Scaled Mouse: An Efficient and Accurate Interaction Technique for 3D Docking in Seated VR

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(a) Position Task   (b) Rotation Task   (c) Position & Rotation Task
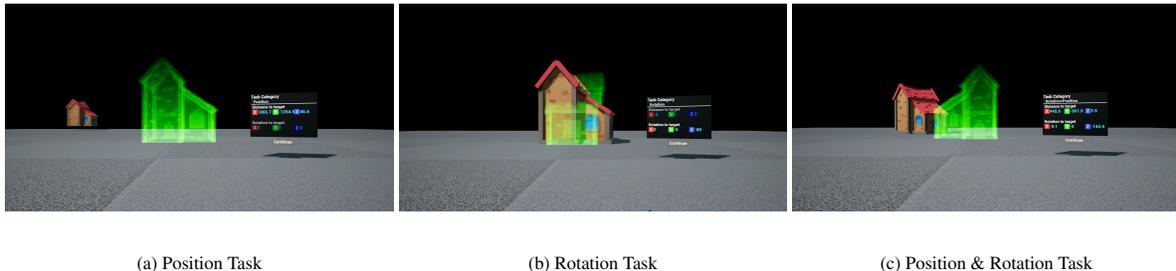
Figure 1: Task interface for the first study, where participants were asked to place the object at the target location, assisted by the visual guidance through the transparent target and the values shown on the movable detail panel, visible on the right side.

ABSTRACT

This paper presents an empirical evaluation of mouse-based interaction in seated Virtual Reality (VR) scenarios as an alternative to traditional VR controllers. We introduce Scaled Mouse, an interaction technique that shows the position of the real mouse in VR and maps standard mouse actions to 3D object manipulation using velocity-based scaling. We present two user studies assessing this method. In the first study, we compared a VR controller against our mouse-based method for manipulation tasks. Results show that the mouse consistently achieved higher rotation accuracy in 3D rotation and docking tasks than the controller, while maintaining comparable task completion times. Building on prior scaled interaction techniques, our second study investigated mouse interaction in a productivity-oriented scenario where users could combine 3D manipulation with a 2D adjustment panel. Scaled Mouse interaction was significantly faster and more accurate than the controller for 3D docking tasks and was rated significantly higher in usability and workload measures. Together, these findings establish the mouse as a viable and effective input device for seated VR contexts, offering both familiarity and accuracy advantages over controllers, particularly for professional and productivity-focused applications.

Index Terms: Mouse-based VR interaction, Seated VR, Scaled interaction, 3D object manipulation, 3D docking.

1 INTRODUCTION

Virtual Reality (VR) technology is increasingly being used for immersive applications in entertainment, training, and work, and is now commonly adopted in seated environments such as offices and living rooms [31, 14, 27, 23, 46]. However, interacting with standard desktop tools (e.g., keyboard and mouse) while wearing a VR headset remains cumbersome; users often need to remove the headset to switch devices. Such interruptions fragment the workflow and undermine immersion, creating barriers to adopting VR for produc-

tivity tasks. Conventional VR handheld controllers, while effective for many 3D interactions, do not provide sufficient precision for fine manipulations [2, 3, 16, 22], and impose a learning curve on users accustomed to traditional interfaces.

In contrast, the standard computer mouse is one of the most familiar and stable input devices. It benefits from years of user experience, surface support for fine-grained control, and well-established mappings for manipulation and docking. Prior research has shown that the mouse can outperform specialized 3D input devices in certain 3D tasks, such as object placement, due to its precision and users' existing expertise [5]. Building on this motivation, we investigate how mouse input can serve as an alternative to VR controllers in seated VR, particularly for tasks that demand accuracy.

To this end, we designed a VR interaction system that maps standard mouse input to object manipulation. We then conducted two user studies to evaluate its effectiveness. The first compared mouse input with controllers in 3D object manipulation and docking tasks. The second extended the evaluation to accuracy-oriented workflows by incorporating a 2D adjustment panel, similar to those found in 3D modeling software, into VR. Our studies investigate manipulation and docking performance, with a focus on accuracy. Accordingly, we do not use Fitts' law measures. Both studies collected quantitative performance metrics, such as accuracy and completion time, as well as qualitative feedback on usability and workload in controlled manipulation tasks in seated VR productivity scenarios.

Through our work, we aim to contribute to the research on interaction techniques for VR, particularly in scenarios where accuracy is essential. Our findings have implications for designing VR interfaces for professional and productivity-oriented applications, where the benefits of VR immersion need to be supported by accurate and efficient interaction methods usable in seated scenarios during the whole workday without having to constantly switch devices.

2 RELATED WORK

2.1 VR Selection and Manipulation Methods

Since the inception of VR, its interaction methods have evolved significantly, with handheld motion controllers currently being the primary input device for VR systems [27], although bare-hand interaction is also often supported in the newest generation. Regardless, the two dominant techniques for 3D object interaction are direct (virtual hand) object interaction and ray-casting [8].

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In direct object interaction, also known as the "virtual hand" technique [26], users reach out and grab virtual objects with the controller, as in reality. This approach is intuitive for objects within arm's reach. Extensions like the Go-Go technique [37] improve the users' reach by non-linearly scaling the user's arm movement to interact with distant objects, but accurate manipulation at a distance remains challenging [8, 30, 21, 25]. On the other hand, ray-casting emits a virtual ray from the controller or virtual hand toward the scene [8]. Users then point the controller and press a trigger to select the first visible object along the ray, to manipulate it. While ray-casting can reach further away objects, it has its disadvantages: first, foreground objects can obstruct the selection of background objects along the ray [26, 10]. Second, both natural hand tremor and tracking noise can cause the ray to jitter [3], making it challenging to reliably select small or distant targets [33, 39, 43].

Hybrid interaction techniques combine direct and remote pointing elements to leverage the benefits of both. For example, the HOMER technique blended ray selection with virtual hand translation for manipulation [8]. Voodoo Dolls allowed users to manipulate a linked miniature copy of a distant object held in hand [36]. A combination of near-field direct manipulation with far-field techniques improved overall accuracy across distances [21].

Scaled HOMER [41] dynamically scales the movement of a controller based on velocity. This scaling mechanism allows for easy transitions between different manipulation scales. During rapid movements, the system facilitates larger adjustments, while slower, more deliberate movements afford fine-scale control [41]. Such velocity-based scaling has been shown to facilitate transitions between coarse and fine movements in VR manipulation tasks. In addition to proposing new techniques, prior work has also examined how task properties and motor factors shape performance in virtual 3D manipulation. For example, Kulik et al. [24] studied motor performance in 3D object manipulation and discussed how difficulty and control demands can influence user behavior and outcomes. We see such modeling as orthogonal to our work, and an interesting direction for future work to further characterize when mouse- and controller-based mappings are most beneficial.

Beyond these canonical techniques, a substantial body of work has proposed methods to improve the precision and stability of controller-based manipulation [29, 17, 19, 41]. These include explicit degrees of freedom separation to reduce unintended coupling, constraint- and tethering-based approaches that guide or restrict motion along predefined paths, or techniques that combine coarse mid-air interaction with secondary mechanisms for fine adjustment. Collectively, for tasks that demand accuracy, these approaches demonstrate that controller-based interaction can be significantly enhanced in some situations by increasing interface complexity. In contrast, our mouse-based technique does not require additional refinement modes or task-specific constraints, but instead leverages familiar desktop input methods to support full 6-DOF manipulation within a single, consistent interaction structure.

We do not claim to outperform all enhanced controller-based interaction techniques. Instead, we investigate whether a familiar desktop device, the mouse, can serve as a competitive and practical alternative for accurate manipulation in modern, seated VR productivity contexts, where users frequently transition between 2D and 3D workflows and can benefit from stable, desk-supported input.

2.2 The Mouse as Input Device for VR

Mouse-based input for accurate spatial control has been investigated since the early days of 3D interaction. Early studies have shown that planar input devices, when combined with appropriate mappings and degree-of-freedom separation, can effectively support multi-DOF manipulation. Zhai et al. [44] demonstrated that the use of smaller muscle groups, e.g., fingers and wrist, can yield higher precision than whole-arm movements in multi-degree-of-

freedom tasks. Similarly, the Rockin'Mouse [1] illustrated how separating degrees of freedom and leveraging a stable planar device can support effective 3D manipulation, while Hinckley et al.'s [20] survey highlighted control stability, physical support, and DOF separation as central design considerations for spatial input techniques.

The wheel mouse is today a standard 2D input device, and several studies have examined its utility for 3D interaction. There, the mouse often performs well when compared to specialized 3D controllers or trackers for some tasks like object placement or view manipulation [5, 40, 35, 7]. For example, prior work showed that the mouse could outperform 3D spatial input devices in a 3D positioning task, which was attributed to users' extensive experience with mouse interaction and the device's inherent stability, i.e., having a physical surface for support [5, 40]. Bérard et al. found that in a 3D placement scenario, the mouse was superior in speed and accuracy to several 3D input methods, which may be counterintuitive given the indirect control of the mouse [5]. Teather and Stuerzlinger similarly reported that the mouse can yield more precise 3D positioning than mid-air controllers, highlighting that familiarity and muscle memory play a role [40]. These observations are consistent with earlier findings on muscle-group involvement and control stability, which suggest that the accuracy advantages of the mouse stem not only from familiarity, but also from fundamental properties of planar input and better sensing. These findings motivate exploring the mouse for VR input, despite it being a 2D device.

The in-depth mouse by Zhou et al. [45] adapts the depth of the cursor to inferred user intent and scene geometry, allowing selection and manipulation at varying depths. Yet, its automatic depth control can misinterpret user intent, limiting user control and expressivity.

We also aim to naturally avoid the problems of perspective caused by depth differences through ray-based interaction. Petford et al. compared a mouse and ray-cast pointing system in an immersive full-room display [34], finding that when targets required the user to turn or involve bodily navigation, ray-casting was more efficient; but for targets directly in front of the user, a mouse achieved better speed and accuracy. This result suggests that in a seated, forward-facing VR scenario, a mouse could be highly effective.

More broadly, surveys of 3D manipulation techniques have emphasized a continuum between desktop-based and immersive interaction rather than a strict separation between them. Mendes et al. [29] highlight how design principles from desktop 3D interaction often transfer to immersive environments, motivating our focus on seated VR scenarios where users sit in front of a desk.

We note that dedicated 3D mice (e.g., SpaceMouse-class devices) provide desktop 6DOF input and are used in some professional areas, but they are less ubiquitous than standard mice and often require additional familiarization. We thus considered them outside the scope of our evaluation.

3 MOUSE-BASED VR INTERACTION TECHNIQUE

Our work targets hybrid interaction that allows users to transition between 2D desktop-style interaction and 3D VR interaction using a single mouse. This hybrid method seeks to simultaneously address three key challenges: (1) Preserving the efficiency of ray-based interaction for selecting distant objects, (2) Mitigating the effects of hand instability commonly observed in mid-air input by leveraging the mouse's high-precision, surface-supported control during manipulation, and (3) Transforming the mouse's inherently precise but relative input into accurate 3D manipulation through carefully designed interaction mappings.

3.1 Mouse Position Initialization and Ray Casting

We designed our system for scenarios where the user wears a VR headset while seated at a desk, today a common use case for VR systems [11, 4, 32, 46]. We utilize the headset's hand-tracking (via the OpenXR API) to obtain the 3D position of the user's hand that

is holding the mouse. During initialization, the user is prompted to move the physical mouse a bit; this allows the system to estimate the mouse's location relative to the user's hand. Given the tracked hand position, once we detect mouse movement, we then place a virtual mouse model in the VR scene aligned under the user's hand. This novel calibration establishes a correspondence between the physical mouse on the desk and its virtual counterpart.

Once initialized, a virtual ray extends from the tip of the mouse model in VR, controlled by the motion of the real mouse: horizontal movement rotates it left/right, and vertical movement up/down. The ray continues until it intersects an object or surface, where a white sphere marks the 3D cursor. A left-click selects the object currently under the ray. We then show an outline as selection feedback, matching the visual highlighting used in our controller baseline. To maintain alignment, small head motions do not disturb the ray. Yet, reflecting the limits of eye rotation [15], if the user's head rotates relative to the ray direction beyond an asymmetric yaw threshold and remains there for more than 2 seconds, the system recenters the ray to the new field of view. Specifically, recentering is triggered when the yaw offset exceeds $-70°$ to the left or $+45°$ to the right. These asymmetric thresholds were determined through early pilots and reflect our seated, right-hand–dominant interaction setup, where large rightward head rotations are less ergonomic and more likely to disrupt precise mouse control. The thresholds are swapped for left-handed users. Users can also press the middle mouse button to instantly recenter the ray, providing a quick reset if the ray is lost or misaligned. We note that these thresholds are a pragmatic design choice for the current setup rather than an optimized or general solution. Locomotion involves teleportation: double right-clicking on a point on the floor moves the viewpoint there.

Rather than mapping the mouse to an absolute 3D position, we interpret its input as a continuous control signal for ray orientation. Specifically, horizontal and vertical mouse motions on the desk incrementally rotate the virtual ray around the vertical (yaw) and horizontal (pitch) axes, respectively. Mouse input arrives from the input subsystem as per-frame axis values (Mouse X and Y). These values are velocity-like signals and integrated over time to update the ray orientation in a frame-rate–independent manner. Let θ_t denote the orientation of the ray proxy at frame t, and $\mathbf{u}_t$ the mouse input. The orientation update is then defined as:

$$\theta_t = \theta_{t-1} + \mathbf{k} \odot \mathbf{u}_t \, \Delta t, \ \ with \ \ \theta_t = \begin{bmatrix} \theta_t^{\text{yaw}} \\ \theta_t^{\text{pitch}} \end{bmatrix}, \ \ \mathbf{u}_t = \begin{bmatrix} u_t^x \\ u_t^y \end{bmatrix} \qquad (1)$$

where $\mathbf{k}$ is a per-axis sensitivity vector, set to $\mathbf{1}$ in our system, and Δt denotes the frame time. Thus, horizontal and vertical mouse motions incrementally update yaw and pitch, respectively. To ensure that the ray comfortably remains within the user's field of view, the resulting orientation is clamped to predefined angular bounds (see above thresholds) before being applied to the virtual mouse proxy. The ray is emitted along the forward direction defined by this proxy.

3.2 Object Manipulation Mappings

After selecting an object with a left-click, the user can then manipulate it using the mouse. We map 2D mouse motions and buttons to 3D translation and rotation operations, which is similar to how one would manipulate an object with controllers. Table 1 gives an overview of how different mouse actions translate in this work to object manipulation in the 3D space. We chose these mappings so that the mouse can support all 6-DOF manipulation operations. With a typical VR controller, a user might hold a trigger and move their hand to drag an object, or push a joystick forward/back to move it in depth; similarly, controller rotations control orientation. Our mouse-based technique achieves the same operations through a combination of mouse movements, clicks, and the wheel. The joystick gain was determined through pilot testing to provide a rea-

sonable baseline (in terms of the speed-accuracy tradeoff) and was kept fixed throughout the experiment.

Table 1: Manipulation technique overview across input methods.

Operation	Mouse-Based Interaction	Direct Object Interaction (Controller)	Joystick Interaction
Selection	Left-click	Press trigger button	
Translation	Left-click & drag	Press trigger button & drag	
Depth Adjust	Left-click & scroll wheel	Press trigger button & push/pull the joystick	
Pitch & Yaw	Right-click & drag	Press grip button, hand rotation	Move the joystick
Roll	Scroll wheel	Press grip button, hand rotation	Press grip button & move joystick
Teleportation	Right double-click	Point to target, long press trigger until indicator appears, then release	
Ray recenter	Scroll wheel click	N/A	N/A

4 FIRST USER STUDY

Our first study was designed to provide a more comprehensive evaluation of object manipulation capabilities in virtual environments. Thus, it compared three interaction techniques (controller-based direct object manipulation, controller-based joystick manipulation, and mouse-based manipulation) to evaluate the functional effectiveness of the mouse-based system for 3D manipulation. The study was approved by the institutional research ethics board.

4.1 Participants

Sixteen participants took part in this study, 11 males and 5 females, with an average age of 26.65±5.09. All participants were right-handed. Participants had diverse backgrounds in gaming and 3D software usage, as well as experience with VR (both distributed roughly uniformly from never to daily use). To ensure comfort, each participant was given time to adjust the Quest 3 headset and inter-pupillary distance (IPD) before the experiment.

4.2 Apparatus

The experimental scenes were created and displayed in Unreal 5.3.2 on a high-performance i9 laptop with NVIDIA 4080 graphics and 64 GB RAM. The scenes were streamed to the headset via a Quest Link cable, with a minimum refresh rate of 90 Hz. Our system utilized a Razer Basilisk V3 Pro mouse as the input device, connected to the laptop via a 2.4 GHz wireless USB receiver. The mouse's DPI was set to 800, and the polling rate was 1 kHz. Additionally, we enabled the smart-reel mode feature, allowing the mouse scroll wheel to adjust between tactile and free-spin modes based on the user's scrolling speed, ensuring optimal control speed and precision.

4.3 Questionnaire and Post-experiment Interview

Upon completion of all experimental tasks, participants were asked to complete two questionnaires: the first focused on investigating the user experience with the three interaction methods, utilizing a Likert scale, and the second one was a System Usability Scale (SUS) questionnaire to assess the effectiveness of the mouse-based interaction schema. As the SUS is primarily intended as a system-level assessment, we administered it only for the proposed mouse-based system to keep the session length reasonable; cross-condition comparisons were instead supported by NASA-TLX and task-specific ratings. At the end of the study, participants were also asked to participate in a short post-experiment interview to record their insights and comments on the system.

4.4 Procedure

Although our task design is informed by prior studies on target acquisition, our work examines 3D manipulation and docking performance under different input techniques, focusing on accuracy, task completion time, and user workload.

Participants first received an explanation of the study, signed a consent form, and experienced a brief demonstration. Seated at a desk, they used their dominant hand for input. We compared three interaction methods: controller-based direct manipulation (controller), controller-based joystick manipulation (joystick), and mouse-based manipulation. After a short tutorial for each, participants performed manipulation tasks in a fixed order: position-only, rotation-only, and combined position–rotation (6DOF docking) [26, 9]. This ordering, with progressively increasing difficulty and cognitive load, was chosen to allow participants to gradually build task understanding and motor control skills before encountering the most demanding condition. Each task type involved five randomized trials, requiring objects to be translated or rotated to match target poses. Time, position error, and rotation error were logged continuously (every 0.1 s). A transparent target outline indicated correct placement, while a side panel displayed pose differences to aid fine adjustments (Figure 1). Once they judged the object placement to be satisfactory, the end of a trial was determined by the participant, guided by both visual and numerical feedback. Although no explicit numerical completion threshold was enforced, all participants were instructed to balance speed and accuracy, aiming for precise placement in minimal time. A complete experimental session, including instruction, practice, and all task conditions, typically lasted 60–80 minutes.

4.5 Experimental Design

To compare the three different interaction techniques, we used a within-subject experimental design. We also investigated the three mentioned task categories: position, rotation, and position & rotation. For the different experimental categories, we recorded either the position difference, the rotation difference, or both of them every 0.1 s, and the operating time for each task.

4.5.1 Results

All dependent variables were tested for normality using the Shapiro–Wilk test. When assumptions were violated, data were log-transformed; if normality still failed, we applied the Aligned Rank Transform (ART) [42] before conducting one-way repeated measures (RM) ANOVA in SPSS 24. We used an alpha level of 0.05 for all tests, with Bonferroni correction for post-hoc analyses.

Position Tasks: For position-only tasks, the interaction technique had a significant effect on position difference, while no significant effect was observed on task completion time. Still, for the position difference, the mouse achieved a final average position significantly closer to the target compared to joystick interaction (Figure 2), indicating greater accuracy.

Rotation Tasks: The interaction technique affected task time significantly, with the mouse enabling faster completion. For rotation difference, the mouse again showed a significantly smaller error, with a large effect size (η^2=0.727), underscoring its substantial accuracy advantage.

Position & Rotation Tasks: When tasks required both position and rotation, the interaction technique significantly influenced time, position difference, and rotation difference. In all cases, the mouse consistently exhibited smaller errors, confirming its higher accuracy compared to other techniques.

4.6 User Feedback

Participants consistently preferred the mouse over the joystick and controller, due to its greater ease of use and perceived accuracy, see Figure 3. Some noted a moderate learning curve and minor friction when switching functions, pointing to refinement opportunities.

Table 2: Study 1 user experience questionnaire descriptive statistics. Ratings are on a scale of 1 (very difficult) to 5 (very easy).

	Median	P25	P75
Mouse manipulation	4.00	4.00	5.00
Controller manipulation	2.00	1.00	2.25
Joystick manipulation	3.50	2.75	4.00

4.6.1 User Experience with the Interaction Methods

To evaluate the perceived effectiveness and the user experience with the input devices and the three interaction methods, we asked participants to complete post-study questionnaires. The questionnaires utilized a 5-point Likert rating scale to assess the ease of use of each method. A score of 5 indicated that the technique was "very easy to use," while a score of 1 was "very hard to use."

For the manipulation tasks, the analysis revealed pronounced differences across interaction methods, as shown in Figure 3. A Friedman test revealed a significant effect of interaction method on perceived ease of use for manipulation tasks ($\chi^2 = 22.035$, $p < 0.001$). As illustrated in Table 2, mouse-based interaction achieved the highest median score of 4.00, while the joystick approach received a median of 3.50, and controller-based interaction scored lowest with a median of 2.00. A Friedman test demonstrated all differences with the controller to be significant ($p \leq 0.001$).

4.6.2 System Usability for the Mouse System

To comprehensively assess the user experience with our mouse mappings, we employed the SUS questionnaire, a widely recognized instrument in usability research [12].

Descriptive statistics showed that the mouse-based system achieved a mean SUS score of 78.125 (SD = 9.46), with a median of 76.25 and scores ranging from 70 to 100, with the data being normally distributed. We used a one-sample t-test to analyze the data, t(15) = 4.28, p $\leq$ 0.001, d = 1.07, which shows that the mouse-based system's SUS score was significantly higher than the widely accepted benchmark of 68 [12], with a large effect size. The questionnaire also showed good internal consistency with a Cronbach's alpha coefficient of 0.73, indicating acceptable reliability.

In the SUS questionnaire, odd-numbered questions are positively worded (where higher scores indicate better usability), while even-numbered ones are negatively worded (where lower scores indicate better usability) [12]. Users reported high confidence in using the system (Q9: M = 4.25), positive evaluation of system consistency (Q6: M = 1.94), and acknowledgment of its ease of use (Q3: M = 4.13). Notably, users felt they could use the system independently with minimal need for technical support (Q4: M = 1.63). However, we also identified areas for potential improvement. The system's learning curve was perceived to be still "a bit steep" (Q7: M = 3.88), and there was space for enhancement of function integration, as users found that switching between different functions was a bit challenging, i.e., changing from position adjustment (left click) to depth adjustment (left click & wheel scroll) (Q5: M = 3.88).

5 USER STUDY 2 – SCALED INTERACTION

Study 1 demonstrated the accuracy advantage of mouse-based interaction in VR, but also revealed limitations: Since the mouse wheel produces fixed-increment adjustments, participants struggled with depth manipulation at larger distances. These issues became more apparent in tasks that required both broad movements and subsequent fine-tuned corrections, highlighting the need for mechanisms that support transitions between coarse and precise control.
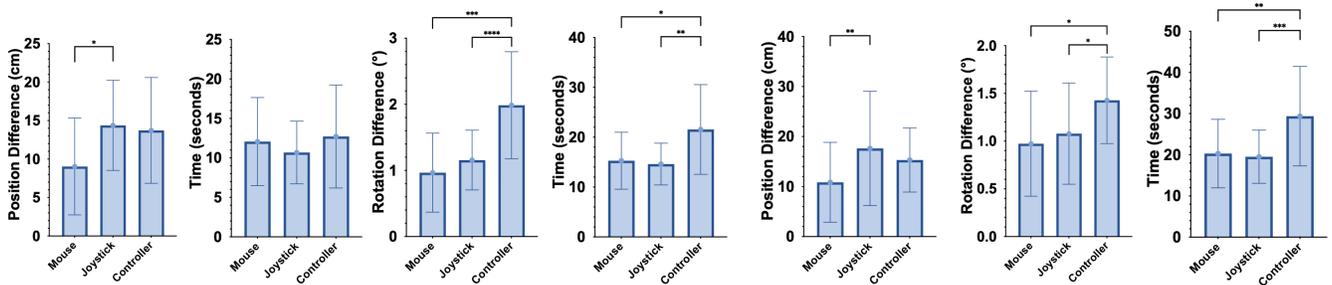
Figure 2: Results for study 1: from left to right, difference for position tasks, time for position tasks, difference for rotation tasks, time for rotation tasks, position difference for position & rotation tasks, rotation difference for position & rotation tasks, and time for position & rotation tasks. ***, **, and * in graphs indicate p < .001, p < .01, and p < .05, respectively. Error bars indicate ±1 standard deviation (SD).
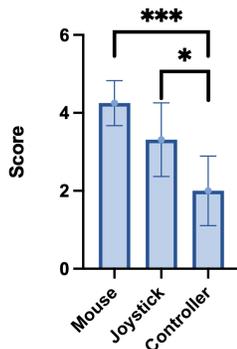

Figure 3: Study 1 user experience results for manipulation tasks. Error bars indicate ±1 standard deviation (SD).

To explore one way of mitigating these challenges, Study 2 investigated scaled interaction techniques. Prior work shows that Scaled HOMER [41] improves controller-based interaction by adjusting movement according to velocity, enabling transitions between rapid repositioning and more precise refinement. Our system complements the non-linear scaling already applied to cursor motions by the operating system [13, 18, 38]. We thus apply velocity-based scaling to the wheel input for depth control and rotation around the x-axis. For this, wheel ticks are aggregated over 0.2-second intervals to estimate scrolling velocity. We then map this velocity to a speed-dependent gain: faster wheel motions apply a higher gain to enable rapid, coarse changes in depth and x-axis rotation, whereas slower motions apply a lower gain to enable fine adjustments. This design follows the principle of Scaled HOMER—velocity-dependent scaling for coarse-to-fine transitions—and was introduced to address the fixed-increment wheel limitation observed in Study 1 while keeping the interaction predictable and low-effort. Also, Study 2 incorporated an optional side panel that displays numerical pose differences and slider controls, intended to support productivity-style workflows in which users combine 3D manipulation with precise 2D adjustments.

Let n denote the number of wheel ticks detected within a fixed time window $\Delta t = 0.2$ s, yielding an estimated scrolling velocity v and based on it, a speed-dependent gain $s(v)$,

$$v = \frac{n}{\Delta t}, \quad s(v) = s_{\min} + kv, \quad (2)$$

where $s_{\min}$ specifies the minimum gain for slow wheel motions, and k controls the sensitivity of the gain to input velocity. The resulting manipulation increment is $\Delta q = s(v)n$, where Δq denotes the depth translation or x-axis rotation increment, depending on the task.

5.1 Pilot for Study 2

Before Study 2, we conducted a formative pilot comparing Scaled Mouse and Scaled HOMER. The pilot was exploratory in nature and was not designed for inferential claims; therefore, its results were not analyzed statistically. Nevertheless, the pilot suggested faster convergence and lower variability with Scaled Mouse for both position and rotation tasks. Participants also reported that controller-based rotation with Scaled HOMER felt difficult to control (pilot P4: "*using a controller to adjust is always counterintuitive*"; pilot P7: "*the controller seems to amplify my rotation in all directions, making it difficult to control*").

Independent of these pilot observations, the design of Study 2 was motivated by the limitations identified in Study 1 and prior work on scaled interaction. In Study 1, the fixed-increment nature of the mouse wheel made it difficult to support both large adjustments and fine-grained corrections, particularly for depth and rotation manipulation. To address this, and following Scaled HOMER, we introduced velocity-based scaling for the mouse wheel.

Further, we introduced an optional 2D panel that exposes numerical pose differences and slider-based adjustments to support fine corrections. Study 2 thus examines whether these design responses help mitigate the accuracy–efficiency trade-offs observed earlier.

A pilot participant with extensive VR development experience and a high familiarity with mouse-based 3D software initially expressed strong skepticism toward mouse-based VR interaction ("*I cannot imagine using a mouse to manipulate in a virtual environment. . . I think my performance will be much better with a controller*"). Contrary to their expectation, their performance showed lower position and rotation errors with the Scaled Mouse. In the post-study interview, the participant reflected: "*The experience with the mouse completely contradicts what I expected. . . despite my experience with the controllers, the mouse provided much better precision than I thought possible in VR.*"

Beyond performance, this participant also highlighted workflow-related considerations relevant to professional contexts. They noted that switching between headset, controller, and desk-based devices disrupted workflow, while mouse-based interaction allowed them to remain within an existing desk-centered workflow ("*With the mouse, I can keep my hand on it while developing and quickly testing my game without changing devices*"). Although anecdotal, this feedback further strengthened our motivation to investigate mouse-based interaction in seated, productivity-focused VR settings.

5.2 Procedure Overview

Study 2 followed the structure of Study 1 to ensure comparability, maintaining a within-subjects design, the task categories (position, rotation, combined), hardware, data collection methods, and post-experiment questionnaires. The study was again approved by the

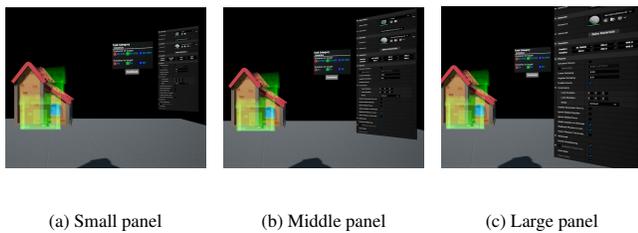(a) Small panel   (b) Middle panel   (c) Large panel

Figure 4: Interfaces for the second study, showing the three panel size conditions: (a) small, (b) middle, and (c) large. Participants were asked to place the object at the target location, supported by both the transparent visual target and the movable detail panel on the right, which displayed precise numerical values for alignment.

institutional research ethics board. The key differences were the interaction conditions tested (Scaled HOMER vs. Scaled Mouse with wheel-based scaling) and the addition of a 2D adjustment panel.

The panel, modeled after those in 3D authoring tools such as Unreal Engine, displayed real-time numerical pose differences and provided sliders for manual parameter adjustment. Unlike Study 1, participants could freely decide whether and when to use the panel.

The experiment used 3 repetitions per task category (9 trials per block), repeated across three panel sizes (small 31° vertical extent, medium ≈ 50°, large ≈ 90°). Thus, each participant completed 27 trials per condition, or 54 in total. The three panel sizes were selected to span a plausible range of VR interface scales, from desktop-like to full field-of-view conditions, enabling us to examine how scale affects usage strategies.

The order of tasks within each block was randomized, and the technique order was counterbalanced between participants. This design preserved consistency with Study 1 while systematically extending the evaluation to include scaling interaction methods. The whole session, including instruction, practice, and all task conditions, typically lasted 70–90 minutes.

5.3 Participants

We recruited eighteen participants (13 males and 5 females), with an average age of 27±4.69. All were right-handed. Participants had diverse levels of prior experience in gaming and 3D software usage, as well as experience with VR. For video games usage, it ranged from never (5) to every day (3), with most reporting occasional use ($\leq$ once a month). For 3D software usage, half of the participants had no prior experience, while four reported daily or weekly use. For the VR experience, 7 participants reported no prior VR exposure, while others had varying levels of familiarity, from once a month to a few times per week.

5.4 Results

Two participants were excluded due to corrupted log files. Data analysis followed the same procedure as in Study 1. Data for dependent variables were tested for normality with the Shapiro–Wilk test. If data were not normal, they were log-transformed; if normality still failed, we applied the Aligned Rank Transform (ART) [42]. Two-way repeated measures (RM) ANOVAs were conducted in SPSS 24. For all tests, we used an alpha level of 0.05, with Bonferroni correction for post-hoc analyses.

Position Tasks: No significant main effects of Technique or Panel size were observed for completion time or position difference (all p > .49).

Rotation Tasks: A significant main effect of Technique emerged for completion time, $F(1, 15) = 6.16$, p = .025, $\omega^2 = 0.23$, with Scaled Mouse (M = 24.16 s, SD = 16.22) outperforming Scaled HOMER (M = 31.63 s, SD = 16.73). No other effects or interactions were significant.

Position & Rotation Tasks: Scaled Mouse achieved smaller position differences, $F(1, 14.7) = 4.63$, p = .045, $\omega^2 = 0.18$, and markedly smaller rotation differences, $F(1, 14.7) = 15.97$, p = .001, $\omega^2 = 0.47$, than Scaled HOMER. The size of the panel also influenced the rotation difference, $F(2, 29.6) = 4.32$, p = .023, $\omega^2 = 0.17$, with the medium panel producing lower errors than the small or large ones. Completion times were faster with Scaled Mouse (M = 33.59 s, SD = 17.73) than with Scaled HOMER (M = 47.69 s, SD = 23.72), $F(1, 15.1) = 26.00$, p < .001, $\omega^2 = 0.59$. Interactions were not significant.

5.5 User Feedback

On the SEQ, participants rated Scaled Mouse significantly higher (M = 4.31) than Scaled HOMER (M = 3.00), Z = –2.87, p = .0018, large effect. Scaled Mouse received an average SUS score of 85.31 (SD = 12.00), well above the benchmark of 68, t(15) = 5.77, p < .0001, large effect.

In the NASA-TLX results, overall workload was significantly lower with Scaled Mouse (M = 7.38, SD = 1.73) than with Scaled HOMER (M = 13.55, SD = 2.87), t(30) = –7.38, p < .0001, d = 2.61. Subscales consistently favored the mouse: lower mental demand (p = .0015), lower physical demand (p < .0001), lower stress (p = .0027), lower effort (p = .030), and lower frustration (p < .001).

6 DISCUSSION

In this section, we discuss the results of each study and provide additional analyses to support their interpretation.

6.1 First User Study

The first study examined the effectiveness of the three different interaction methods for 3D object manipulation tasks in virtual environments. We analyzed task completion time, position difference, and rotation difference to capture both efficiency and accuracy.

For position-only tasks, we did not observe a statistically significant difference in completion time. Although mouse-based interaction showed a slightly longer mean completion time than the joystick, this was not significant. In contrast, position difference differed markedly between techniques: mouse-based interaction yielded significantly smaller position differences than the joystick, while the controller had comparable or slightly higher differences.

Although participants were instructed to balance speed and accuracy, we observed that position-only tasks were completed with the mouse on average slightly slower. Given that this difference was not statistically significant, we attribute this effect to differences in perceived control and resulting user strategies rather than to inherent inefficiencies of the interaction technique. In particular, the higher perceived accuracy of the mouse appeared to encourage participants to invest more time in fine adjustments.

Qualitative feedback from post-experiment interviews supports this interpretation. Participants reported greater confidence and a stronger sense of control when using the mouse, for example: "*I feel that using the mouse (for manipulation) is the fastest*" (P6), "*I believe I could achieve higher accuracy with the mouse, so I wanted to make each task as precise as possible. But, with the controller, I give up earlier, only aiming to get it roughly in the designated area*" (P9), and "*Using the controller for accurate operations felt more like luck. I couldn't feel that this method of operation was controlled; my hand was constantly shaking (when pointing)*" (P16). These comments suggest that participants adopted different operational strategies depending on the interaction technique, prioritizing speed with the controller and accuracy with the mouse.

To account for such strategy differences and reduce the influence of individual speed–accuracy trade-offs, we complemented the standard completion time analysis with an analysis based on task progress. Rather than comparing absolute completion times, this approach examines how position and rotation differences evolve as
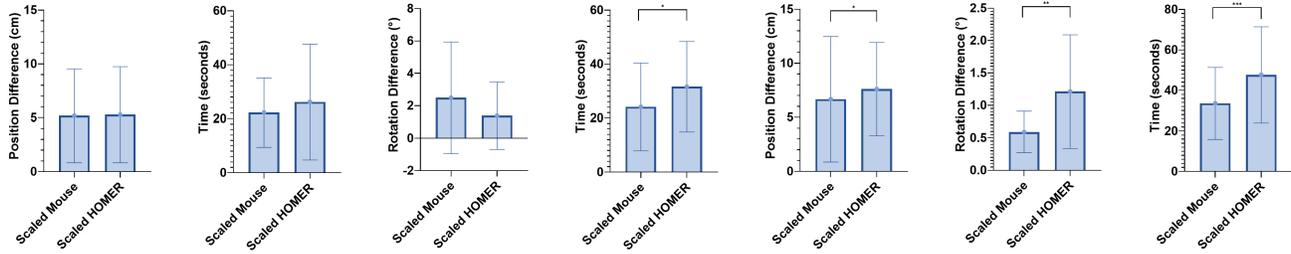
Figure 5: Results for study 2: from left to right, difference and time for position tasks, difference and time for rotation tasks, and position and rotation difference and time for position & rotation tasks.
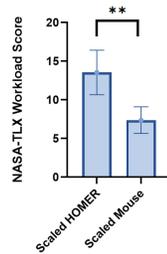

Figure 6: Mean NASA-TLX workload scores for study 2 (with standard deviation bars) for Scaled HOMER and Scaled Mouse. Scaled Mouse had a significantly lower perceived workload.

a function of task progress, enabling comparisons across interaction techniques at equivalent stages of manipulation.

Because participants varied both in how long they took to complete tasks and in the final level of accuracy they achieved, direct comparisons based solely on the completion time or the final error may obscure important behavioral differences. By plotting position and rotation differences against task progress, we provide a normalized view of performance between participants and techniques. As shown in Figure 7, this analysis allows us to compare the interaction methods at comparable points in the manipulation process, regardless of individual differences in speed or final accuracy.

Examining the evolution of position difference over task progress in Figure 7a, we observe that all three interaction techniques exhibit a broadly similar reduction pattern for most of the task. Throughout the majority of the task progress, the trajectories of the mouse, controller, and joystick frequently overlap and cross, indicating comparable behaviour in reducing large positional differences. Still, during the middle of the task ($\approx$ 15%–50%), mouse-based interaction tends to exhibit lower position differences than both controller and joystick. This interval corresponds to the main positioning phase, where users perform large goal-directed movements rather than fine corrections.

Differences between techniques become more apparent only near task completion. In this late stage, mouse-based interaction consistently reaches lower residual position differences than controller- and joystick-based interaction. This indicates that, while all techniques are reasonably effective at reducing large errors, the mouse enables participants to achieve more precise final alignment.

A similar two-phase pattern emerged for rotation tasks. Average completion times were 21.5 s for the controller, 15.3 s for mouse-based interaction, and 14.6 s for joystick input. As shown in Figure 7b, all techniques exhibited steadily decreasing rotational differences over time. In particular, around 50% task progress, rota-

(a) Position Tasks

(b) Rotation Tasks

(c) Pos. & Rot. Tasks (Position Difference)

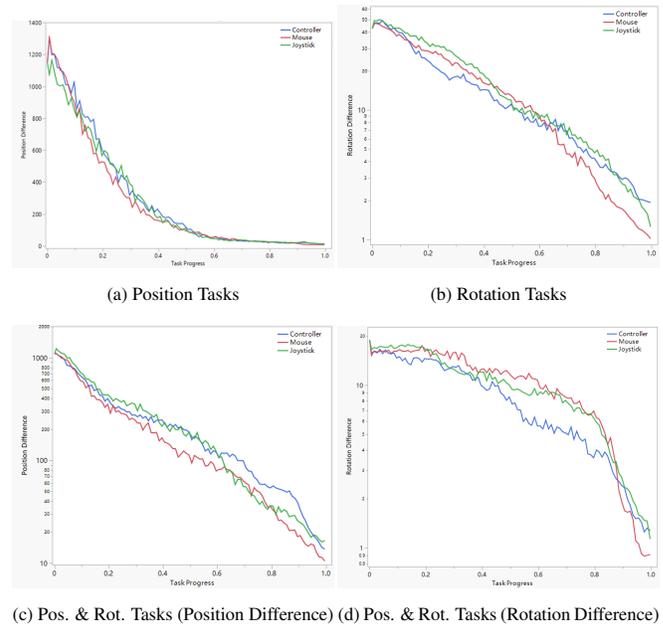(d) Pos. & Rot. Tasks (Rotation Difference)

Figure 7: Comparative visualization of accuracy across interaction modes over task progress in user study 1 (note the logarithmic scale used to highlight some of the differences).

tional differences converged between techniques, indicating a natural transition point between coarse and fine manipulation.

Before this point (until 50% completion), the controller showed a clear advantage, enabling rapid, large-scale rotational adjustments, followed by the mouse, while the joystick performed the worst. After convergence (50–100% completion), differences between techniques re-emerged: the mouse consistently outperformed both controller and joystick input, steadily reducing rotational difference and achieving the highest final accuracy.

For combined position-and-rotation tasks, participants required, on average, 29.38 s with the controller, 20.94 s with the mouse, and 19.52 s with joystick input. Analysis of Figure 7c shows that, for equivalent task progress, the mouse typically achieved a lower position error, indicating a more accurate control in less time. In contrast, as shown in Figure 7d, the controller maintained an advantage during the early rotation stages, but the mouse again dominated during fine adjustment, achieving the lowest overall rotational error.

Across all types of tasks, mouse-based interaction consistently demonstrated superior performance for accuracy-demanding operations, particularly during fine adjustment. In contrast, controller-

based interaction excelled at rapid, large-scale transformations, especially in early rotation stages, but was less effective for sustained fine control. These findings align with previous observations by Besançon et al. [6] on complementary strengths of mouse and controller input, while extending them to immersive VR contexts.

These operational differences also reflect the psychological expectations and strategies of users. Participants frequently invested more time in fine adjustments when using the mouse, indicating a greater sense of control and operational confidence. Although mouse-based interaction sometimes incurred slightly longer completion times than joystick input, it consistently achieved higher accuracy. This suggests that users naturally adopted a more conservative, accuracy-oriented strategy when interacting with the mouse.

This effect was particularly pronounced among VR novices. Three participants (P11, P12, P13) with no prior VR experience reported that mouse-based interaction felt more intuitive and easier to adopt than controller-based interaction. One participant noted: "*the mouse is familiar and predictable, but the controller requires me to learn new movements and deal with hand stability issues I didn't expect*" (P11). These observations suggest that mouse-based interaction may provide a more accessible entry point for new VR users, allowing them to leverage existing skills while acclimating to immersive environments.

(a) Position Tasks   (b) Rotation Tasks

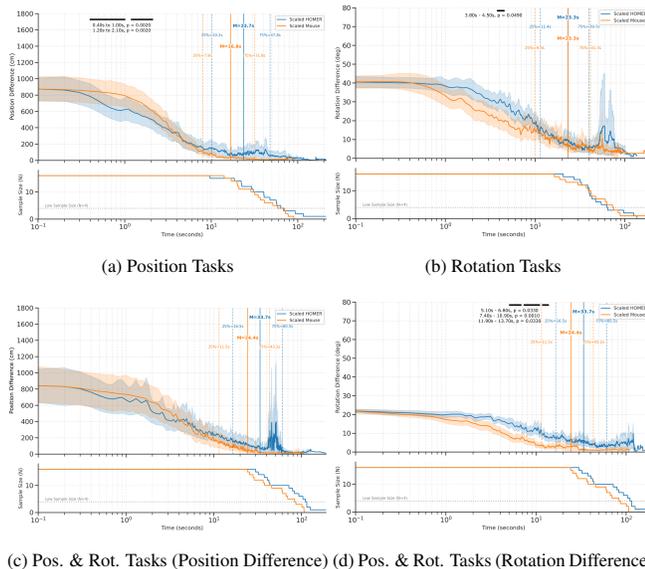(c) Pos. & Rot. Tasks (Position Difference) (d) Pos. & Rot. Tasks (Rotation Difference)

Figure 8: (Top) Comparative visualization of accuracy across scaled interaction modes over time plotted on a semi-logarithmic scale (linear Y-axis, logarithmic X-axis) to highlight convergence across different magnitudes. Shaded regions represent 95% confidence intervals. Black horizontal bars indicate time intervals with significant differences ($p < 0.05$). Vertical dashed lines denote the 25th percentile, median, and 75th percentile completion times. (Bottom) The number of active samples (N) over time.

6.2 Second User Study

The second study directly compared Scaled Mouse and Scaled HOMER and examined the role of an auxiliary 2D control panel at three different sizes. Across all task types, Scaled Mouse consistently outperformed Scaled HOMER, achieving both faster completion times and smaller errors, with the strongest effects observed for rotation and combined tasks. These results align with observations from the pilot study, in which participants described controller-based rotation as "counterintuitive" or "amplified."

The introduction of the panel did not alter this pattern. While one might expect a controller, often regarded as the default six-degree-of-freedom input device, to excel at rotation and combined manipulation, our results did not support this assumption. Although participants readily used the controller for coarse translation, accurate and efficient rotation remained challenging. In contrast, Scaled Mouse provided more predictable mappings and finer control, which explains its pronounced advantage in rotation-dominated tasks.

Panel size had only limited effects. The medium-sized panel unexpectedly yielded slightly (but significantly) lower errors than the small or large variants in terms of rotation error. However, there were no effects of panel size for completion time or position error, nor were there interactions between panel size and technique. This suggests that overall performance was driven primarily by the main interaction technique rather than by panel size.

Analysis of the logged data further indicates that participants treated the panel as a fallback rather than a primary interaction feature. Panel usage was consistently lower for mouse-based interaction (8.3–13.1% of trials across tasks) than for the controller (20.1–22.9%). Mouse users rarely relied on the panel, consistent with their higher accuracy during direct manipulation. In contrast, controller users more frequently turned to the panel to compensate for the instability of mid-air input, particularly during rotation.

Participant comments corroborate this interpretation. Mouse users often reported that the panel was unnecessary or slower than direct manipulation (e.g., "*With the mouse, I almost never used the panel. The mouse was already precise enough for me*" (P13)), whereas controller users described the panel as a corrective aid when rotation mappings became difficult to manage, e.g., "*When I was rotating with the controller, sometimes I forgot exactly how to get the object into the right angle, so I used the panel to fix it*" (P4).

To better illustrate performance stability and variability, raw trajectories were resampled via linear interpolation at 0.1s and then smoothed using a Gaussian filter ($\sigma = 1.0$) to highlight general trends for visualization, as shown in Figure 8 with 95% confidence intervals. As these confidence bands are descriptive and do not allow time-resolved inference, we applied a non-parametric cluster-based permutation test (CBPT) [28] on the interpolated trajectories to assess significant differences between techniques over time.

The time axis uses a logarithmic scale to reveal fine-grained dynamics during the initial phase of the task. As illustrated in the bottom panel, the sample size naturally diminished as faster participants completed the trial. Consequently, the error trajectories in the later stages represent a smaller subset of participants who required more time to complete the task. As participants completed tasks at different times, the number of contributing data points decreased toward the later portions of each plot. As a result, confidence intervals naturally widen in the rightmost regions, eventually reflecting data from only a single remaining participant. To avoid spurious significance driven by low sample sizes in the tails, the CBPT analysis was restricted to time intervals where at least 4 participants per group were active ($N \geq 4$).

Overall, clear differences between techniques emerge. Scaled HOMER is only significantly better for positioning tasks between 0.5 and 2 seconds. In all other cases, Scaled HOMER shows larger fluctuations earlier in the task and more rapidly widening confidence intervals, suggesting greater overshooting, repeated corrections, and higher inter-participant variability. Across position, rotation, and combined tasks, Scaled Mouse exhibits smoother error trajectories and relatively narrower confidence intervals for most of the task duration, indicating more stable and consistent performance across participants. In particular for rotation, Scaled Mouse exhibits superior performance between 5 and 13.5 seconds, i.e., in the fine-adjustment phase.

Taken together, these findings indicate that Scaled HOMER performs well only in initial large-scale movements but is less sta-

ble during accuracy-demanding phases. In contrast, Scaled Mouse supports both efficient coarse adjustments and reliable fine tuning across all tasks. The auxiliary panel served primarily as a compensatory mechanism for the controller, rather than as a core component of the workflow. These results reinforce the conclusion that Scaled Mouse offers a robust and predictable interaction technique for accurate manipulation in seated VR, particularly for rotation-intensive and combined tasks.

6.3 Implications for Design

Beyond performance metrics, the ability to use a mouse throughout an entire session enables VR workflows that are difficult to support with controller-centric interaction alone. In seated, productivity-oriented VR contexts, users often alternate between 3D object manipulation, parameter adjustment, and traditional desktop tasks. Scaled Mouse supports this continuity by allowing users to remain in a desk-centered workflow without switching input devices.

For example, in 3D level design tasks, a user may iteratively place and align objects in a VR scene while simultaneously adjusting numerical parameters such as position offsets, rotations, or constraints through 2D panels. Using a mouse for both 3D manipulation and 2D adjustments allows for seamless transitions between coarse spatial positioning and fine-grained numerical refinement, similar to established desktop workflows in tools such as Unreal Engine or CAD software. In development and testing workflows, such as VR application prototyping, users frequently alternate between code editing, parameter tuning, and in-headset testing. Mouse-based VR interaction allows developers to keep one hand on the mouse throughout these cycles, supporting rapid iteration without repeatedly putting down or picking up VR controllers.

7 LIMITATIONS

Although our study provides insight into mouse-based interaction for seated VR, several limitations should be acknowledged.

First, the order of task categories was fixed: participants always completed position tasks first, followed by rotation tasks, and finally combined tasks. This ordering was intentionally chosen to gradually increase task complexity, a common practice in user studies to support onboarding and reduce early frustration. Nevertheless, a fixed task order may introduce learning or fatigue effects that could influence performance in later tasks, potentially affecting comparisons between interaction techniques. Although we expect these effects to be consistent across conditions, future studies could further investigate the impact of task ordering through partial or adaptive counterbalancing strategies.

Second, the sample size in both studies was limited. Participants were predominantly young adults with generally high levels of computer proficiency and varying degrees of VR experience. While this demographic aligns with typical users of productivity-oriented VR systems, it may not fully represent a broader population, including older users, individuals with different physical abilities, or users with limited prior exposure to desktop input devices. Also, we did not quantitatively measure long-term comfort or fatigue, which may play an important role in extended VR usage.

Our studies involved only right-handed users. Although the proposed system can be easily adapted for left-handed users by mirroring the input mapping, we did not empirically evaluate such configurations. Future work should explicitly assess handedness-related differences to better understand accessibility.

A limitation of our study 2 is the use of a persistent 2D refinement panel, which reflects a deliberate design choice aligned with seated, productivity-oriented VR scenarios. While effective in this context, such a panel represents a transfer of desktop interaction paradigms and may not work that well within a VR-native solution, particularly for controller-centric or fully immersive workflows.

Another limitation relates to prior experience. Most of the participants were highly familiar with mouse-based interaction, while their proficiency with VR controllers varied. This imbalance may have contributed to the observed performance advantages of the mouse. While this finding remains meaningful—highlighting the accessibility and low entry barrier of mouse input for novice VR users—it is important to acknowledge that part of the performance difference may stem from pre-existing expertise rather than solely from the intrinsic properties of the interaction techniques.

Finally, the experimental tasks were controlled and focused on the placement, rotation, and combined adjustments of the objects. Although they capture the core components of 3D manipulation and docking, they do not reflect the full complexity of real-world VR applications such as professional modeling, collaborative workflows, or game-like interactions. As a result, our conclusions are most applicable to laboratory-style manipulation tasks in seated VR. Future work should examine whether the observed advantages of mouse interaction extend to more complex, dynamic, and ecologically valid scenarios, as well as to longer-term usage.

8 CONCLUSION AND FUTURE WORK

We introduced and evaluated mouse-based interaction as an alternative for seated VR scenarios, a context that is increasingly common in both professional and everyday use [11, 4, 32, 46]. Our system integrates a conventional desktop mouse into VR in a novel manner by tracking the user's hand through the OpenXR hand tracking of the headset, calibrating a virtual mouse model to its physical counterpart, and projecting a controllable virtual ray from it.

This design supports continuous interaction performance during object manipulation in VR, visual feedback through object outlining, and robust re-centering via heuristics grounded in eye–head coordination limits [15]. Teleportation for locomotion further ensures a complete, self-contained interaction solution that requires no switching to other devices.

Across two studies, we showed that mouse-based VR interaction consistently supports accurate 3D object manipulation. Study 1 demonstrated significant advantages over VR controllers in accuracy, highlighting that a familiar 2D input device can outperform native 3D controllers for seated, accuracy-focused tasks. Study 2 extended our investigation to scaled interaction techniques, comparing Scaled Mouse against Scaled HOMER, supported by an auxiliary 2D adjustment panel. Results showed that Scaled Mouse tended to achieve faster completion times and smaller errors, especially for rotation and combined tasks. Subjective measures also consistently favored Scaled Mouse: Participants rated it easier, more usable, and less demanding than Scaled HOMER. The optional panel was used flexibly, supporting fine-grained corrections without increasing task time, particularly at a medium scale.

Together, these findings demonstrate that the mouse, long optimized for precise desktop work, can also provide high efficiency and usability for 3D manipulation in VR when carefully adapted. Our contributions are threefold: (i) a system that integrates a conventional mouse into seated VR through an explicit initialization step that aligns the physical mouse with the user's tracked hand, enabling consistent ray-based control and robust re-centering; (ii) empirical evidence from two user studies showing that mouse-based interaction can provide competitive—and in several cases superior—accuracy and usability compared to standard VR controllers in seated 3D manipulation tasks; and (iii) an adaptation of velocity-based scaling and optional panel support to facilitate transitions between coarse and fine adjustments for depth and rotation in VR.

Future work should examine long-term ergonomics of mouse-based VR interaction, as well as strategies to minimize fatigue during extended use. Finally, exploring hybrid solutions that combine mouse-based interaction with complementary modalities such as gaze or voice could further enhance productivity.

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