With the rise of VR technologies, researchers have started adapting these established evaluation methods for 3D spaces, introducing new challenges in implementing and interpreting this standardized task.

2.2 Fitts' law-based studies in virtual reality

While numerous studies have attempted to extend Fitts' law to 3D selection tasks in VR environments [15, 34], these investigations have generally failed to examine the independent effect of depth on user performance. Most research has treated depth as a compound variable that affects both target width and amplitude, rather than isolating its unique impact on selection behavior.

Research applying Fitts' law in VR has typically followed three distinct approaches. The first approach maintains consistent depth while varying VAs, similar to traditional 2D studies [52, 61, 26]. The second approach keeps depth fixed while varying target width, which restricts our understanding of how depth influences selection performance [10, 7, 49, 18]. The third approach varies both target width and depth simultaneously [22, 50, 6, 10]. This method, however, introduces significant confounds between the effects of depth and perceived size, a challenge noted early on by Teather and Stuerzlinger [57, 56], who highlighted how perspective influences performance with 3D projected targets.

To address this, a pivotal shift in the literature was the adoption of visual angle-based models. Kopper et al. [28] famously proposed a model for distal pointing that replaced linear distance and width with their angular equivalents, arguing they better represent the user's perceptual task. However, the exact form of this angular model remains debated; Lane et al. [29], for instance, recently revisited this work with modern hardware and found that a simpler angular model outperformed Kopper's more complex quadratic formulation, underscoring the need for robust and standardized evaluation tasks.

Furthermore, recent work has revealed that even when attempting to control for depth and visual angle, other variables can significantly influence results. A series of studies by Batmaz et al. have shown that perceptual factors like the vergence-accommodation conflict (VAC) [3] and biomechanical factors like grip style [9] and task ergonomics [8] can act as powerful confounding variables. Their work demonstrates that an uncomfortable physical posture can even mask or reverse the expected negative effects of the VAC [5, 8]. Similarly, Li et al. [31] showed that the choice of cursor offset technique to handle varying depths dramatically impacts selection performance. These studies collectively show that a wide array of perceptual, biomechanical, and technical factors are intertwined with the effect of depth, making controlled, systematic investigation essential.

Although these studies have enhanced our understanding of selection behavior in VR, they share a significant limitation: the inability to fully and systematically separate depth's effect from VA. Our study addresses this gap by systematically investigating depth effects, allowing us to better understand depth's comprehensive influence on selection behavior.

3 Experiment 1: Effect of Target Depth Dependent on Visual Angle

3.1 Experiment 1: Methods

3.1.1 Participants

The first experiment involved 20 participants (10 females and 10 males) with an average age of 22.70 years (SD = 2.15). All participants were right-handed with normal or corrected-to-normal vision, and had an arm length from shoulder to the fingertip exceeding 0.6 m to ensure all participants could comfortably reach targets in the Virtual Hand condition. The Institutional Review Board approved the research protocol, and all participants provided written informed consent prior to participation.

3.1.2 Apparatus

A Meta Quest Pro VR headset was used for all experiments. The participants sat in a chair and used the controller in their right hand to complete the experimental task, with instructions to maintain a stable posture. The virtual environment was developed using Unity (version 2022.3.51f1). Shadows were disabled, and lighting was minimal, positioned 3 m above the participant's head on the y-axis to maximize uniform visibility. Fig. 2 illustrates the experimental setup.

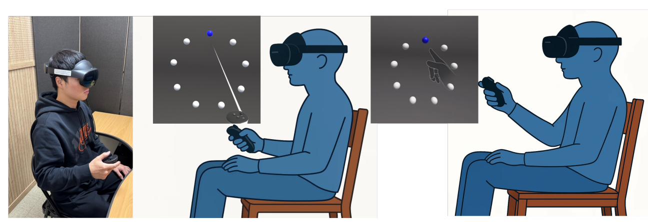

Figure 2: The experimental environment (left) and the multi-directional tapping task setup with Raycasting (middle) and Virtual Hand (right) in the virtual environment. The center point of the target ring was equal to the eye height [44].

3.1.3 Design

This study employed a within-subjects design with 4 target depths, 3 target widths, and 3 target amplitudes to evaluate two selection techniques commonly used in VR applications: Raycasting and Virtual Hand. Raycasting enables users to interact with distant objects by pointing at targets using a virtual ray projected from a controller or hand. In contrast, Virtual Hand allows direct manipulation of virtual objects within arm's reach by simulating the user's hand movements in the virtual environment. Four target depth levels were tested for each interaction technique. For Raycasting, depths were set to 0.5, 2, 5, and 10 m, whereas for the Virtual Hand technique, depths of 0.3, 0.4, 0.5, and 0.6 m were used. These depth levels were chosen based on commonly used ranges in prior VR studies [45, 22], while also ensuring coverage of a wide range of target VAs. For Raycasting, target VAs ranged from 0.2° to 0.8° in the farthest condition and from 4.0° to 15.9° in the closest condition. For Virtual Hand, VAs ranged from 0.8° to 3.3° in the farthest condition and from 1.7° to 6.7° in the closest condition. As illustrated in Fig. 1, target width and amplitude configurations remained consistent across all depth conditions, generating the same index of difficulty (ID) values ranging from 2 to 6 across all depth conditions. Please refer to Fig. 1 for the exact target widths and amplitudes used in the experiment.

Each participant completed two sessions per technique, with each session consisting of 36 test conditions (4 target depths × 3 target widths × 3 target amplitudes). The initial session served as practice and was excluded from the data analysis. Each participant completed 9 trials per condition, with 36 conditions for each interaction technique, totaling 648 trials per participant.

3.1.4 Procedure

Using a counterbalanced design, participants were randomly divided into two groups. The first group performed tasks with Virtual Hand before proceeding to Raycasting, while the second group completed these tasks in the opposite sequence. The multidirectional tapping task required participants to tap alternately between targets arranged in a circular pattern, with instructions to perform pointing movements as quickly and accurately as possible, following the ISO 9241-411 standard [21]. Test conditions were presented in randomized order. Between trials, there was a 2-second blank interval with no target displayed. After completing the tasks, we conducted follow-up interviews to explore participants' perceptions of depth's impact on performance and their underlying reasons. The experiment lasted approximately 40–50 minutes, and participants received KRW 30,000 (approximately USD 20) as compensation for their participation.

3.1.5 Data analysis

The study employed three key performance metrics for analysis: movement time (MT), error rate (ER), and effective throughput (TP) [37, 2]. To calculate TP, which quantifies the information processing rate by combining both speed and accuracy, we first computed the effective measures. We computed the effective target distance (A_e) by averaging actual movement distances, and the effective target width (W_e) by calculating the standard deviation of endpoint coordinates projected onto the task axis (SD_x). For this calculation, the endpoint coordinate was defined as the intersection point of the ray with the target's plane. We then multiplying (SD_x) by 4.133 to represent 96% of target hits (Z-score of ±2.066). This adjustment normalizes the error rate to 4%, enabling reliable cross-study comparisons [2]. The effective index of difficulty (ID_e) was then calculated as $ID_e = \log_2(A_e/W_e + 1)$, and finally, throughput was computed as $TP = ID_e/MT$. This approach ensures that our throughput measurements are independent of speed-accuracy trade-offs and less susceptible to device noise, providing more reliable comparisons across conditions [39, 56, 31]. Following established methodologies from previous pointing and crossing studies [23, 39], we included all trial data in the analysis, even those containing errors, to ensure a comprehensive evaluation.

To develop a more comprehensive understanding of user behavior, detailed analyses were conducted on various behavioral data captured by the Meta Quest Pro. We measured multiple behavioral aspects because depth effects in VR selection are multifaceted—cursor movement reveals control precision changes, controller movement captures biomechanical adaptations, and eye tracking shows visual processing demands. Cursor movement patterns were analyzed using well-established accuracy metrics for computer pointing devices [40], such as task axis crossing (TAC), movement direction change (MDC), orthogonal direction change (ODC), movement offset (MO), movement error (ME), and movement variability (MV). These parameters provided valuable insights into the characteristics of cursor movement. Controller movement was evaluated by examining mean controller height position (CH), controller movement distance (CMD), and controller mean angular velocity (CAV) [46]. The Meta Quest Pro's eye-tracking capabilities were further leveraged to assess critical visual attention metrics, including fixation duration per target (FDPT), saccade duration per target (SDPT), fixation frequency per target (FPT), and measurements of saccade amplitude per saccade (SAPS) and saccade velocity (SV). The selection of these specific eye-tracking metrics was guided by prior research demonstrating their associations with cognitive workload, visual attention patterns, and emotional arousal in human participants [53]. Detailed description regarding these behavioral measures is available in the Supplemental Material.

To identify outliers, the interquartile range (IQR) method was employed, defining potential outliers as participants whose ER exceeded 1.5 times the IQR. However, no such outliers were detected, so the analysis proceeded with the complete dataset without any participant exclusions. Lastly, linear regression analyses were performed for each depth condition to explore the relationship between MT and ID_e. Unadjusted R^2 values were used to assess the goodness of fit for the regression models.

Statistical analyses were conducted using repeated measures ANOVA (RM-ANOVA) with three within-subject factors: target depth, width, and amplitude. When Mauchly's test indicated a violation of sphericity, Greenhouse-Geisser corrections were applied. For significant effects, post-hoc pairwise comparisons were conducted with a Bonferroni correction. All analyses were performed at $\alpha = .05$ using Python 3.10.11 and R 4.4.1.

3.2 Experiment 1: Results

We present key statistical values related to the effect of target depth here. Comprehensive statistical results including all interaction effects and post-hoc tests, linear regression plots of MT against ID_e, and detailed descriptions of all behavioral metrics with their definitions and units, are provided in the Supplemental Material. Additionally, additional eye-tracking metrics (SAPS and SV) that showed limited depth-related patterns are reported in the Supplemental Material to maintain focus on the primary findings. Table 1 shows the RM-ANOVA results in Experiment 1.

3.2.1 Performance

The analysis revealed significant effects of target depth consistently across all performance metrics for Raycasting (see Fig. 3). Specifically, MT was significantly lowest at 2 m compared to all other depth conditions. As depth increased beyond 2 m, a significant increase in MT was observed, with 5 m showing significantly lower MT than 10 m. At 0.5 m, MT was higher than at 2 m and did not differ significantly from the values at 5 m and 10 m. ER showed a clear pattern related to depth. The 0.5 m and 2 m conditions yielded similar ERs, and the difference between them did not reach statistical significance. However, ER increased significantly at 5 m and reached its highest value at 10 m. Similarly, TPs at 0.5 m and 2 m were higher compared to longer depths, with no significant difference between the two. Beyond 2 m, TP progressively and significantly decreased at 5 m and 10 m.

Table 1: RM-ANOVA results in Experiment 1. *$p<.05$, **$p<.01$, ***$p<.001$; applies to all tables and bar graphs.

	Raycasting			Virtual Hand		
	F_{df}	p	η_p^2	F_{df}	p	η_p^2
Performance						
MT	$F_{1.48,28.12}=17.90$	***<.001	.089	$F_{2.14,40.70}=6.13$	**.004	.013
ER	$F_{1.80,34.20}=102.44$	***<.001	.392	$F_{2.18,41.45}=11.37$	***<.001	.030
TP	$F_{2.39,45.34}=86.88$	***<.001	.339	$F_{2.58,48.96}=4.26$	*.013	.018
Cursor movement						
TAC	$F_{1.79,34.09}=39.11$	***<.001	.247	$F_{2.58,49.08}=7.98$	***<.001	.026
MDC	$F_{1.26,23.85}=53.80$	***<.001	.268	$F_{2.62,49.71}=24.31$	***<.001	.057
ODC	$F_{1.36,25.85}=64.57$	***<.001	.316	$F_{2.57,48.91}=11.60$	***<.001	.027
MO	$F_{1.02,19.33}=40.46$	***<.001	.394	$F_{1.95,37.12}=2.56$	.092	.012
ME	$F_{1.01,19.16}=230.03$	***<.001	.828	$F_{2.28,43.36}=28.16$	***<.001	.116
MV	$F_{1.01,19.22}=244.63$	***<.001	.820	$F_{2.02,38.47}=18.45$	***<.001	.086
Controller movement						
CMD	$F_{1.00,20.78}=151.11$	***<.001	.763	$F_{1.39,26.48}=6.42$	*.011	.031
CH	$F_{1.24,23.61}=65.54$	***<.001	.300	$F_{2.57,48.85}=14.94$	***<.001	.007
CAV	$F_{1.09,20.80}=119.71$	***<.001	.734	$F_{2.47,46.93}=6.40$	**.002	.016
Eye movement						
FDPT	$F_{1.39,26.35}=27.59$	***<.001	.136	$F_{2.15,40.85}=11.07$	***<.001	.024
SDPT	$F_{1.07,20.31}=615.82$	***<.001	.926	$F_{1.58,30.09}=58.17$	***<.001	.188
FPT	$F_{1.08,20.55}=678.96$	***<.001	.926	$F_{1.66,31.49}=54.65$	***<.001	.175

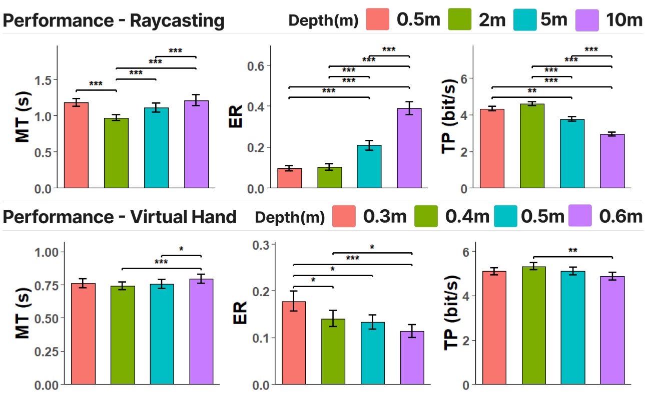

Figure 3: Mean performance measures across target depths for each selection technique. Error bars indicate the standard error of the mean; applies to all bar graphs.

For Virtual Hand, all performance metrics also showed significant results (see Fig. 3). MT exhibited significant differences, although the distinctions were less pronounced. MT at 0.6 m was significantly higher compared to at 0.4 m and 0.5 m. For ER, significant trends emerged, with ER generally decreasing as depths increased from 0.3 m to 0.6 m. However, ER at 0.5 m did not follow this trend, showing no significant difference compared to 0.4 m or 0.6 m. Significant differences were also observed in TP, but only the 0.4 m condition was significantly higher than the 0.6 m, with no other significant differences observed.

3.2.2 Cursor movement

Raycasting exhibited significant effects of target depth across all cursor movement metrics (see Fig. 4). As depth increased, TAC, MDC, and ODC generally showed significant increasing trends, with specific exceptions: The difference in TAC between 5 m and 10 m conditions was not statistically significant; MDC consistently increased significantly across all depths; and ODC showed no significant difference between 0.5 m and 2 m. In contrast, MO, ME, and MV showed significant decreases with increasing depth, except for MO which showed no significant difference between 5 m and 10 m.

For Virtual Hand, all variables showed significant results except for MO (see Fig. 4). TAC was significantly lower at 0.3 m and 0.4 m compared to at 0.6 m. MDC demonstrated a significant increasing trend with depth, except at 0.4 m, which did not differ significantly from 0.3 m and 0.5 m. ODC was significantly higher at 0.6 m compared to all other depths, while no significant differences were found among the remaining depth conditions. Conversely, ME and MV were significantly higher at 0.3 m than at all other depths, with no significant differences observed among the other depth levels.

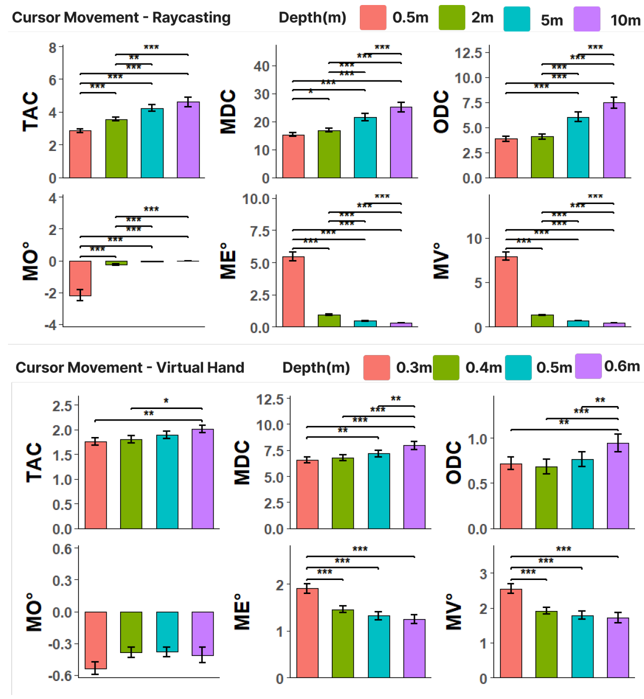

Figure 4: Mean cursor movement measures by target depth for each selection technique in Experiment 1.

3.2.3 Controller movement

When analyzing controller movement, all variables exhibited statistically significant effects of target depth when employing the Raycasting technique (see Fig. 5). CMD demonstrated significant differences across all depths, consistently decreasing as depth increased. For CH, significant differences were observed only between 0.5 m and all other depths. Similar to CMD, CAV showed significant differences across all depths, with values progressively decreasing as depth increased.

The Virtual Hand condition also showed significant results across all metrics (see Fig. 5). CMD revealed a significant difference, with 0.5 m being significantly higher compared to 0.3 m. For CH, values at depths of 0.3 m and 0.4 m were significantly lower than those at 0.5 m and 0.6 m. Finally, for CAV, the 0.6 m was significantly lower compared to depths of 0.4 m and 0.5 m.

3.2.4 Eye movement

Significant effects of target depth were observed across all eye tracking metrics with the Raycasting method (see Fig. 6). FDPT showed significant increases with depth, except between 0.5 m and 2 m. Conversely, all other variables exhibited significant decreasing trends across all depth intervals as depth increased.

The Virtual Hand method also yielded significant results across all metrics (see Fig. 6). FDPT was significantly higher at 0.6 m compared to all other depths, with no significant differences observed among the remaining depth conditions. SDPT significantly decreased with increasing depth across all intervals. FPT also decreased significantly, except between 0.4 m and 0.5 m, where no significant difference was found.

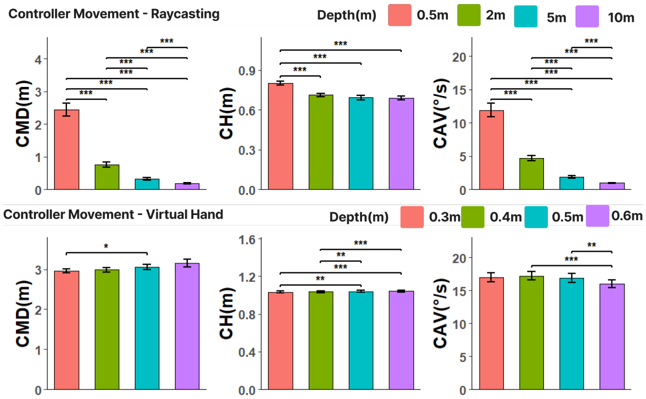

Figure 5: Mean controller movement measures by target depth for each selection technique in Experiment 1.

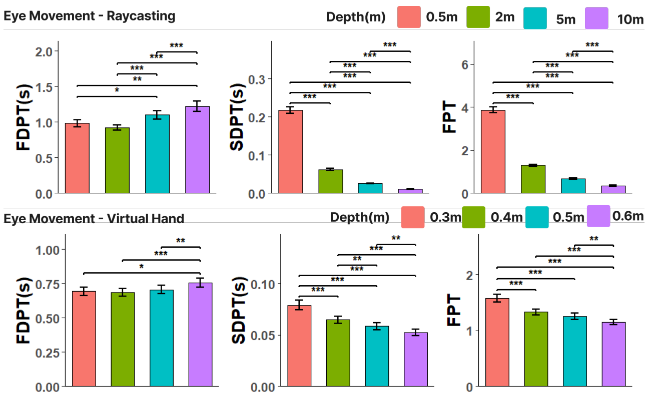

Figure 6: Mean eye movement measures by target depth for each selection technique in Experiment 1.

3.2.5 Model fitting

To investigate the influence of depth on the applicability of Fitts' law, we calculated the R^2 values for four linear regression models corresponding to each interaction method. The analysis revealed depth-dependent variations in model fit. For Raycasting, the best fit was observed at 2 m ($R^2 = 0.95$), with reasonably strong predictive power at 0.5 m ($R^2 = 0.74$). However, model reliability declined substantially at 5 m ($R^2 = 0.58$) and deteriorated further at 10 m ($R^2 = 0.07$). In contrast, the Virtual Hand method showed less dramatic depth-related variation. The strongest model fits were found at 0.5 m ($R^2 = 0.86$), 0.4 m ($R^2 = 0.80$), and 0.3 m ($R^2 = 0.72$), although performance dropped notably at 0.6 m ($R^2 = 0.47$).

3.3 Experiment 1: Discussion

3.3.1 Raycasting

In the Raycasting condition, changes in target VA due to depth significantly affected performance despite consistent absolute target sizes. Performance degraded as depth increased beyond 2 m, with MT and ER increasing while TP decreased. This decline stems from intertwined challenges in both the visual and motor tasks. First, the visual task became more demanding as targets appeared smaller at greater depths. This, in turn, required a more challenging motor task involving higher precision for cursor control. The difficulty in executing this precise motor task is evidenced by an increase in corrective movements, such as TAC, MDC, and ODC [51]. Eye tracking data further supported this interpretation, showing increased FDPT at greater depths, indicating longer visual processing times for this challenging visual input [53]. Second, the motor task was further complicated by the amplification of input noise; in Raycasting, small angular movements of the controller translate to larger cursor displacements at greater distances, making precise control increasingly challenging. Hand tremor and other input noise are magnified proportionally with depth, compounding the selection difficulty for the motor system [17]. Participant feedback corroborated these observations, with P1 noting, "*As the depth increased, targets seemed to get smaller,*" and P9 explaining, "*As targets appeared farther away, they looked smaller, and the trembling in my hand holding the controller made selection more difficult.*"

Interestingly, the closest depth (0.5 m) also presented visuomotor challenges, which exhibited higher MT than 2 m, and comparable ER and TP values. As seen in the CH measurements, participants had to raise their hands significantly higher to interact with targets at this close depth. This occurred because the increased VA at close range caused targets to extend beyond the user's field of view (FOV), creating a difficult visual search task. As a result, the motor task was compromised by biomechanical constraints such as raised arm postures and restricted movement range, which made precise Raycasting more difficult [33, 43]. These constraints led to less efficient hand movement patterns (increased CMD and CAV) and compromised cursor stability (higher MO, ME, and MV) [16]. The increased FPT values further indicate that participants needed more visual efforts to process targets that extended beyond the FOV. Participant feedback reinforced these findings. P2 stated, "*The closest depth was challenging because the targets wouldn't fit in my FOV simultaneously,*" while P4 added, "*Despite targets being easier to select when closer, they didn't fit in my FOV, requiring me to lift or turn my head frequently, which was tiring.*" Additionally, P14 noted, "*The closest condition was inconvenient because targets didn't fit entirely in my view, though selection itself wasn't difficult.*" For other eye tracking metrics (e.g., SDPT, SAPS, and SV), we observed expected decreasing trends with increasing depth. These results reflect the fact that larger VAs at closer depths required more extensive visual scanning behavior.

Our analysis regarding model fit further supported these findings. The relationship between ID_e and MT was most reliable at the 2 m depth, where the regression model achieved the highest R^2 value. As depth increased beyond this point, particularly at 10 m, the predictive power of the model declined sharply. This deterioration in model fit occurred because, at extreme depths, all target width conditions appeared similarly small, causing the model to fail in capturing meaningful variations in task difficulty [54]. This challenge with traditional Fitts' law at large distances is precisely why specialized performance models for distal pointing in VR have been proposed and refined [29, 28]. Likewise, at very close depth (0.5 m), performance was affected by additional factors beyond target size, such as the aforementioned visual and motor challenges, which reduced the accuracy of the Fitts' law model [32, 42].

3.3.2 Virtual hand

In the Virtual Hand condition, we observed distinct performance patterns across different depth levels, offering valuable insights into direct manipulation in VR. MT was highest at 0.6 m compared to other conditions. This performance decline at greater depths can be understood through the interplay of visual and motor challenges. The smaller VAs at greater depths presented a more difficult visual task, which in turn required a more demanding motor task: more deliberate and time-consuming hand movements to ensure accuracy. The struggle in the motor task is reflected in behavioral metrics, specifically, increased TAC, MDC, and ODC, while the increased FDPT suggests longer processing time for the more challenging visual input [30].

Interestingly, ER decreased as depth increased, despite target size remaining constant across all conditions. At the closest depth (0.3 m), participants encountered two primary challenges: a visual task challenge where targets extended beyond their FOV, necessitating additional head movements, and a motor task challenge where the confined interaction space forced awkward hand and arm postures [35]. This was supported by elevated ME and MO at 0.3 m, indicating reduced precision in motor control. Similar to Raycasting, FPT were notably higher at this depth, suggesting greater visual processing demands. These combined biomechanical and visual attention requirements likely contributed to the elevated ER, despite targets appearing larger due to increased VA [32].

Unlike Raycasting, TP remained relatively consistent across depths for Virtual Hand, suggesting greater robustness to depth variations within the arm's reach. Participant feedback supported this finding, with P5 stating, "*All four depth conditions felt similar in difficulty.*" However, a slight drop in TP was observed at 0.6 m, which was attributed to physical discomfort rather than perceptual limitations of participants [5]. P3 and P5 reported, "*My arm became painful when targets were far away,*" while P7 and P8 remarked, "*Having to extend my arm further at greater depths was more physically demanding.*" Remaining eye movement metrics showed expected decreasing trends as depth increased, corresponding to changing VAs and movement amplitudes. However, these depth-related differences were less pronounced than in Raycasting, likely due to the narrower range of depths tested for Virtual Hand.

Our Fitts' law analysis revealed the strongest relationship between ID_e and MT at 0.5 m depth, with the highest R^2 values. Predictive accuracy diminished at extremely close (0.3 m) and far (0.6 m) depths, suggesting that 0.4–0.5 m may represent an optimal interaction zone for Virtual Hand techniques—aligned with established VR comfort zones [35].

Collectively, the findings provide strong support for H1. As hypothesized, performance varied significantly with depth, a pattern clearly linked to the changing visual angle at extreme near and far distances. However, this very link created a methodological confound between depth and VA. To disentangle these variables and test H2, we conducted a second experiment that held VA constant across all depths.

4 Experiment 2: Effect of Target Depth Independent of Visual Angle

4.1 Experiment 2: Methods

4.1.1 Participant, apparatus, procedure, and data analysis

We recruited 20 new participants (8 females and 12 males, mean age 22.45, SD=3.21) for Experiment 2. The apparatus, procedure, and data analysis methods were identical to Experiment 1. Data from two participants were excluded as outliers (ER > 0.4). The key difference was in the experimental design, as described below.

4.1.2 Design

This experiment employed a within-subjects design with 4 target depths, 3 target widths as VA (1°, 2.5°, and 4°), and 3 target amplitudes as VA (25°, 35°, and 45°) to evaluate Raycasting and Virtual Hand techniques. For Raycasting, we tested depths of 0.5, 2, 10, and 100 m, while Virtual Hand maintained the same depth range as Study 1 (0.3, 0.4, 0.5, and 0.6 m). The inclusion of the 100 m condition, though extreme, was intentional to test our hypothesis that beyond a certain depth threshold, depth has negligible impact on pointing performance when visual angle is held constant. These depth conditions were selected to examine a wide spectrum of binocular disparities [24], ranging from high disparities at close depths to minimal disparities at far depths. As illustrated in Fig. 1, unlike Experiment 1, we maintained consistent target VAs across all depth conditions by proportionally adjusting target sizes with depth. Target sizes were pre-calculated based on the viewing distance to ensure consistent visual angles. To prevent variations during trials, participants were instructed to maintain a stable seated posture throughout the experiment. Additionally, at the start of each trial, targets were positioned relative to the participant's current head position, compensating for any minor postural shifts between trials. We used the VAs from Experiment 1 that produced the highest R^2 values—specifically, those corresponding to the 2 m depth for Raycasting and 0.5 m depth for Virtual Hand.

4.2 Experiment 2: Results

Table 2 shows the RM-ANOVA results in Experiment 2.

Table 2: RM-ANOVA results in Experiment 2.

	Raycasting			Virtual Hand		
	F_{df}	p	η_p^2	F_{df}	p	η_p^2
Performance						
MT	$F_{2.33,44.36} = 8.10$	***<.001	.025	$F_{2.21,41.93} = 18.80$	***<.001	.044
ER	$F_{2.25,35.94} = 4.63$	*.013	.014	$F_{2.48,39.62} = 4.21$	*.024	.017
TP	$F_{2.69,51.20} = 23.66$	***<.001	.077	$F_{2.27,43.16} = 2.60$	.079	.011
Cursor movement						
TAC	$F_{2.45,46.48} = 4.19$	*.015	.016	$F_{2.42,45.91} = 5.57$	**.004	.024
MDC	$F_{2.43,46.19} = 0.63$	.566	.002	$F_{2.32,44.00} = 10.32$	***<.001	.029
ODC	$F_{2.35,44.68} = 3.33$	*.038	.009	$F_{1.86,35.35} = 2.29$	.120	.009
MO	$F_{1.31,24.98} = 7.72$	**.006	.050	$F_{2.31,43.94} = 16.36$	***<.001	.047
ME	$F_{1.28,24.40} = 20.36$	***<.001	.088	$F_{2.55,48.39} = 0.76$	.501	.004
MV	$F_{1.26,23.91} = 12.64$	***<.001	.051	$F_{2.67,50.69} = 1.57$	.211	.007
Controller movement						
CMD	$F_{2.00,38.02} = 1.88$	.167	.007	$F_{2.39,45.36} = 1095.66$	***<.001	.795
CH	$F_{1.78,33.80} = 44.01$	***<.001	.021	$F_{1.79,34.08} = 3.66$	*.041	<.001
CAV	$F_{1.38,26.29} = 4.54$	*.032	.012	$F_{2.13,40.47} = 140.02$	***<.001	.148
Eye movement						
FDPT	$F_{2.28,43.40} = 8.48$	***<.001	.027	$F_{2.18,41.43} = 12.16$	***<.001	.029
SDPT	$F_{1.49,28.34} = 1.16$	.314	.004	$F_{1.92,36.49} = 66.15$	***<.001	.226
FPT	$F_{1.64,31.25} = 1.55$	.229	.005	$F_{1.64,31.20} = 55.99$	***<.001	.197

4.2.1 Performance

The results revealed distinct performance patterns across different depths for both interaction techniques (see Fig. 7). For Raycasting, the shortest depth resulted in a significantly longer MT compared to depths of 10 m and 100 m. However, statistical comparisons did not reveal significant differences between the 2 m condition and other depth conditions. Regarding ER, although 0.5 m exhibited higher ER compared to other depths, these differences were not statistically significant. Similarly, TP remained generally consistent across depths, except for 0.5 m which demonstrated notably lower performance.

For Virtual Hand, moderate variations in performance were observed across depths (see Fig. 7). The longest MT was recorded at 0.6 m, followed by 0.5 m. In contrast, shorter MTs were observed at 0.3 m and 0.4 m. ER was significantly higher at 0.3 m compared to 0.5 m and 0.6 m, while the 0.4 m condition did not differ significantly from the other depths. Finally, the analysis did not reveal any significant differences in TP across the various depth conditions.

4.2.2 Cursor movement

For Raycasting, significant effects of target depth were observed in all variables except MDC (see Fig. 8). Although TAC and ODC showed statistical significance in the ANOVA, post-hoc comparisons revealed no significant pairwise differences, suggesting minimal practical variation across depth conditions. MO was significantly higher at 0.5 m compared to 100 m, with no other significant pairwise differences. Both ME and MV were significantly higher at 0.5 m than at all other depths, with no significant differences observed between the other depths.

For Virtual Hand (see Fig. 8), TAC was significantly lower at 0.3 m than at 0.6 m, with no significant differences observed among the other depths. MDC was significantly lower at 0.3 m and 0.4 m compared to 0.6 m. ODC did not show any significant effects. MO significantly increased with depth, except at 0.5 m, which showed no significant differences compared to the adjacent depth. Lastly, no significant effects were observed for ME and MV.

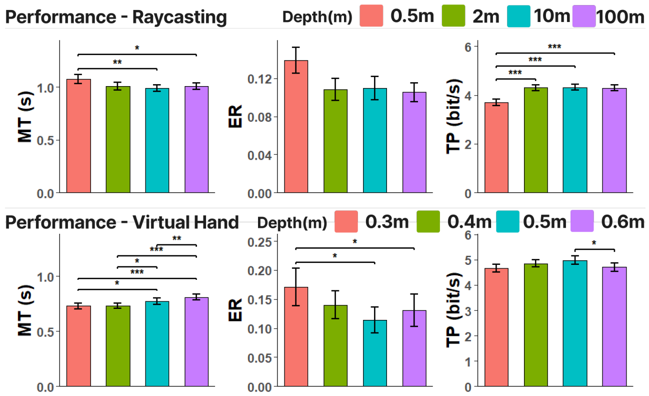

Figure 7: Mean performance measures by target depth for each selection technique in Experiment 2.

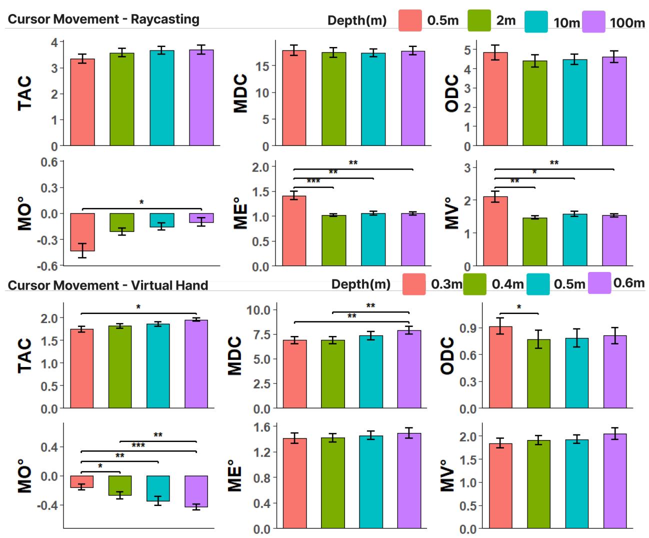

Figure 8: Mean cursor movement measures by target depth for each selection technique in Experiment 2.

4.2.3 Controller movement

For Raycasting, CMD showed no significant effect of depth (see Fig. 9). In contrast, CH demonstrated significant differences, being higher at 0.5 m compared to all other depths, and at 2 m compared to 100 m. Although CAV showed statistical significance in the ANOVA, post-hoc comparisons revealed only a non-significant trend, with 0.5 m exhibiting the lowest values among all depths.

For Virtual Hand (see Fig. 9), both CMD and CAV exhibited significant effects, with values significantly increasing across all depth intervals. In contrast, CH showed a significant effect in the ANOVA, but post-hoc comparisons revealed no significant pairwise differences, suggesting minimal practical variation between depths.

4.2.4 Eye movement

In the Raycasting condition (see Fig. 10), FDPT was significantly affected by depth, with higher values at 0.5 m than at 10 m and 100 m. In contrast, SDPT, and FPT showed no significant depth effects.

For Virtual Hand (see Fig. 10), all variables exhibited significant effects related to depth. FDPT was highest at 0.6 m compared to all other depths. SDPT, and FPT significantly increased as depth increased.

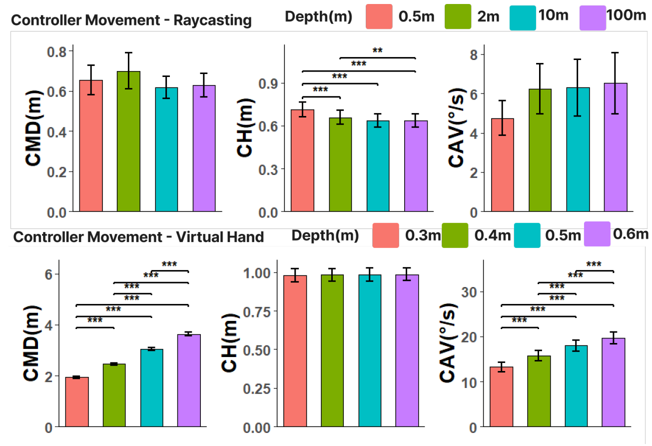

Figure 9: Mean controller movement measures by target depth for each selection technique in Experiment 2.

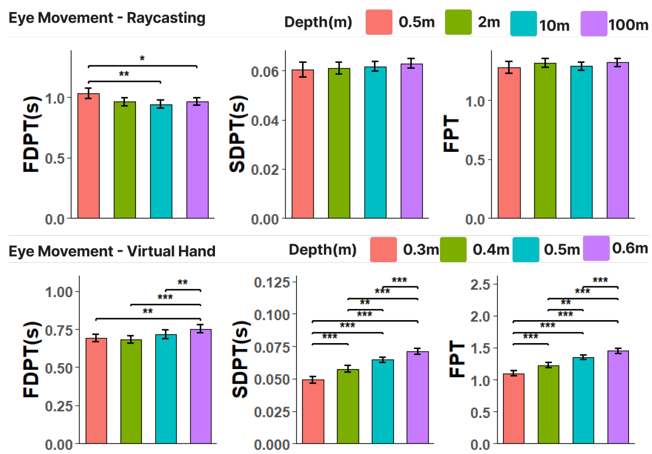

Figure 10: Mean eye movement measures by target depth for each selection technique in Experiment 2.

4.2.5 Model fitting

As in the first study, R^2 values were calculated to assess model fit. For Raycasting, strong linear relationships between MT and ID_e were found in all depth conditions. Unlike the first experiment, the highest R^2 value of 0.94 was observed at the farthest depth (100 m), followed by 2 m ($R^2 = 0.91$) and 10 m ($R^2 = 0.89$), with only minor differences between them. The closest depth (0.5 m) yielded the lowest R^2 value (0.82). Despite this slight decrease at the closest depth, all depth conditions maintained good model fits with $R^2 > 0.82$, demonstrating strong adherence to Fitts' law predictions regardless of depth.

In contrast, Virtual Hand exhibited more noticeable variations across depths. The highest R^2 value (0.79) was observed at 0.5 m, followed closely by 0.6 m ($R^2 = 0.76$). Considerably lower values were observed at 0.3 m ($R^2 = 0.66$) and 0.4 m ($R^2 = 0.62$). This pattern suggests that the predictive accuracy of the Fitts' law model is more depth-dependent in Virtual Hand than in Raycasting.

5 Experiment 2: Discussion

5.1 Raycasting

Our results revealed that when VAs remain constant, depth itself has a less pronounced effect on performance compared to the substantial impact of varying VAs observed in Experiment 1, largely isolating the influence of the motor task from the primary visual task. In the Raycasting condition, performance was primarily affected at the closest depth (0.5 m), while remaining relatively stable from medium (2 m) to far depths (100 m). This pattern can be attributed to challenges in the motor task, even when the visual task was held constant. First, although VAs were controlled across all conditions, targets at the closest depth (0.5 m) were positioned near the participant's head. As evidenced by increased CH, participants were forced to raise their hands to interact with these close targets. This motor challenge, in the form of an elevated hand posture, likely led to increased muscle fatigue, resulting in longer MT and lower TP [25]. Participant feedback supported these findings, with P6 mentioning: *"When targets were too close, I tended to lean my body backward."* This observation, along with reports from other participants indicating increased hand movements and postural adjustments at closer depths, suggesting consistent compensatory strategies for physical discomfort. The higher values in MO, ME, and MV further support this interpretation, indicating less stable cursor control at close depths. Additionally, the significantly increased FDPT at 0.5 m suggests that participants required longer visual fixations to process targets positioned at such challenging close proximity [32].

Second, regarding ER, the proximity between the controller and target at 0.5 m introduced dual motor control challenges: small rotational movements of the controller caused exaggerated cursor movements, making precise control more difficult, and the raised hand position increased physical instability and tremors, as evidenced by elevated MO, ME and MV values [33, 43]. These factors collectively contributed to the performance decline observed at the closest depth.

The consistent performance observed at greater depths (2, 10, and 100 m) suggests that once targets are beyond a certain range, depth has minimal impact on Raycasting performance when VAs are controlled. This stability can be attributed to the inherent nature of Raycasting [12], where the physical action required for pointing remains relatively constant regardless of target depth. Interestingly, the introduction of consistent VAs across depths appears to have reduced the perceived differences in task difficulty. Compared to the contrasting patterns seen in Experiment 1, the more uniform behavioral and eye-tracking measures in Experiment 2 provide compelling evidence that participants perceived a similar level of difficulty across most depth conditions in the second experiment. Participant feedback further supported these findings, with participants reporting difficulty distinguishing depth differences beyond the 0.5m condition, where physical constraints became apparent. Our Fitts' law model analysis demonstrated robust fit across all depth conditions ($R^2 > 0.82$), with the highest predictive accuracy observed at the farthest depth (100 m, $R^2 = 0.94$). This finding contrasts sharply with Experiment 1, where the model fit deteriorated significantly at extreme depths. The consistently strong fit in Experiment 2 indicates that when VAs remain consistent, Fitts' law effectively predicts MT regardless of depth. This supports the conclusion that VA, rather than depth itself, is the primary factor influencing selection performance when biomechanical motor challenges are minimal.

5.2 Virtual hand

For Virtual Hand condition, our results revealed that even with a constant visual task, the motor task depth continues to significantly influence performance even when VAs remain constant, following patterns similar to those observed in Experiment 1. Our findings indicate an optimal performance range between 0.4–0.5 m, with performance degradation observed at both closer (0.3 m) and farther (0.6 m) depths.

MT increased proportionally with depth, consistent with prior work showing that with shorter depths requiring less physical effort [4], a trend also confirmed by CMD metrics in our data. This relationship directly reflects the intrinsic nature of motor task in Virtual Hand interactions, in which physical hand movements are mapped directly to virtual movements. Unlike Experiment 1, where absolute sizing minimized movement disparity across depths, our VA-controlled approach required participants to traverse greater absolute distances at farther depths, leading to more pronounced MT differences as a direct consequence of increased motor effort.

While TP did not vary significantly across depth conditions, ER revealed an intriguing pattern. Despite consistent target VAs, ER tended to decrease from 0.3 m to 0.5 m as the absolute target width increased with depth, which may have facilitated selection. However, errors slightly increased at 0.6 m, likely due to increased physical discomfort from extended reaching movements [4]. This interpretation is supported by Penumudi et al., who found that target locations in the multi-directional tapping task in VR significantly impact biomechanical strain on the neck and shoulders [44]. Additional behavioral metrics, including TAC, MDC, and MO, also revealed increased difficulty at greater depths, collectively supporting a U-shaped performance curve. The increasing TAC, MDC, and MO, all indicate greater difficulty in maintaining precise control as reaching depth extends. These metrics collectively suggest an optimal interaction zone that balances target accessibility with arm comfort [33].

Participant feedback strongly supported these objective measurements. P15 highlighted the physical strain associated with reaching for distant targets, stating: *"When targets were farther away, my arm would hurt and i struggled to maintain accuracy."* P11 offered a similar observation: *"As the depth increased, I had to move my head more and stretch my arm further, which was tiring."* On the other hand, interacting with targets at the closest depth presented distinct challenges. P9 observed: *"When targets were too close, my hand would accidentally trigger errors while moving between targets."* These subjective reports correlate with our objective findings, which indicate peak efficiency at intermediate depths (0.4–0.5 m), with notable declines at both extremes.

Overall, our findings demonstrate that even under VA-controlled conditions, the physical constraints of Virtual Hand interaction introduce a strong depth–performance dependency. Unlike Raycasting, where performance remains relatively stable across greater depths once VAs are controlled, Virtual Hand performance is fundamentally tied to the biomechanical constraints of human arm movement, making optimal depth range a critical consideration for interface design.

Thus, the combined results from Experiment 2 offer compelling support for H2. As predicted, depth continued to be a significant factor even with constant VA. The distinct performance patterns that emerged between Raycasting and Virtual Hand successfully revealed the unique biomechanical and motor control demands of each technique.

6 Implications

Our findings offer important insights for standardizing the use of a multi-directional tapping task in VR. For Raycasting, using absolute target sizes across varying depths creates inconsistent task difficulty, even with a constant task ID. When targets retained the same dimensions, performance varied markedly across different depths due to changes in VA. However, when we scaled target size proportionally with depth to maintain a consistent VA, performance remained relatively stable from medium to far depths, with noticeable differences only at very close range (0.5 m). Additionally, our findings indicate that the linear relationship between MT and ID_e breaks down when the VA is extremely small. Given that VA more accurately reflects actual task difficulty and facilitates the avoidance of extreme values during the experimental design phase, it should be used as the primary standard for defining target parameters [27].

Furthermore, for evaluating Raycasting-based pointing tasks, our results indicate that testing at various depths beyond 2 m, while aligned with the original intent of Raycasting for selecting distant objects, may not be essential when using a multi-directional tapping task, as user performance remains consistent across these conditions. However, when evaluating at closer depths such as 0.5 m, researchers should account for both the significant performance drop and behavioral pattern changes observed at this range. These distinct variations underscore the importance of incorporating depth conditions into task design and interpretation of results, as they represent fundamentally different operational regimes rather than simple performance gradients.

In contrast, for Virtual Hand interactions, depth continued to affect performance even when visual angles were held constant, though these differences were less pronounced than in the first experiment. While TP showed no significant differences across depths in the second experiment, other metrics like MT and ER still demonstrated meaningful variation, particularly at the extremes (0.3 m and 0.6 m). This sensitivity to depth likely stems from the biomechanical constraints inherent to Virtual Hand techniques, which involve direct physical manipulation within a limited interaction range.

For evaluating pointing performance with Virtual Hand techniques, our results from both experiments suggest that VA should serve as the primary parameter for standardizing the task, while acknowledging that depth still remains an important factor. We recommend conducting tests across a range of depths within the reachable range (approximately 0.3–0.6 m). If resource constraints prevent this, setting target depths to approximately 0.4–0.5 m represents the optimal interaction zone that balances accuracy and physical comfort. Researchers should carefully report and standardize depth parameters to ensure reliable cross-study comparisons, as performance metrics remain sensitive to depth changes even when visual angles are controlled. This careful standardization is essential for developing cumulative understanding about interaction performance in VR environments.

7 Limitation and Future Work

It is essential to consider certain constraints that might affect how we interpret our results. First, the depth-related effect sizes (η_p^2) we observed were relatively small, especially when compared to those of VA and amplitude. This can be attributed to the nature of the multi-directional tapping task, in which Fitts' law predicts that target size and depth between targets primarily determine performance variations.

In addition, our findings are closely linked to the particular VR equipment and virtual environment we used. The Meta Quest Pro's technical characteristics, including field of view, resolution, focal plane, and stereo rendering techniques, may have impacted our depth perception observations. Although this headset represents a current mainstream approach, studies using alternative VR devices might produce different results. Our deliberately simplified virtual environment, created to examine depth effects in isolation, doesn't include the complex depth cues present in natural settings, such as shadows, textures, perspective, and occlusion. This could restrict how directly our findings apply to typical VR applications where these various cues combine to influence user perception and performance. While our controlled setting provides important foundational insights about depth's role in selection behavior, performance patterns might differ in more complex, realistic environments.

Lastly, our research focused on a finite number of specific depth levels, which may not capture all the subtle aspects of depth perception in VR. Future studies could build on our work by examining selection behavior in more visually complex environments with multiple depth cues, testing target selection across more varied depth ranges, and considering how individual differences affect depth perception. Additionally, extending this research to augmented and mixed reality contexts would be valuable, as the combination of virtual and physical elements might yield different depth perception patterns. Such expanded research would better reflect actual VR applications and help develop more thorough models of selection behavior in virtual environments. Testing across different VR headsets would also strengthen the applicability of our findings throughout the VR field.

8 Conclusion

In this study, we systematically investigated how target depth affects user performance in VR multi-directional tapping tasks across two experiments. Our first experiment revealed that when target width remains constant, visual angle changes due to depth significantly impact performance, with Raycasting performing optimally at 2 m and deteriorating at both closer and farther depths, while Virtual Hand showed best results within a narrow 0.4–0.5 m range. Building on these findings, our second experiment maintained consistent visual angles across depths and demonstrated that depth itself continues to influence performance even when controlling for perceptual factors. For Raycasting, performance remained largely consistent at depths beyond 2 m but degraded at close range (0.5 m), suggesting that standardized protocols should focus on visual angle rather than absolute size for distant interactions. Conversely, while the depth-related differences were less pronounced compared to Experiment 1, Virtual Hand remained sensitive to even minor depth variations (around 0.1 m), showing its best performance near 0.5 m. This outcome indicates that biomechanical constraints persist as a key factor, even when visual angle is held constant. Notably, participants could discern performance differences between depth conditions despite identical visual angles, emphasizing the perceptual and interactive nuances introduced by depth. These findings underscore the importance of careful depth consideration in VR research methodologies and provide empirical evidence-based guidelines for standardizing multi-directional tapping tasks in virtual environments, which should help improve comparability across future studies while preserving established ISO methodological standards.

Supplemental Materials

All supplemental materials are available on OSF at `https://osf.io/2veqg/?view_only=7810702e12a7428189b89ff1ba5d0717`, released under a CC BY 4.0 license. In particular, the materials include (1) a PDF file containing full statistical results, including interaction effects, post-hoc analyses, MT vs. ID_e regression plots, and concise definitions with units for all behavioral measures; (2) a PNG image showing a third-person perspective of the target setup in Experiment 2; and (3) two demo videos illustrating the tasks used in Experiments 1 and 2.

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