A Novel Bare-Handed Manipulation Technique for Distant Objects in Virtual Reality

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ABSTRACT

Manipulating distant 3D objects in virtual reality (VR) with bare hands remains a challenge despite advancements in hand-tracking technology. We introduce the Two-Hand Fingertip-Palm (THFP) technique, which extends the interactive zone to the entire non-dominant hand to manipulate distant objects precisely. A user study comparing THFP to a bare-hand variant of HOMER (BHOMER) revealed that THFP achieves 75% greater accuracy, particularly in complex tasks like hanging a painting on a slanted wall, though it is 47% slower. THFP also received higher usability ratings (SUS) and reduced cognitive and physical demands (NASA-TLX), highlighting its user-centric design. These findings demonstrate THFP's potential for improving distant object manipulation in VR.

Index Terms: Hand tracking, Virtual reality, Distant object manipulation.

1 INTRODUCTION

VR technology has recently evolved significantly, also through advancements in real-time hand tracking, which enable users to manipulate virtual objects without physical controllers [4, 13, 25, 31, 66]. While these improvements have substantially enhanced the user experience, there is a lack of two-handed interaction techniques, especially those involving direct contact between the hands.

Building upon the work of Mendes et al., who explored various techniques for manipulating 3D objects but did not address bare-handed manipulation for controlling remote 3D objects in VR [38], our research introduces a novel interaction concept for distant object manipulation with bare hands and evaluates it quantitatively. Drawing inspiration from early two-handed interaction techniques [59] and Yu et al.'s on-body and mid-air interactions [71], our technique employs the user's hands as interfaces. The entire palm and fingers of the non-dominant hand (NDH) serve as interaction surfaces, allowing the dominant hand (DH) to perform gestures and manipulations as if using a "device".

Our innovative approach further leverages finger-based axis constraints to enhance manipulation accuracy, a challenge rarely addressed in previous work. The MAiOR, PinNPivot, and Plane, Ray & Point methods used constraints to improve precision but were limited to interaction within arm's reach as they relied on widget handles attached to the objects [40, 27, 23]. Combining the benefits of touch-based and widget-based interactions, our technique offers precise control over *distant* objects, while leveraging intuitive on-body gestures for complex manipulations in virtual environments (VEs). This novel interaction mechanism not only addresses the accuracy limitations of mid-air manipulation but also significantly reduces physical demand and frustration, making complex 3D distant object manipulations more intuitive and accessible.

2 RELATED WORK

Existing techniques for distant object manipulation in VR predominantly focus on arm extension, ray-casting virtual pointers, worlds in miniature (WIM), various widgets, or a blend of these strategies. Implementation often relies on controllers, with bare-hand techniques receiving less attention. Bare-hand methods tend to concentrate on direct manipulation, often falling to support operation on objects beyond arm's reach, or being confined to rudimentary movements without precise object manipulation.

Arm extension: The go-go interaction technique [57] used a non-linear mapping to convert the user's head-to-hand distance into a virtual controller distance. The stretch go-go technique [10] allows the virtual hand to be placed at any distance through a "reeling" metaphor. These two techniques lacked precise control mechanisms for accurately manipulating small objects at substantial distances. The FingerMapper technique [65] mapped small finger motions to full-scale virtual arm movements, but without axis constraints. While offering higher precision with reduced physical motion and fatigue, the technique led to much-increased task completion times, with a steeper learning curve and higher mental demand.

Ray-casting: Early ray-casting techniques [36] evolved via the "fishing reel" metaphor [10] to move objects closer and further. Balaa et al. presented a comprehensive survey also noting limitations of ray-casting, such as difficulties in moving objects along the depth axis and performing arbitrary 3D rotations and translations [6]. The image-plane method enabled interaction with distant objects through head- and hand-directed ray-cast pointers, though control was challenging, particularly at greater distances [34]. Some techniques made the selection of distant objects easier, but did not fully support subsequent object manipulation [2, 39].

The HOMER method combines ray-casting with hand-centered manipulation, affording 6DoF control but suffers drawbacks with small or distant objects [10]. For bare-hand interaction, the Gaze + Pinch technique and ForceExtension techniques used gesture-based controls for manipulation but struggled with precise control and rotation of distant objects due to issues like false-positives and amplified angular displacements [50, 18]. All of these underscore the challenges of precise manipulation within VEs, highlighting the need for more refined control and feedback mechanisms.

WIM and Scaled World: Mine et al.'s "head-butt zoom" technique [43] enabled users to switch views by leaning forward or backward, later generalized to AR [8], but they struggled with precise selection and loss of broader context during zooming. The WIM technique [48, 61, 42, 69, 29] presents a miniature 3D model of the environment in the user's hand, enabling manipulation through said miniatures, but precision is a challenge due to the small scale. "Voodoo dolls" [51] enabled size modification of virtual objects using physical devices, but does not support bare-hand interaction. Bacim et al. [5] proposed advanced 3D selection strategies that improve object selection but still fall short in handling precise selections. Poros [54] utilized hand tracking to manipulate distant objects by replicating spaces within the user's reach. Despite this innovative approach, Poros requires significant setup time and could be visually confusing due to overlapping proxies or multiple marks, and its user study mainly assessed the concept rather than empirical performance, such as rotation and translation accuracy.

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3D Manipulation Widgets Widget-based manipulation techniques offer handles and widgets for positioning and rotating objects in VEs [46, 64, 74]. Yet these methods demand users learn the correspondence between the widgets and the distant object they control, which can be confusing with multiple rotation handles. Similarly, Lee et al. developed multiple methods to interact with distant objects by manipulating a scaled replica within arm's reach through controllers [33]. These approaches aim to improve precision but can suffer from reduced precision from non-dominant hand involvement, scalability issues with complex or large objects, or occlusion of a distant object by its replica. Babu et al. presented Direct BMSR and Scaled HOMER + Near-field Scaled Replica View (NFSRV) [3] which also shows the object context in the replica. These innovations enhance depth perception and contextual awareness but also reveal challenges around the context radius size and potential for occlusions or collisions in complex environments, particularly when dealing with small or very large target objects.

Hand-Centered Direct Manipulation: Bettio et al. [9] introduced bare-hand tracking for VR, enabling direct 3D interaction with models within display space. Pietroszek and Lee [52] proposed a method for selecting and moving objects using a virtual hand metaphor, and LaViola Jr et al. [32] employed direct mapping of the user's real hand's pose onto a virtual hand model. These methods are straightforward to learn and intuitive to use but can only be used to pick and manipulate nearby items.

Bellarbi et al. [8] combined Zoom-In with direct virtual hand manipulation in AR, enabling distant virtual object manipulation but requiring precise calibration and potentially obscuring important details during zooming. Zoom-fwd [41] utilized hand gestures to dynamically zoom based on the user's hand distance from the target. Yet, this technique faced usability challenges, including precise rotation of distant objects, limited evaluation in complex scenarios, and difficulties with user adoption, raising concerns about its effectiveness in and scalability for more complex VEs. Yao et al. [70] developed a dual-controller technique with an adjustable virtual pointer for direct manipulation at various distances. Yet, due to the small size of the pointer, achieving precise control over the pointer's orientation is challenging for tasks demanding accuracy.

Other Approaches: MAiOR facilitates direct object grabbing and translation with additional rotational controls within arm's reach using a virtual lever bar but necessitates learning gestures and modes [40]. Plane, Ray & Point [27] enhanced manipulation precision through constraints to restrict object movement, using hand gestures, while PinNPivot [23] simplified adding rotational constraints but all these were limited to interaction within arm's reach.

The Force Push method utilized hand tracking to apply physics-based forces to distant objects through intuitive gestures, primarily focusing on translation tasks, but not rotations or other 3D manipulations [72]. BodyOn [71] integrated on-body and mid-air interactions to leverage the unique properties of on-body interactions and the high degree of freedom from mid-air interactions to attempt precision control enhancements. Yet, it requires learning the mapping of different finger pinches to control separate functions and could increase cognitive load, especially for novice users. They also did not provide a quantitative evaluation nor adequately discuss the manipulation of distant objects, particularly rotations [71].

Multiple studies explored using smartphones as controllers in AR/VR [14, 24, 30, 35]. Although methods like HandyCast offer effective control over distant 3D objects, they are limited in embodiment and have challenges in tracking, expressiveness, ergonomics, and haptics, especially when used with VR HMDs [30].

Summary: Despite the variety of existing approaches for manipulating distant objects in 3D, it is difficult to identify a single best option that could be used in all interaction scenarios. For translating objects, most previous work also did not evaluate diagonal movements. Also, most previous work for remote object manipulation typically uses controllers. We surveyed existing 3D object manipulation techniques in VE [5, 6, 7, 8, 9, 11, 10, 14, 16, 17, 19, 20, 22, 21, 23, 28, 30, 32, 34, 35, 43, 44, 46, 47, 48, 49, 51, 52, 53, 57, 58, 60, 61, 62, 64, 65, 68, 70, 74, 50, 18, 41, 54, 72, 39, 40, 71, 3, 15, 1], but found that **only seven** [8, 65, 50, 71, 74, 3, 15] present solutions for bare-hand translation and rotation of remote objects.

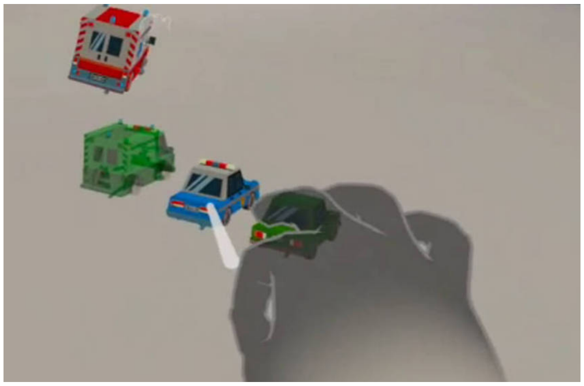

Figure 1: Demonstration of BHOMER technique.

3 CHOICE OF BASELINE TECHNIQUE

As we investigate bare-hand techniques for remote object manipulation, we ignored all controller-based approaches (including the original HOMER). Further, we decided against a baseline limited to arm's reach (even bare-hand interaction), as this would be unfair. We acknowledge that users can always navigate so that the object is within arm's reach before manipulation, but point out that such navigation takes non-trivial time, as the user has to judge precisely where they will be within arm's reach. This can be especially challenging for farther away objects or objects at different elevations, where multiple teleportations or lengthy steering might be needed.

While the original comparison of Voodoo Dolls and HOMER [51] indicated Voodoo Dolls might offer superior precision for tasks requiring fine control, this held only within the accuracy and manipulation range afforded by the small world replica and the hand of the user may occlude the object replica during manipulation. Direct BMSR + NFSRV also suffers from similar problems [3].

The adoption of a HOMER variant for bare-handed selection and manipulation in the Oculus Integration SDK underlines its suitability as a benchmark [55]. Messaci et al. also used HOMER as a baseline for their Zoom-fwd technique [41]. Additionally, our variant of HOMER resembles techniques like Gaze + Pinch [50] and BodyOn [71], which employ ray-casting for object selection and gesture-based controls for manipulation. Consequently, our research adopts this bare-hand version of optimized HOMER as a comparative benchmark, recognizing its relevance and adaptability for evaluating new methodologies for distal object manipulation.

3.1 Bare-Hand HOMER (BHOMER)

The bare-hand variant of the HOMER available in the Oculus Integration SDK uses ray-casting for object grabbing, where the user projects a slightly curved ray from their palm towards the scene. Upon object selection, rather than attaching the object to the ray, a "ghost hand" is moved to the object's position to enhance the precision of interaction. Once the object is grabbed (through a pinch with the index finger and thumb), it becomes tethered to the ghost hand, facilitating direct manipulation with simultaneous translation through changing the angle of the arm and rotation through the angle of the wrist, akin to the arm extension technique. For substantial object movement in depth, users need to "clutch" the object multiple times via stretching or contraction of the arm, and similarly for

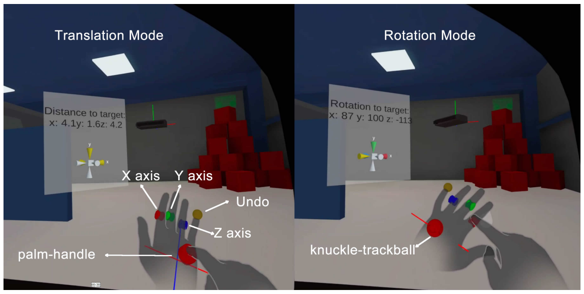

Figure 2: Demonstration of our THFP technique.

rotations that exceed natural wrist flexion. Yet, the Oculus implementation offers only fairly imprecise control.

Our implementation of bare-hand HOMER termed *BHOMER* improves the manipulation precision by decreasing "Wrist-Strength" and tweaking other parameters in the Oculus SDK. Through pilot testing, we ensured that participants could complete all tasks within our experiment with reasonable accuracy, including achieving rotations within 10 degrees of the target orientation.

4 TWO-HAND FINGERTIP-PALM TECHNIQUE (THFP)

Our THFP technique differentiates between translation and rotation controls, allowing users to switch between these modes simply by flipping their NDH. Translation mode is activated when the NDH palm faces the user; turning it to show the back switches the control to rotation mode. During all interactions, only the relative position of the index fingertip of the DH to the surface of the NDH influences the manipulation of the object (Figure 2).

In translation mode, users can either utilize a virtual sliding handle on the NDH's palm for rapid, planar movements or employ wheel handles on the fingers for precise adjustments along the x, y, and z axes. The palm handle enables intuitive movement adjustments by simply altering the orientation of the palm, such as tilting it to move objects diagonally. The finger-mounted wheel handles map the drag distance directly to the movement speed.

The rotation mode is exposed on the back of the NDH, featuring a trackball to freely orient objects and three wheel handles for meticulous adjustments around the x, y, and z axes. Inspired by mouse mappings for 3D rotations [75], this assignment facilitates quick, approximate rotations, and also fine rotational control.

To improve user control and correct manipulation errors, an undo button is incorporated at the tip of the NDH's pinky finger, permitting quick reversions to previous object states with a simple touch of the DH's index finger. The user interface reduces the potential for errors through color-coded visual cues that match the axes of movement with corresponding colors on the wheel handles, simplifying axis identification and adjustments.

The THFP technique also integrates tactile feedback by allowing the DH's fingers to touch the NDH, improving the stability and precision of interaction in VEs. This addresses the lack of physical support in typical VR setups, as identified by Mine et al. [43], and enables precise, bare-handed control of object manipulation, addressing challenges highlighted by Bowman et al. [10].

5 RESEARCH QUESTIONS

Based on our new method's properties, we evaluated its efficiency and accuracy in completing experimental tasks relative to the BHOMER technique when manipulating a distant 3D object outside of arm's reach. We pose the following research questions:

RQ1: How efficient is our THFP technique relative to the BHOMER technique for distal object manipulation?

RQ2: How does THFP perform relative to BHOMER in terms of accuracy when moving a distant object?

RQ3: How does THFP perform relative to BHOMER in terms of accuracy when rotating a distant object?

RQ4: Does THFP have a high degree of usability?

RQ5: Does THFP invoke higher mental and physical demand than BHOMER?

6 USER STUDY

6.1 Participants

A diverse group of 12 volunteers from the local university community participated in this study, comprising three males and nine females. Their age distribution was as follows: three people were between 18 and 24 years old and nine were between 25 and 34 years old. Their involvement with video games varied, with four playing daily, one a few times a week, four about once a week, and three less than once a month. Familiarity with 3D software and VR was also explored: six had never used 3D software before, while on the higher end, two engaged with it daily. Regarding VR, eight had never experienced it before, while two used it a few times a week. All participants were right-handed. All participants were briefed prior to the experiment and provided informed consent.

6.2 Apparatus

Our bare-handed VR interaction system was implemented as a Unity application (ver. 2021.3.31f1) running on an Oculus Quest 2 headset. The system utilizes the Oculus Integration SDK (ver. 57) for hand tracking, through the built-in cameras of the headset. At the same time, the Unity application enables participants to complete tasks, records the task completion time wirelessly in a database, and logs all the movement and rotation data of the object locally 10 times per second. Task completion time is recorded in seconds, position difference is measured in meters, and rotation difference is quantified in degrees. For distant 3D object selection, we employ the SDK's built-in curved ray-cast feature. Pinching the index finger and thumb together confirms the selection. For distant 3D object manipulation, we used BHOMER and our new THFP technique as the two interaction techniques.

6.3 Procedure and Experimental Design

A within-subjects design evaluated both techniques across six tasks (A–F, Figure 3), each involving distinct shapes, sizes, and spatial transformations (e.g., diagonal placements, tilted objects, vertical movements, and rotations). Initial object distances ranged from 4 to 9 m, with target placements spanning 4 to 16 m, covering various lateral, vertical, and diagonal movements and rotations.

After providing consent and completing a pre-assessment, participants received a tutorial and were trained on each technique. They then performed all six tasks with one method followed by the same six tasks with the other method in counterbalanced order. Task completion times were recorded, and participants pressed a red button when finished. Upon completion, the participants completed the SUS and NASA-TLX surveys [37] to address usability and workload (RQ4, RQ5) and participated in a semi-structured interview to provide qualitative feedback.

7 RESULTS

7.1 Data Analysis

We used JMP 15 for the quantitative analysis of the collected data. Shapiro-Wilk tests indicated a non-normal distribution for task completion time, position difference, and rotation difference across various conditions ($p < .0001$). Yet, for "mild" deviations from normality due to skew, applying a post-hoc transformation is an acknowledged method to maintain the integrity of ANOVA results [26, 63]. Consequently, a log transformation was applied

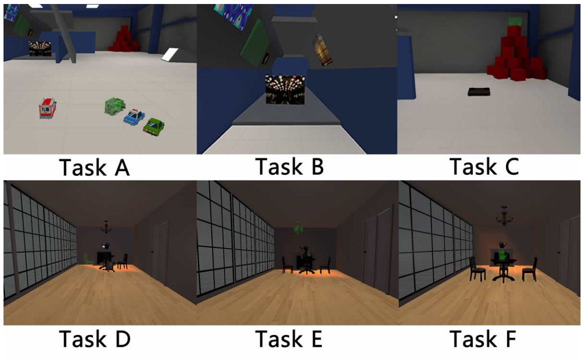

Figure 3: Screenshots of the six tasks used in our experiment.

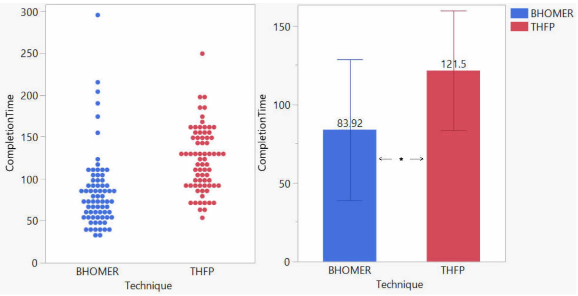

Figure 4: Scatter plot of individual task completion times and bar chart of average completion times with BHOMER vs. THFP. ***, **, and * in graphs indicate $p < .001$, $p < .01$, and $p < .05$, respectively. Each error bar shows the 95 % confidence interval.

before performing Repeated Measures (RM) ANOVA. If the data was still not normal, we used a nonparametric test. While we used 2x6 repeated-measures ANOVA, we frequently collapsed the data for tasks, as there were few significant differences among them, see below. For brevity, we report only significant results.

During the user study, numerous comments regarding THFP were recorded. Many participants expressed that they experienced a heightened sense of control, leading to an inclination to spend additional time on the system to attain precise results. Conversely, for the BHOMER technique, some participants found it challenging to ascertain proximity to the target goal due to the object being distant (and thus visual differences being small), leading to increasing pose errors after having already reached a (more) optimal pose. We also noted a variance of strategies, with participants alternating between initiating rotation or translation in different sequences.

7.2 Overall Performance Analysis

The primary outcome indicates that although THFP typically leads to slower task completion, it markedly enhances precision in both position and rotation, particularly during fine-tuning.

7.3 Task Completion Time Analysis

A Shapiro-Wilk test on task completion time identified that the data was normally distributed after log transform. Levene's test confirmed the homogeneity of variances for interaction technique and task. The RM ANOVA on time revealed significant differences for interaction technique, F(1, 11) = 25.97, p = .0003, ω^2 = 0.66 and task type F(5, 55) = 3.18, p = .0136 with a small effect size of ω^2 = 0.15. Overall, our system exhibited a longer mean completion time (M = 121.51, SD = 38.12) compared to BHOMER (M = 83.92, SD = 44.92), with THFP being approximately 45% slower than BHOMER (Figure 4). Although there is a significant impact on task completion time, a Tukey HSD post hoc test revealed that only Tasks C and F were statistically different from each other. Together with the small effect size, we decided to ignore task differences.

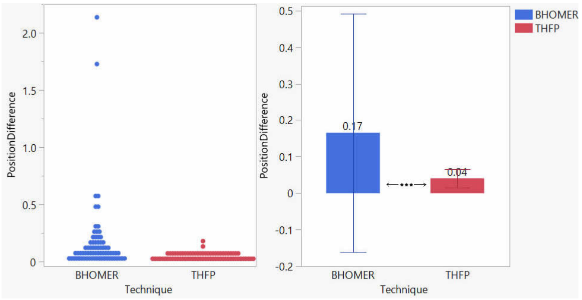

Figure 5: Scatter plot of individual position difference and bar chart of average position differences with BHOMER vs. THFP.

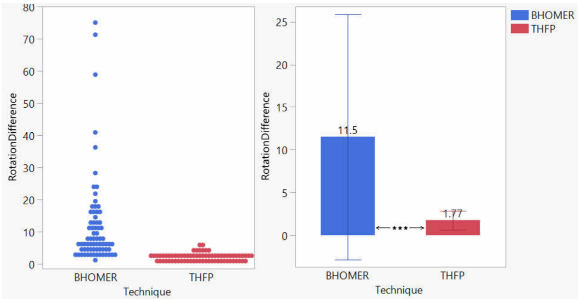

Figure 6: Scatter plot of individual rotation difference and bar chart of average rotation differences with BHOMER vs. THFP.

7.4 Position Difference Analysis

Following log transformation, a Shapiro-Wilk test affirmed data normality for position differences. Levene's test revealed a violation of the homogeneity of variances. As a result, we used Welch's ANOVA to analyze the data, given its tolerance to unequal standard deviations. This ANOVA identified that the THFP technique has significantly higher accuracy for the position than the BHOMER technique, F(1, 108.1) = 33.37, $p < .0001$, ω^2 = 0.23. THFP exhibited a significantly lower mean position difference (M = 0.04, SD = 0.03) than the BHOMER technique (M = 0.17, SD = 0.33) (Figure 5). Using the THFP technique, there was an improvement of approximately 76.47% in distance accuracy.

7.5 Rotation Difference Analysis

A similar trend was observed for rotation differences, with THFP showing a lower mean (M = 1.77, SD = 1.12) relative to the BHOMER technique (M = 11.53, SD = 14.36) (Figure 6). After log transformation, the data was normal but Levene's test revealed a violation of variance homogeneity, prompting the use of Welch's ANOVA, which detected a significant difference between techniques, F(1, 133.06) = 137.34, $p < .0001$, ω^2 = 0.50. The result indicated our technique improved rotation accuracy by approximately 84.65% compared to the BHOMER technique.

7.6 SUS Analysis

Based on the SUS survey, our analysis identified a favorable reception toward our system's usability among participants. Shapiro-Wilk confirmed normal distribution, whereas Levene's test revealed a significant deviation from variance homogeneity. Our system achieved an average SUS score of 80.83 (SD = 4.81), significantly surpassing the well-acknowledged benchmark of 68 [12]. Welch's

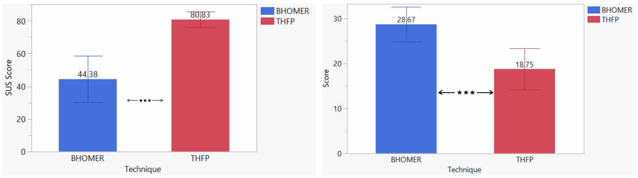

Figure 7: Mean(SUS Score) vs. Technique (left) and Mean(NASA-TLX) vs. Technique (right).

ANOVA highlighted that, in comparison to BHOMER, THFP received significantly higher SUS ratings (M = 44.38, SD = 14.23), with F(1, 13.479) = 70.73, $p < .0001$, $\omega^2 = 0.15$, indicating users found our system to be more user-friendly and intuitive (Figure 7). Further investigation revealed that participants reported high confidence in THFP (M = 4.33), significantly outperforming BHOMER with 2.92. THFP also scored higher in consistency and ease of use (both M = 4.58), compared to BHOMER's 2.25. While these results highlight THFP's strengths in user confidence, consistency, and usability, a mean score of 1.92 for system cumbersomeness and the perceived complexity and the initial learning required before using our system effectively were noted as improvement areas (both M = 2). Despite the overall positive feedback, some users encountered challenges, highlighting the need for potentially simplifying the user experience in future iterations.

7.7 NASA-TLX Analysis

In the NASA-TLX analysis, THFP demonstrates a clear advantage. The RM ANOVA results show a significantly lower overall workload score for THFP (18.75) compared to BHOMER (28.67), F(1, 11) = 55.73, $p < .0001$, $\omega^2 = 0.81$ (Figure 7). These findings indicate that THFP significantly reduces perceived workload across all categories, underlining its efficiency and user-friendly design. Supporting these quantitative results from the NASA-TLX, participants' verbal feedback further emphasizes the practical benefits of THFP. Users described THFP as "relaxing" and praised its precise control, highlighting the ease of "dragging objects with their fingers" which felt more "precise and relaxing." In contrast, feedback on BHOMER highlighted its physical demands, with users reporting increased arm fatigue and likening the experience to a workout. This qualitative feedback aligns seamlessly with the statistical data, reinforcing the superior user experience offered by THFP.

A Wilcoxon test demonstrated that THFP significantly improved task completion success, with a lower average of 2.33, indicating fewer failures, compared to BHOMER's average of 4.25., with z = -2.86 and $p < .05$. Also, our system required significantly lower physical demand from users, evidenced by an average score of 3, as opposed to BHOMER's 6.08, with z = -4.11 and a $p < .05$. Regarding user effort and frustration, THFP showed significantly lower scores (Effort: M = 3.17; Frustration: M = 3.33) than BHOMER (Effort: M = 5.25; Frustration: M = 5), with z = -3.28 and -2.82, respectively, both with $p < .05$. Thus THFP not only enhances task completion rate and user satisfaction but does so with less physical demand and frustration on the user, identifying it as a more effective and user-centric approach.

7.8 Equal-time Comparison

We used logs of objects' position and rotation differences relative to their target positions and rotations at 0.1-second intervals to analyze performance over time. Figure 8 shows the mean position and rotation differences per user. The extended duration of the blue curves (BHOMER) compared to the red curves (THFP) does not imply a longer overall completion time for BHOMER. Instead, it reflects that a few individual users dedicated more time to BHOMER, as also visible by the outliers in Figure 4. Yet, despite some users allocating more time to BHOMER, they did not achieve higher accuracy than with THFP. In cases where users spent similar amounts of time with both techniques, our approach consistently yielded superior positional accuracy. Moreover, both position and rotation differences exhibit a similar pattern approaching task completion, with the blue curves for BHOMER appearing more jagged than the relatively smoother red curves of THFP. This suggests that with BHOMER users made more frequently minor adjustments to position and rotation but still struggled to achieve a stable and accurate location and orientation.

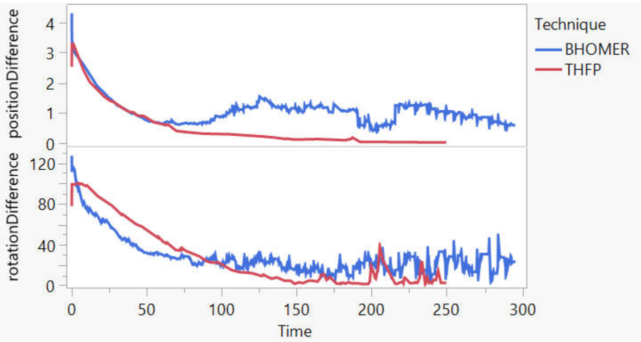

Figure 8: Mean (positionDifference & rotationDifference) vs. Time.

The visualization also reveals that the advantage of THFP in rotation difference is not as consistent as its advantage in position. THFP begins to show an advantage in terms of orientation approximately 80 seconds into the task, reflecting many users' strategy of prioritizing position adjustments over fine-tuning rotation. Once detailed adjustments begin, THFP converges to significantly more accurate results. Although THFP has some fluctuations due to too rapid or erroneous manipulations, these are generally less pronounced than BHOMER's. This indirectly demonstrates the challenges users face in achieving accurate rotational control with BHOMER, even with repeated adjustments. The increased fluctuation of the data in the right half of the graph is due to fewer data points being available at longer time intervals (and thus less averaging), which causes more spikes to appear (Figure 8). E.g., the spike in position discrepancy at 200 seconds is attributable to a large manipulation error and subsequent corrections, rather than a systematic issue of THFP.

While BHOMER may have a faster overall completion time, it exhibits considerable variation and plateaus at lower accuracy levels for both position and rotation. In contrast, THFP achieves consistently better overall pose accuracy. Further, THFP has the potential for further improvements with advancements in finger tracking and other optimizations. In contrast, BHOMER appears to be limited by a human's ability to control their hand pose accurately. THFP's user-friendly controls, undo feature, and user interface with numerical feedback enable users to swiftly detect and correct deviations, as illustrated by the sharp triangular shapes in the graph. These features significantly improve accuracy upon task completion, surpassing the performance of BHOMER.

8 DISCUSSION AND LIMITATIONS

Our findings indicate that THFP generally achieves more precise distant object placement and orientation than BHOMER. Although THFP required about 30 additional seconds per task, participants willingly invested this extra time to achieve finer, more stable final results. This supports *RQs 2–4*, indicating that the single-axis constrained manipulations of THFP enabled greater accuracy. Additionally, the NASA-TLX results, combined with user feedback, suggest that THFP demanded less physical and mental effort than

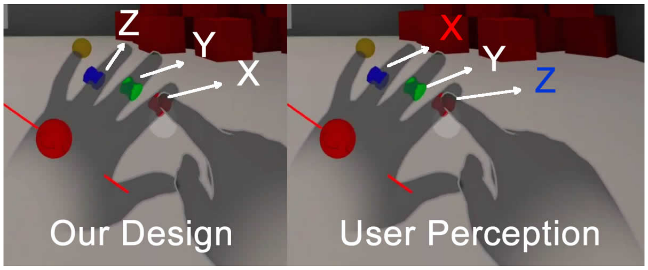

Figure 9: The THFP technique's design vs. a design favored by about one-third of participants, who expected axis assignments to flip accordingly when the hand orientation changed.

BHOMER (*RQ5*), confirming that participants found the precise, proprioception-guided approach more natural and less fatiguing. This reduced effort is particularly notable in scenarios where users might operate within tight physical confines or interact with numerous distant objects over extended periods.

While participants could quickly achieve approximate orientations, refining objects to near-perfect alignment took longer. This added time was partly due to the deliberate strategy of using single-axis controls for fine adjustments, rather than continuously repositioning the entire object with freehand gestures. BHOMER's difficulties, such as the instability caused by tremors and/or less predictable tracking, made it difficult to match the accuracy of THFP, especially at greater distances. THFP's reliance on proprioception rather than mid-air finger positioning (as in BHOMER) likely contributed to a more relaxed, confident user experience.

However, these benefits come with some design trade-offs. We based THFP on intuitive hand gestures and minimal arm movement, yet hand tracking remains a technical challenge. Although advances have been made [56], users occasionally experienced tracking loss, especially when holding their non-dominant hand (NDH) close to the torso, moving hands too quickly, or encountering occlusions. Bright lighting and improved hardware (Quest Pro) mitigated, but did not fully eliminate, these issues. Future more robust hand-tracking algorithms or multi-camera setups could significantly enhance the stability and reliability of techniques like THFP.

Another noteworthy observation concerns the conceptual mapping of finger axes to object transformations. While our flipping gesture to toggle between translation and rotation proved overall intuitive, about one-third of participants expected the axis assignments to "rotate" as their palm orientation changed (Figure 9). This misunderstanding led to errors and frequent use of the undo feature. Adopting axis mappings that dynamically adjust to palm orientation, or providing clearer visual cues, may better align with user expectations. Additionally, participants suggested extending THFP to include scaling, e.g., through a scaling widget on the thumb. Such expansions could further enhance the technique's versatility without compromising its core strengths in precision and comfort.

We also found that participants often relied heavily on the slow, axis-constrained "wheel handles" rather than the faster "palm handle" intended for coarse positioning. Although this strategy reduced errors, it also increased task times. Future iterations of THFP might consider adaptive control-display ratios or "smart" modes that facilitate rapid initial positioning followed by automatic transitions to fine-tuning. Similarly, BHOMER could benefit from implementing axis constraints, velocity-based scaling features [68], or finer control modes to reduce the adverse impact of tracking noise and jitter—particularly at greater distances or when performing complex, multi-axis manipulations.

From an experiential perspective, THFP's proprioceptive approach is promising for immersion. However, including non-diegetic UI elements (e.g., handles on virtual fingertips) may slightly reduce the plausibility illusion. Meanwhile, in accordance with the findings of Zhang et al. [73], users reported that the feedback panel significantly reduced cognitive load by providing numeric difference values. Future work might explore more diegetic integrations that blend interaction elements seamlessly into the VR environment or adapt the visual design to feel more natural and physically grounded.

There are other limitations to consider. Our sample was relatively small (N=12) and predominantly female, limiting generalizability. While similar studies have used comparable sample sizes [51, 62], future research should include larger, more diverse populations and repeated measures to confirm the stability of these findings. We also encourage exploring demographic variables, such as familiarity with VR or gaming, and user characteristics like handedness. Although left-handed adaptation is straightforward, integrating support for a broader set of user profiles and skill levels would offer a more complete understanding of the usability of both techniques. Furthermore, expanding the range of tasks, object sizes, and environmental densities could bolster the generality of our results.

In summary, THFP's accuracy, reduced effort, and stable results demonstrate its potential for distant VR object manipulation. By refining axis mappings, hand tracking, and integrating adaptive features, both THFP and BHOMER could evolve to accommodate a broader range of users, tasks, and virtual contexts — ultimately enhancing the immersion and overall utility of VR interfaces.

9 CONCLUSION

In conclusion, our research expands the potential of bare-hand interaction in VR/AR by introducing our novel THFP method to manipulate distant 3D objects accurately. Our findings highlight its promise in advancing intuitive and effective interaction techniques. As VR/AR evolves, this method's incorporation into current systems will improve 3D object manipulation in immersive environments, enriching the user experience and expanding the use of VR/AR technologies in design and architecture. Finally, integrating THFP with gaze-based object selection [45, 50], similar to Apple Vision Pro's interaction method [67], would allow users to focus on their intended object rather than on the object manipulation method, improving usability and accuracy of control.

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