Re-evaluating Virtual Reality Manipulation Techniques for Precise Alignment of Complex 3D Objects

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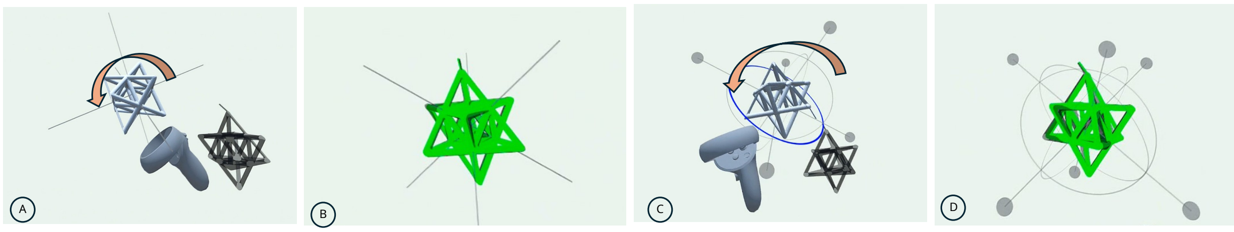

Fig. 1: Participant's view during the alignment task. The manipulation object is the opaque, white object. The target is the translucent, black object. The manipulation object turns green on valid alignment within the target object. (A&B): The AMP-IT interaction technique. (C&D): The WISDOM interaction technique. B and D show successful alignment using each technique and the protrusion added to both the object and target for asymmetry.

Abstract—Prior research has developed a number of manipulation techniques that can achieve precise object placement in virtual reality, but studies of these techniques typically use simple objects. We conducted a study comparing two existing techniques, (AMP-IT and WISDOM), during alignment of objects with complex geometry to evaluate the potential influence of geometric complexity on the performance, usability, workload and preference. Our findings indicate that participants had faster completion times and higher trial completion rates with AMP-IT on high-precision alignment tasks, contrary to earlier findings that used simple objects. Yet WISDOM is still preferred and considered more usable, despite increased workload and poorer performance, exposing participants' willingness to trade objective performance for comfort during use.

Index Terms—Precise Manipulation, Virtual Reality, Advanced Manufacturing, Manipulation Techniques.

1 Introduction

Precise manipulation techniques for Virtual Reality (VR) are used across multiple domains such as medical and dental surgical simulation training, or assembly tasks involving digital twins [43]. In particular, VR has emerged as a promising medium for tasks related to additive manufacturing, as virtual representations of 3D-printed parts can be aligned with computer-aided design models for visual defect inspection within Virtual Environments (VEs) [7, 8, 22], allowing users to more readily identify poorly printed parts. This alignment requires a high level of precision to accurately assess the quality of the 3D parts, and very few manipulation techniques offer the level of precision required for these alignment operations, revealing the ongoing challenge of designing effective interaction techniques for precise manipulation in VR environments [32].

To address this challenge of precise alignment, prior work has explored the design and evaluation of 3D manipulation techniques to improve precision. In particular, we build on the work of [40], who developed two novel techniques for high-precision alignment tasks in VR: AMP-IT and WISDOM. AMP-IT interprets hand speed as a cue for the amount of motion applied to the object, with fast movements producing coarse motion and slower movements enabling precise adjustments. WISDOM combines the Simple Virtual Hand (SVH) technique [5], which mirrors user motion exactly, with widget-based constraints that allow manipulation along only one axis at a time for high-precision control. Full descriptions of these techniques can be found in Section 3.2.

In their study, [40] conducted two experiments comparing the effectiveness of these techniques in both standard and high-precision alignment tasks using a simple cube object. The tasks had varying levels of difficulty, with standard-precision tasks consisting of *Very Easy*, *Easy*, and *Medium* trials and the high-precision consisting of *Hard* and *Very Hard* trials determined by the size of the target. Both experiments compared techniques to assess the impact of scaled mapping on user performance, perceived usability, task workload, and preference. In both experiments, the novel techniques achieved better performance than comparison techniques from the literature.

Specifically, in their second experiment, WISDOM emerged as the more effective technique for high-precision tasks, with participants using the SVH mode for rapid coarse alignment and the Widgets mode for precise adjustments. Participants not only had better performance with the WISDOM technique, but they also expressed a greater preference for WISDOM in terms of usability and felt it reduced workload. While these experiments provided valuable advances towards addressing the challenge of precise manipulation in VR for alignment, the use of a simple geometric object does not comprehensively represent the challenges posed by real-world alignment tasks, which can involve irregular or non-axis-aligned meshes. Because precise alignment of complex objects can be harder to judge visually (there are more parts that need to be checked for alignment), and because it may be difficult to understand how to use single degrees of freedom to achieve better alignment, we speculate that the performance, usability, workload, and preference

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could change when using the techniques to align such complex objects.

This work makes the following contributions:

1. We provide further evaluation of the AMP-IT and WISDOM techniques, by assessing user performance, perceived usability, task workload, and preference during alignment tasks using complex real-world data.
2. We determine what differences exist during precise manipulation with novel techniques when a task is changed from aligning a simple object, as seen in [40], to a complex object.
3. We validate prior findings as well as identify how those findings change when transitioning from simple to complex geometries.
4. We contribute an expanded understanding of these VR manipulation techniques that can aid in the selection and refinement of techniques for real-world alignment tasks.

In contrast to earlier results, our investigation revealed that participants achieved lower completion times and higher trial completion rates with AMP-IT compared to WISDOM when manipulating a geometrically complex object. Yet, WISDOM was preferred by participants and perceived as more usable even though our results show participants felt it required a greater task workload.

2 Related Work

VR manipulation techniques are necessary for effective interaction in immersive environments, as techniques with poor designs can impact usability and performance. Direct manipulation techniques such as SVH have served as a foundation of VR interaction approaches. SVH uses a 1:1 C/D ratio mapping that allows users intuitive and natural manipulation of objects in the VE [5]. However, this technique can suffer from user hand instability and fatigue that may cause errors during tasks [1,20] and can be limited to interacting with objects within reach of the user [37,42].

2.1 Precise Manipulation

Frees et al. [14], expanded on the SVH approach through PRISM, a technique designed to scale the amount of translational movement applied to the virtual object, based on hand movement speed, to increase the user's accuracy and control over the object. The effectiveness of this scaled manipulation was further explored in experiments examining manipulation for long and short-distance tasks [47], navigation through multiscale environments [23] and assembly operations [38]. Auteri et. al. combined the PRISM and Go-Go [36] techniques, for precise manipulation of distant objects and found significant improvements over using the Go-Go technique alone [2]. Even so, PRISM's translation scaling is applied independently to the three world-coordinate axes, which may not align with the object's natural coordinate system, and while the independent axis-scaling helps users to move along a straight line, conducting diagonal moves becomes more challenging [14]. PRISM does not apply rotational scaling to the axes independently, but instead applies a single scaling threshold to the entire rotation quaternion.

Another approach to precise manipulation in immersive environments is through the use of virtual widgets, which allow the user to control a single degree-of-freedom at a time, providing a useful constraint when using in-air tracked input that tends to be unstable. Widgets have been shown to excel in virtual docking tasks [32,45], and their ability to restrict movement to an individual axis improves precision and clarity [30]. These widgets can be attached directly to the virtual object or controlled through a handheld interface [32]. However, the use of widgets does not always improve user performance [25], as early iterations did not include movement scaling.

Both PRISM and virtual widgets have been instrumental in spawning many additional, novel approaches to precise manipulation within VR environments. Contributions in this area have explored the use of virtual [17] and augmented mirrors [29], shape [19] and gesture-based [46] inputs as well as snapping mechanisms [10] and grid constraints [15] to improve precision. Mendes et al. provides a comprehensive survey of these as well as other techniques [30]. Yet, even though these methods improved the precision of manipulation, their evaluations only assessed the techniques with a simple geometric object. This motivates our question of how such techniques perform when applied to the alignment of more complex objects.

2.2 Geometric Complexity and Precision

The relationship between geometric complexity and precise manipulation is not a trivial one. To our knowledge, literature regarding this relationship in VR is still sparse and few studies have examined if high-precision manipulation techniques remain effective when object geometry becomes more complex. Understanding the impact of complexity on performance is important, as it adds a challenging layer to manipulation tasks. The geometric complexity of a 3D object affects both visual working memory capacity and cognitive load [9,12]. This complexity has also been found to impact user performance, especially completion time during precise alignment tasks in AR [26,27] as users may need "more time to understand complex 3D models" [39]. Previous research by Martin-Gomez [28] introduced the concept of complementary textures as a means of improving precise alignment of virtual and real world objects of various shapes and sizes, but how the alignment was affected by the complexity of these objects was not taken into account. Shuai et. al. [41] explored the effects of complexity on object observation tasks in VR. They categorized object complexity into into three dimensions: occlusion, structure, and texture. They found occlusion and texture to significantly impact task completion time, but their examination of complexity was conducted in the context of search and classification tasks in VR and did not consider how the accuracy or precision of the manipulation was influenced by changes in complexity. Zhang et. al. evaluated how their proposed method for point-cloud alignment was influenced by objects of varying complexity; however, their comparisons were made between VR and 2D systems and the scope of their work focused on coarse, rather than precise, alignment [50]. Batmaz et. al. examined motor skills in VR with virtual objects of varying complexity and size. The authors concluded that object complexity is an integral part of precise alignment of object borders and recommended using simple structures over complex ones whenever possible [4]. However, this perspective limits our understanding of the full capabilities of newly developed manipulation techniques, as evaluating them solely on the simplest objects fails to reveal how they may perform under more demanding conditions that users may encounter in real-world applications.

Despite the advances of the aforementioned literature, significant gaps remain in our understanding of how these novel VR manipulation techniques perform with increased geometric complexity. Understanding the performance of manipulation techniques under increased complexity is imperative for not only determining long-term viability, but also identifying any limitations that may prove detrimental to real-world adoption. This work aims to address these gaps by evaluating how geometric complexity affects the performance, usability, workload, and preference of the AMP-IT and WISDOM manipulation techniques during alignment tasks with high precision requirements.

3 Experiment

3.1 Research Questions & Hypotheses

The goal of our experiment was to better understand the relationship between geometric complexity and manipulation technique effectiveness in practical applications involving high-precision alignment tasks. Thus, we reproduced the comparisons of the AMP-IT and WISDOM techniques reported by [40], substituting their simple cube object with a geometrically complex object representative of those used in additive manufacturing. Precise alignment is a crucial step for deeper analysis, e.g., strut-level visualization and inspection of additively manufactured lattice structures [31], as even small deviations can lead to significant dimensional errors and poor component fit. We use additively manufactured parts as a use case since this process offers high geometric freedom, enabling intricate internal features, complex shapes, and tight tolerances. Precise alignment in VR is needed to ensure these complex geometries are accurately represented in the manufactured part.

We address the following research questions:

RQ1 How does the performance of the AMP-IT and WISDOM techniques compare when conducting precise alignment tasks with a geometrically complex 3D object?

RQ2 How does users' perceived usability and workload compare between the AMP-IT and WISDOM techniques when applied to precise alignment tasks involving a geometrically complex 3D object?

RQ3 How do user preferences compare between the AMP-IT and WISDOM techniques when manipulating a geometrically complex 3D object?

Although [40] found no statistically significant differences between the AMP-IT and WISDOM techniques, we suspect that the use of a more complex object may have an impact on the performance and user experience of high-precision 3D manipulation techniques. While it is unclear what these effects might be, the use of a complex object can present additional challenges of occlusion [41], visual alignment [26, 27], and increased cognitive load [9], as mentioned previously.

Despite the lack of statistical significance in the overall results, [40] identified several trends that we used to inform the hypotheses below. The WISDOM technique showed trends towards better task completion times in high-precision tasks, perceived control and effectiveness due to its explicit-degree-of-freedom widget based interaction, and was more strongly preferred by participants. Based on these trends and the use of the same task with the same precise manipulation techniques, we anticipate similar findings to this previous work. Specifically:

H1 WISDOM will outperform AMP-IT in precision tasks when aligning a geometrically complex object.

H2. WISDOM will demonstrate a lower perceived workload and better usability when compared to AMP-IT.

H3. Participants will prefer using WISDOM over the AMP-IT technique.

3.2 Experiment Design & Measures

For this study, we developed the AMP-IT and WISDOM techniques used by [40] to the specifications outlined in their work.

The AMP-IT (Adaptive Mapping for Precise InTeraction) technique extends PRISM (Precise and Rapid Interaction through Scaled Manipulation) [14] to improve precision and control. AMP-IT dynamically adjusts the Control/Display (C/D) ratio based on hand speed, with fast hand speeds corresponding to quick and imprecise movements and slow hand speeds corresponding to slower, more deliberate movements. The user's hand speed is continuously estimated over a short temporal window by measuring the controller's displacement over time, allowing the technique to respond smoothly to changes in the user's intent. Motion is analyzed independently for each translation and rotation axis, if the user's hand speed on a given axis falls below a predefined threshold, movement along that axis is filtered out to avoid any unwanted hand movements or tremors. This approach allows independent control of all six degrees of freedom, which the authors refer to as implicit degree of freedom separation, enabling more stable and precise adjustments while preventing gimbal lock.

AMP-IT redefines PRISM's linear scaling by using an exponential function to smooth transitions and minimize unintended movements through the filtration of motion resulting from hand instability. The hand speed and scaling factors are calculated in the object's local coordinate system rather than global world coordinates for more instinctive control as the movements align with the object faces. This also results in a reduction of diagonal drift and better facilitates precise motion along the intended axes.

The second technique, WISDOM (Widget-based Indirect Scaled mapping with Direct Object Manipulation), is a hybrid technique, combining direct manipulation via the Simple Virtual Hand metaphor (SVH) [5] with widget-based manipulation [40]. The SVH mode provides direct mapping, or 1:1 C/D ratio, between the user's physical hand and the virtual hand in the VE, whereas the Widgets mode provides scaled mapping for each of the six individual degrees of freedom, which are controlled one-at-a-time. Users can switch between the two modes to allow fast and imprecise manipulation with SVH and fine-grained refinement with Widgets.

The widgets are represented as visual gizmos, including spherical handles for translation and circular rings for rotation, and follow similar conventions found in 3D modeling and game development tools. Users can grab the widgets in order to manipulate a specific degree of freedom. To address the hand instability during precise adjustments, the Widgets mode applies hand-speed-based scaling similar to AMP-IT, adapting the C/D ratio along the active axis. While AMP-IT focuses on continuous hand-speed scaling, the Widgets mode of WISDOM applies similar scaling concepts to each axis separately without filtering other axial movements, as only one degree of freedom is manipulated at a time.

Additionally, we used similar metrics as the previous work to ensure reproducibility and for better comparison of results. We implemented a within-subjects experimental design to investigate the effects of two independent variables, *Difficulty* (*Easy* and *Hard*) and *Technique* (AMP-IT and WISDOM) on several dependent variables, both objective and subjective. Our objective variables included trial completion time, number of clutches (i.e., controller trigger button presses), and trial completion rate. In the case of the hybrid WISDOM technique, we also included a variable to determine which mode was enabled during the trial, SVH or Widgets, and the frequency of the switches between the two.

Our subjective measures included the unweighted NASA-TLX questionnaire [18], a custom usability survey (CUS) based on the System Usability Scale (SUS) [6], and a post-study preference questionnaire. The NASA-TLX was used to assess task workload on a 7-point Likert scale. The CUS was constructed to gather insights into the ease of learning and use of the specific translation and rotation components of each technique and included 10 items with responses on a 5-point Likert scale. We did not calculate an overall CUS score, but instead analyzed responses to individual items. The post-study questionnaire was designed to explicitly assess participants' preference regarding the two techniques based on: 1) Manipulation, 2) Control, 3) Efficiency, 4) Naturalness of the technique during translation, and 5) Naturalness of the technique during rotation. Responses to the post-study preference questionnaire were audio-recorded for qualitative analysis. The full versions of both the CUS and the post-study surveys can be found in the supplementary material.

3.3 Environment

The VE for the study was created using the Unity Game Engine[1] version 2021.3.10f1 and the XR Interaction Toolkit[2] version 2.3 and consisted of a virtual room with a gray floor. The floor served as a representative of the boundaries of the virtual space (approx. 1-2m) and visual indicator of where the participants needed to be positioned within the scene. The walls of the virtual room were tinted yellow to provide better contrast with the complex 3D objects within the scene. The VE created and the hardware used for this experiment were consistent with those previously used by [40], allowing for replicability and comparison with the previous work's performance metrics and user preferences.

Users manipulated an octet lattice unit cell provided from a dataset of additive manufacturing octet lattice structures[3], throughout the study. This octet lattice unit cell is representative of a typical object that would be used within real-world additive manufacturing workflows, although for this use case it has been reduced in scale. The complex geometry of the object was ideal for answering our research questions regarding what specific aspects of the object's geometry may be responsible for changes in performance and preference metrics, as the object provides an example of models created from 3D scans used in additive manufacturing.

The octet lattice object has a cuboid shape making it similar to the box object used in [40]; however, its truss structure provides a sufficient

[1] https://unity.com

[2] https://docs.unity3d.com/Packages/com.unity.xr.interaction.toolkit@2.3

[3] https://data-science.llnl.gov/open-data-initiative

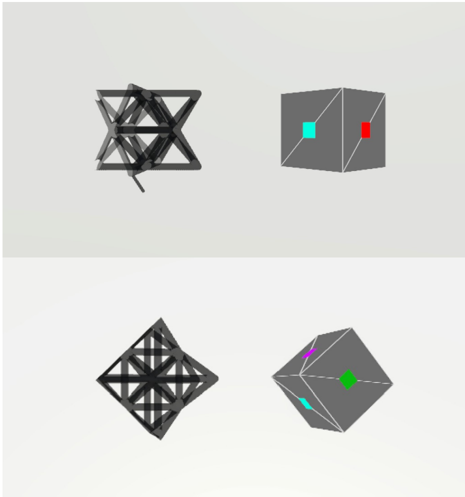

Fig. 2: Objects used in the evaluation of the AMP-IT and WISDOM techniques shown at two different angles. The lattice cuboid object (left) was used for the current work, the primitive cube object (right) was used in the previous work by Rodrigues et. al. [40]

amount of complexity as now users must not only make sure that the corners of the object are aligned, but the inner structures as well (Fig. 2). The use of an individual object of a single complexity allows for a targeted examination of the precise manipulation techniques in a more controlled manner and is a necessary step towards first identifying the presence of these initial differences when the complexity of an object is increased. The object was edited to have a small protrusion on one of its corners (see Fig. 1). This was added so that there would be only one possible orientation to correctly align the object with the target.

In the VE, the object was duplicated to create the static target. The manipulation object was rendered in opaque gray, while the target was transparent black. These colors were chosen to ensure that participants could visualize both the object and the target without obstruction, meaning they could see the moving object through the static transparent target as they worked towards alignment. See Fig. 1. The target was scaled to be slightly larger than the manipulation object, with the scale factor depending on the task difficulty level. Participants had to place the manipulation object completely inside the target in order to successfully complete a trial.

3.4 Equipment

Participants were equipped with a Meta Quest 2 HWD and hand controller [4] (for their dominant hand only) to interact with the manipulation object. The Quest 2 has a resolution of 1832 x 1920 per eye and a refresh rate of 90Hz. The controller used in the experiment was mapped to a virtual controller within the scene. To interact with the manipulation object, participants would hold the trigger button on the controller to grasp the object and move it in their desired direction. Once they released the trigger button, the object would be released and movement would cease. This manipulation would occur regardless of whether the controller was touching the object. The Widget interactions in WISDOM required participants to touch the widgets and hold down the trigger button on the virtual controller while moving their hand along the desired axis. This would result in the object moving in the same direction along the same selected axis. The second controller was operated by the experimenter and was used to start and stop the trials.

3.5 Task

The task for the experiment required participants to manipulate the manipulation object (Fig.1) until it was fully aligned within the stationary target, having both the correct position and rotation (within a threshold). Participants completed the task while standing and were allowed to physically move around the space to better determine how to complete the object alignment. When successfully aligned, the manipulation object would turn green as a visual indicator that it was in the correct position and orientation, and the trigger button could be released. If the trigger was released and the object remained green, the trial was completed; if the trigger was released and the object was no longer green because it had moved outside the target, then the participant would need to continue aligning the objects. Participants were given a three-minute time limit to complete each trial.

At the start of each trial, both the manipulation object and the target were positioned at specific locations within the scene. The manipulation object had no initial rotation and was always positioned at the participant's eye level. A predefined set of poses (positions and orientations) were used to position the target. These poses were randomly generated once and remained consistent across all participants. The distance from the user to the target was fixed at 50 cm along the z axis, and was constrained to not surpass 50 cm for both the x and y axes.

There were two levels of difficulty for the task, *Easy* and *Hard*. This difficulty was determined by the target size. For *Easy* trials the target size was 10% larger than the manipulation object, while for *Hard* trials the target size was 1% larger. Participants also practiced using the techniques during a training level in which the target size was 15% larger than the manipulation object.

3.6 Participants

Twenty-five participants (five female, three preferred not to answer) were recruited through Virginia Tech email lists. Their ages ranged from 19-36 ($\mu = 24.3$) years. Three participants reported "Never" having used VR before, eleven of the 25 participants reported having used VR "1-3 times," six had used VR "5-10 times," and five had used VR "More than 10 times." Twenty-three participants were right-handed, one was ambidextrous, and one was left-handed. Participants were compensated in the form of volunteer credit. The experiment was approved by Virginia Tech Institutional Review Board under protocol #23-209.

3.7 Procedure

Participants arrived at the experiment location, where they were provided further details regarding the study and gave their verbal consent to participate. Participants then completed a background questionnaire consisting of age, gender, occupation, VR experience, and hand dominance. A short presentation was provided for the participants to introduce the study's objectives, the task to complete, and the AMP-IT and WISDOM techniques. After the presentation, the participants were outfitted with the Meta Quest 2 HWD and instructed on how to use the controller to manipulate the manipulation object during the trials.

The participants completed a training trial before the main task, allowing them to familiarize themselves with the techniques. The training trial task was kept the same as the main task, as spatial training has been found to diminish variation in participants spatial abilities [3, 11, 16, 24, 44]. During the main task, the trials were completed in *Difficulty* blocks (*Easy*, *Hard*) with technique sub-blocks (AMP-IT, WISDOM). Within each technique sub-block, the participants completed four trials. Each participant completed a total of 16 trials, excluding the training trials. The participants completed both the NASA-TLX and the CUS after each technique sub-block. A refresher training trial was provided to the participants between the *Difficulty* blocks. The order of the *Difficulty* and *Technique* was alternated between participants to avoid ordering effects. We used four unique counterbalanced orders; however, participant 25 was tested after counterbalancing was complete, resulting in a partially counterbalanced design. Once the main task was finished, the post-study questionnaire was administered. The investigator read each item of the questionnaire aloud to the participant to which the participant would respond verbally as a co-investigator filled in the questionnaire with the participant's rankings. The participant rankings and the explanations for their selections were also recorded and transcribed for qualitative analyses.

[4] https://www.meta.com/quest/

4 RESULTS

To test the assumption of conditional normality, a Shapiro-Wilk test was performed on both the Completion Time and Clutch Count data. All combinations were shown to have a statistically significant deviation from normality. To analyze the effects of *Difficulty* and *Technique* on trial completion rates, completion time, number of clutches, the NASA-TLX, and the CUS, we employed a nonparametric analysis of variance (ANOVA) using the Aligned Rank Transform (ART) [48]. This method was chosen due to its robustness in handling non-normal distributions and its ability to examine interaction effects in factorial designs. Additionally, we conducted post hoc pairwise comparisons using the ART-C procedure [13], with p-values adjusted using the Bonferroni method to control for multiple comparisons. An alpha level of .05 was used to determine statistical significance.

We also evaluated the potential of VR Experience as a potential covariate of our performance metrics, in efforts to determine the root of the variability among our participants. Our analysis revealed that performance patterns were consistent across VR experience levels.

4.1 Task Performance

We observed the rate at which participants successfully completed the trials and found a significant effect of *Difficulty* (F(1, 72) = 673.34, $p < .001$), *Technique* (F(1, 72) = 23.76, $p < .001$), and the interaction between the two (F(1, 72) = 23.76, $p < .001$).

The post-hoc comparisons between the proportion of *Easy* trials completed with AMP-IT (100%) compared to WISDOM (100%) revealed no significant differences (t(72) = 0, $p = 1.0$). However, there were significantly more *Hard* trials completed with AMP-IT (29%) than WISDOM (8%) (t(72) = 4.78, $p < .001$).

Our analysis of completion time revealed a significant effect of *Difficulty* (F(1, 371) = 1440.68, $p < .001$)and an interaction effect (F(1, 371) = 4.36, $p < 0.037$).

The pairwise comparisons tests for *Difficulty* showed that the *Easy* trials were completed significantly quicker than the *Hard* trials (t(371) = -37.98, $p < .0001$). For *Easy* tasks, participants using AMP-IT ($\mu = 23.56$, $\sigma = 2.02$) completed the trials faster on average than those using WISDOM ($\mu = 24.29$, $\sigma = 3.04$) ($t(371) = 3.64$, $p < 0.0019$). Similarly, for *Hard* tasks, AMP-IT trials ($\mu = 156.96$, $\sigma = 4.23$) had, on average, faster completion times than WISDOM ($\mu = 174.54$, $\sigma = 2.03$) ($t(371) = -2.88$, $p = 0.025$) (Fig. 3).

While the ART-ANOVA identified a significant difference between the means of the techniques for the *Easy* trials, the means and variance appeared to be very similar. To better understand this, we conducted a Cohen's d analysis with confidence intervals. For *Easy* trials, the effect size was very small (d = 0.028, 95% CI: [-0.249, 0.306]). The confidence interval spanned zero and suggested that despite showing a significant difference, there is no meaningful difference between the techniques for the *Easy* trials. This discrepancy between statistical significance and practical significance is likely due to our sample size of 400 trials, meaning that even minor variations could result in perceived significance. For the *Hard* trials, the Cohen's d analysis revealed a medium effect size (d = 0.532, 95% CI: [0.249, 0.815]). The positive confidence interval supports our finding that there is a meaningful difference between techniques for difficult tasks.

Figure 4 shows the results for the number of clutches (i.e., the number of times participants released the object during the trial) for all levels of *Difficulty* and *Technique*. For the number of clutches, we identified effects for *Difficulty* (F(1, 371) = 829.58), $p < .0001$) , *Technique* (F(1, 371) = 99.72), $p < .0001$) , and an interaction between the two (F(1, 371) = 23.70), $p < .0001$)

Pairwise comparisons for both *Easy* ($t(371) = 8.01$, $p < 0.0001$) and *Hard* trials ($t(371) = 5.61$, $p < 0.0001$) showed that AMP-IT required significantly more clutches than WISDOM. Specifically, in the *Easy* trials, participants using AMP-IT made on average of 15.48 clutches, ($\sigma = 1.24$) compared to the 8.62 ($\sigma = 1.15$) clutches made while using WISDOM. Similarly, in the *Hard* trials, participants executed 58.83 clutches ($\sigma = 3.02$) with AMP-IT and 41.19 ($\sigma = 1.59$) with WISDOM.

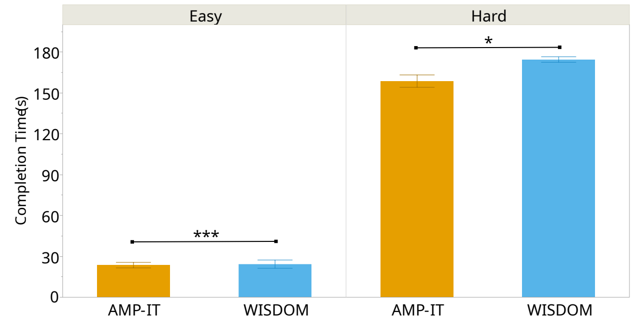

Fig. 3: Bar chart illustrating Completion Time across *Difficulty* (*Easy*, *Hard*) and *Technique* (AMP-IT, WISDOM). The x-axis represents the combinations of *Difficulty* and *Technique*. The y-axis shows the completion time in seconds. Significant differences between groups are denoted by asterisks (*) with AMP-IT showing a significantly lower completion time for both *Easy* and *Hard* trials compared to WISDOM.

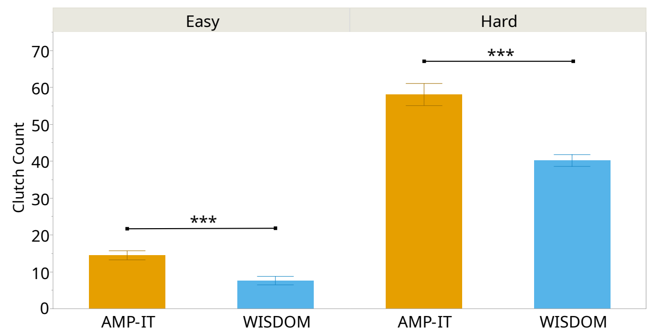

Fig. 4: Bar chart visualizing the number of trigger button presses, or Clutch Count, across *Difficulty* (*Easy*, *Hard*) and *Technique* (AMP-IT, WISDOM). The x-axis represents the combinations of *Difficulty* and *Technique*, while the y-axis shows the number of clutches. Significant differences between groups are denoted by asterisks (*) with AMP-IT showing a significantly greater amount of clutches for both the *Easy* and *Hard* trials.

We observed the usage between WISDOM's Widgets and SVH modes across the two levels of *Difficulty*. According to a Wilcoxon signed-rank test, there was a statistically significant difference in the percentage of time SVH was used (Z = 4.15, $p < .0001$) between *Easy* trials (median = 99.26%, IQR = 3.77) and *Hard* trials (median = 37.62%, IQR = 31.53). Additionally, we observed the frequency of mode switches that occurred between the two difficulties. We found the difference between the median number of switches within the *Easy* trials (0 switches) and the *Hard* trials (6 switches) was statistically significant according to a Wilcoxon signed-rank test (W = 562, $p < .0001$)

4.2 Workload and Usability

All items of the NASA-TLX showed a significant effect of *Difficulty* on perceived workload: Mental ((F(1, 72) = 151.70, $p < .0001$), Physical ((F(1, 72) = 24.23, $p < .0001$), Temporal ((F(1, 72) = 149.78, $p < .0001$), Performance ((F(1, 72) = 75.22, $p < .0001$), Effort ((F(1, 72) = 146.61, $p < .0001$), and Frustration ((F(1, 72) = 149.62, $p < .0001$). There was a significant effect of *Technique* on both Performance (F(1, 72) = 4.96, p = 0.029) and Frustration (F(1, 72) = 6.37, p = 0.014). Overall, participants felt that they had a poorer performance (t(72) = -2.23, p = 0.029) using WISDOM and felt more frustration using the technique (t(72) = -2.53, p = 0.014). An interaction effect between *Difficulty* and *Technique* on Temporal workload (F(1, 72) = 6.58, $p < .0001$) was also identified; however, post-hoc tests revealed no significant pairwise differences. Fig. 5 shows the mean score for each item of the NASA-TLX per difficulty.

The unweighted CUS responses were used to ascertain the differ-

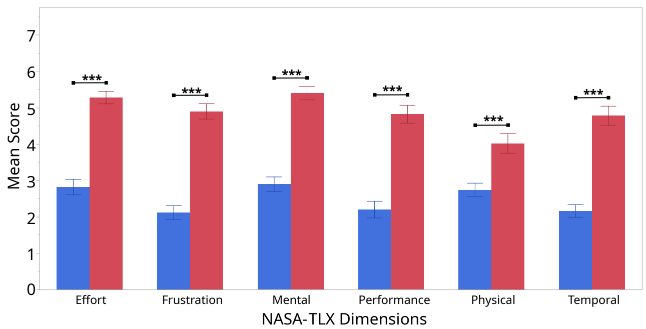

Fig. 5: NASA-TLX scores for *Easy* (blue) and *Hard* (red) difficulties. The x-axis displays the workload dimensions and the y-axis shows the mean scores.

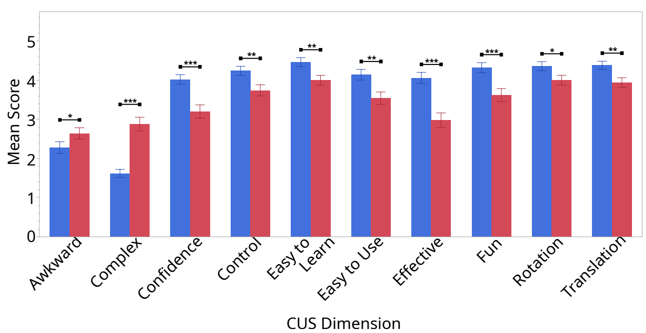

Fig. 6: Mean scores for dimensions of the CUS questionnaire for both *Easy* (blue) and *Hard* (red). The x-axis represents the CUS dimensions and the y-axis represents the mean scores.

ences on an item by item basis. Similar to the NASA-TLX, results for the CUS showed a significant effect of *Difficulty* on all items (Fig. 6). There was a significant effect of *Technique* on both Rotation (F(1, 72) = 4.87, $p < .0001$) and Confidence (F(1, 72) = 5.08, $p < .0001$)

The post-hoc pairwise comparisons indicated that participants found the techniques more usable in the *Easy* trials than the *Hard*, as expected. Participants also found that WISDOM was more usable for natural rotation than AMP-IT (t(72) = -2.21, $p = 0.031$), but participants reported more confidence when using the AMP-IT technique (t(72) = 2.25, $p = 0.027$). The post-hoc tests for complexity did not reveal any statistically meaningful comparisons.

4.3 Technique Preferences

The post-study ranking questionnaire asked participants to select their preferred technique for five items inquiring on the ease of manipulation of the object (Manipulation), how efficiently participants felt they completed the task using the technique (Efficiency), how much control they felt they had over the object (Control), how apt they were translating the object with the given technique and how natural the translation felt (Translation), and how apt they were rotating the object with the given technique and how natural the rotation felt (Rotation).

Out of 125 total outcomes from the 25 participants, 46 favored AMP-IT and 79 favored WISDOM. A two-sided exact binomial test indicated that these proportions were statistically significantly different from chance ($p = 0.004$).

Additionally, we observed the preferences on an item-by-item basis and adjusted the p-values for multiple comparisons using a Bonferroni correction. Out of 25 outcomes, we observed a significant difference in preference between the number of participants who preferred AMP-IT (5) to WISDOM (20), when rating Natural Rotation ($p = 0.020$), as shown in (Fig. 7). No other significant differences were identified after the Bonferroni corrections.

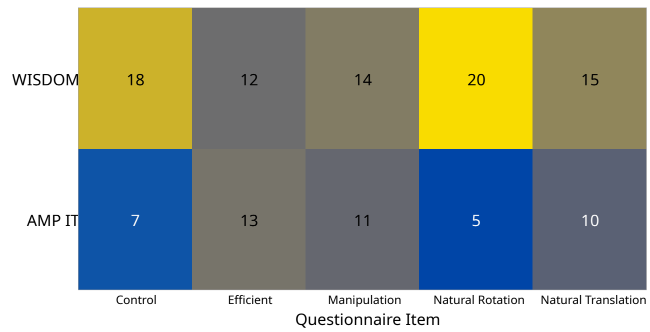

Fig. 7: Heatmap representing the count of responses for items of the post-study questionnaire evaluated across two techniques: AMP-IT and WISDOM. The items (e.g., Control, Efficient, Manipulation, Rotation, and Translation) are displayed on the x-axis, while the techniques are on the y-axis. The count within each cell indicates the number of participants who preferred the technique for a given item. The color gradient represents the percentage, ranging from blue to gold.

4.4 Qualitative Analysis

We conducted a relational analysis [21, 35] of the audio-recorded responses collected during the post-study ranking questionnaire. This approach was selected as the questionnaire prompted participants to respond to targeted questions about their technique preference for Manipulation, Efficiency, Control, Translation, and Rotation. We believed that extracting these responses from their question-specific contexts risked obscuring important nuances about participants' reasoning for their selections. The audio recordings were transcribed using Microsoft Word Online [5], and the subsequent coding was performed in Atlas.ti[6].

Our analysis revealed three predominant themes: (1) axial control, (2) axis visualization, and (3) movement sensitivity. Additionally, several participants commented on technique preference related to task difficulty, which provided useful insights into how participants' preferences changed with increasing difficulty. Table 1 presents a summary of the negative relationships found between the themes identified and the individual items of the questionnaire.

We will also note here that as WISDOM is a hybrid technique, participants often did not differentiate between its two modes when discussing their preferences and therefore there was no consistent way in which to differentiate between the modes. In the cases in which the participants did specify the mode, we analyze and discuss the differences between them.

Axial Control. This theme describes the axial control afforded by each of the techniques. Participants (n = 22) predominantly commented on the comprehensive multi-axis control available with AMP-IT and the individual axis control of the Widgets mode in WISDOM. We found that participants appreciated the direct control they had over the manipulation object with AMP-IT, even when scaled.

The multi-axis control of AMP-IT eliminated the need for sequential axis-by-axis adjustments, as during rotation the participants found it easier to rotate the manipulation object on any axis instead of being relegated to using one axis at a time like in WISDOM. As P4 noted, "It [AMP-IT] doesn't require extra calculation of combination of rotations [. . .] so I guess that's why it felt more natural to me."

Similarly, when using the SVH mode of WISDOM participants enjoyed the direct mapping of the mode for moving the manipulation object, as summarized by P3: "because it had that 1 to 1 [. . .] it felt like I was directly [. . .] holding the object in the same way that I'm holding something in real life and if I want it to move a certain distance closer to me [. . .] I just moved my arm that much closer." However, the individual axis control of Widgets received mixed evaluations. Some participants (n=19) found it beneficial for precise adjustments as mentioned by P23, ". . . the widgets would help you make more precise

[5] https://www.microsoft.com/en-us/microsoft-365/word
[6] https://atlasti.com/

Table 1: Negative relationships identified between themes and questionnaire items.

Technique	Theme	Item	Reason
AMP-IT	Axis Visualization	Rotation	Uncertainty of object movement due to lack of visual feedback during rotation
	Movement Sensitivity	Rotation	Difficulty predicting rate of movement required for rotation
WISDOM	Axis Visualization	Efficiency	Visualization of rotational axes made it difficult to view object position
	Movement Sensitivity	Efficiency	Increased potential for errors due to hand instability
		Control	
		Rotation	

movements exactly along the lines of the axes and the circles of rotation." However, others struggled to decompose their desired movements into individual axial parts, as P14 noted, "When I grab a widget, I'm only looking at that one [axis] and I can't - it's hard for me to see how it influences the rest of it." This single-axis control proved challenging when rotating with WISDOM, yet despite the challenges participants still expressed their preference for WISDOM's approach, suggesting that the perception of having finer control sometimes outweighed their actual performance.

Axis Visualization. This theme explores how the visual representation of the axes influenced participants' (n=18) interactions with each technique. When using AMP-IT, participants responded that the axis visualization worked well for all aspects of the movement, with the exception of when rotational movements were required. As P25 commented, AMP-IT was "a lot less busy to look at because there were [less of] the highlighted stuff. It was just [. . .] the axes." Specifically, in the case of rotation, the lack of visualization made it difficult for some participants to understand how their movement would be applied to the object. As P9 shared, using AMP-IT didn't help to complete the trials as "it didn't have the axis [to] help me to think about [. . .] how to rotate the object" and further elaborating that if "I want to rotate the object [. . .] I don't know which position I need to put my controller in."

WISDOM's axis visualization presented an interesting tradeoff. The participants perceived the visualizations as more of an obstacle than an aid. Speaking about AMP-IT, P4 said: "I'm able to just focus, I'm able to just see it more and then I don't have the Widgets kind of blocking my view." Yet, WISDOM's axis visualization still provided a clearer movement mapping that assisted participants in understanding how the movements being made with the technique would affect the object. P23 commented: "I felt it was easier for me to visualize the rotation. I think translation is - I think that's pretty much easy [. . .] but the the three rotational directions are a little hard. So WISDOM is better to visualize."

Movement Sensitivity. This theme discusses the sensitivity of movement mapping for each technique. Participants (n=22) commented on the immediacy or reduction of movement, technique instability, and the naturalness of the techniques.

Three participants described AMP-IT's N:1 mapping as "slow" and experienced difficulty predicting how their movement would be applied to the rotation of the object when using AMP-IT. P19 reported, "AMP-IT [. . .] felt a lot harder to rotate because [. . .] I just felt like I couldn't get the rate movement down". However, this proved advantageous as the dampened movements of the technique minimized extraneous actions and reduced errors during object alignment. Their sentiments are summarized by P20 ". . . on the first technique [AMP-IT], I think. . . it was a little better because you could, in all axes move, with slow speed and so when you have to do [. . .] something very accurate it helped on that part, but still it made me uncomfortable". Participants also appreciated the naturalness of AMP-IT as P5 commented: "I can control the object [. . .] more freely to move it like [. . .] I wanted to move."

WISDOM was preferable for responsiveness due to the direct 1:1 mapping of the SVH mode, which allowed movement speed to match that of the participants. This approach conveyed a sense of enhanced realism and naturalness, though it also came with increased susceptibility to hand instability as referenced by P26 - "I think there's more potential with WISDOM, [. . .] but I [. . .] felt even just moving my finger off the trigger would move things with WISDOM and and that being a little more stable was helpful sometimes", and P20 - "But in the [. . .] hard difficulty, [. . .] you couldn't be so precise with your hand. I mean, it's very difficult to be that precise. So I felt even though, again, I didn't feel comfortable at all. I think I was a little more efficient with the first technique [AMP-IT] on the hard."

Difficulty Dependency. Though it was not explicitly prompted, some participants (n=9) identified task difficulty as a determinant for technique preference. These participants expressed that AMP-IT's precise control was beneficial in aiding their performance in the *Hard* trials. P25 commented, "I thought I liked WISDOM better, but then [. . .] with the harder ones when I'd used AMP-IT, it was a lot better for [. . .] the finer details." P3 noted, "I feel like that [AMP-IT] was the better one because I actually was able to complete all the easy ones and the hard ones. I only missed the one."

Other participants stated that the quick and intuitive nature of WISDOM was better suited for the *Easy* trials, likely referencing the SVH mode specifically. P21 supported this stating, " WISDOM is easier for the easier ones", and P25 reported, "for the easier ones, I like WISDOM a lot more." Again, despite WISDOM's success being limited to the *Easy* trials, participants still chose WISDOM as their preferred technique due to its intuitiveness and direct mapping. As P11 noted, " I liked the WISDOM one better, but I was getting success with the AMP-IT."

5 Discussion

Our results, both quantitative and qualitative, provide insights into the benefits and shortcomings of both the AMP-IT and WISDOM techniques. In this section, we assess how the introduction of a geometrically complex object impacted the evaluation of these techniques through comparison with the previously conducted work.

5.1 Performance

Our hypothesis *H1*, in line with prior work [40], posited that WISDOM would outperform AMP-IT across task difficulties. Our analyses of trial completion time and trial completion rate showed that AMP-IT outperformed WISDOM; thus, *H1* was not supported.

When comparing our results with the previous evaluation of AMP-IT and WISDOM, we observed a notable difference in user performance between the techniques' when the geometry of the object was made more complex. Contrary to the previous findings in which WISDOM trended towards a superior performance in both *Hard* and *Very Hard* trials, our study showed that participants completed significantly more *Hard* trials using AMP-IT. This finding was also supported by our qualitative analysis in which participants commented on their preference and success with AMP-IT when completing the *Hard* trials (Sect. 4.4).

The impact of the increased geometric complexity became more prominent when comparing completion rates across studies. While the previous work reported a combined 71% completion rate (4.28 out of 6 trials) for *Hard* and *Very Hard* difficulties when using WISDOM, our study showed only an 8% success rate with WISDOM for the *Hard* trials, suggesting that fewer trials overall were completed due to the use of a more complex object. Although we cannot directly compare AMP-IT's completion rates due to unreported data from the previous work, WISDOM's reduced success rate suggests that the complex object made the use of WISDOM for precise alignment much more difficult. This impact of the additional complexity on WISDOM was further evidenced by increased completion times and frequent switching of manipulation strategies or modes throughout the more difficult trials. Furthermore, the visualization of the axes for the WISDOM technique, with its spheres and circles, contained much more visual noise as suggested by several participants during the qualitative analysis. This additional visual noise may have hindered the participants' ability to understand the misalignment between the object and the target when interacting with a more complex object.

The *Hard* trials in our study averaged 165.79 seconds, substantially higher than the average completion times for both the *Hard* (μ = 111.85) and *Very Hard* (μ = 146.78) trials in previous work. The increased geometric complexity also manifested as higher Clutch Counts, with the count increasing from 32 in the previous study to 58 in the current work, indicating a need for more frequent repositioning and adjustments throughout the trials.

WISDOM's manipulation strategies were also affected when used with a more complex object, with SVH mode usage increasing from 1.96% in previous work to 37% in our study. The frequent mode switching combined with the low success rate of only 8% (compared to the previous 23.78%) suggests greater difficulties in developing effective strategies when the geometric complexity of an object is increased. The completion rate of 29% with AMP-IT also suggests that this technique maintains a greater robustness to complexity challenges and further suggests that complex objects make precise alignment much more difficult overall, while highlighting AMP-IT's superior performance in handling complex geometries.

5.2 Perceived Usability and Task Workload

We hypothesized (*H2*) that WISDOM would demonstrate better usability and less workload when compared to AMP-IT. Our results indicate that WISDOM has greater usability, but requires more workload; thus, H2 was only partially supported. The CUS results indicate that participants found WISDOM more usable overall, particularly during rotation. Our NASA-TLX results show that WISDOM was perceived as having higher workload across all survey items except physical demand. These sentiments were reflected in our qualitative analysis, as some of the participants felt they needed to conduct additional "calculations" in order to understand how their rotation would be applied to the objects (Sect. 4.4), supporting our NASA-TLX findings. Nevertheless, they still rated rotating with WISDOM as significantly more usable than with AMP-IT.

The previous study [40] showed that participants found WISDOM to be more usable, with no significant difference in workload between the two techniques. The geometric complexity of the object likely influenced perceived usability and workload. Having more intricate details required for alignment may have contributed to an increased task workload throughout the trials, specifically, in the case of WISDOM, in which the individual axial adjustments were found to be more challenging, supporting previous findings presented in [9]. However, being able to adjust the complex object by its individual axes provided the participants an overall greater perception of usability.

5.3 User Preference

Hypothesis *H3*, that WISDOM would be the preferred technique for aligning a geometrically complex 3D object, was supported by the results. WISDOM emerged as the favored method for both *Easy* and *Hard* trials, despite the fact that participants not only experienced lower success rates in trial completion, they also experienced greater frustration and felt they performed worse while using WISDOM. This preference implies an interesting disconnect between objective performance and subjective experience, suggesting that comfort and intuitiveness may carry more weight in user preference than actual performance metrics. While this preference is in line with what was identified in the prior work [40], further examination reveals differences in what specific aspects of the techniques were preferred. In the prior work, participants preferred AMP-IT for natural rotation, however, in this study, they preferred WISDOM. One possible explanation for this shift is that when manipulating a geometrically complex object, having an intuitive and natural method of interaction, as afforded through the SVH mode of WISDOM, provides a level of familiarity that allows users to focus on task completion rather than figuring out how to use the technique.

6 Design Considerations

Our analyses revealed considerations for improving precise manipulation in VR environments with geometrically complex objects.

6.1 Techniques may benefit from context-sensitive axis visualization

The development of context-sensitive axis visualization could benefit manipulation techniques, by providing movement feedback while minimizing additional visual complexity and offering greater information clarity. For example, AMP-IT's lack of axis visualization made rotation difficult during the trials, and WISDOM's persistent axis visualization made participants feel they could not use the technique efficiently. Both of these issues could be addressed by dynamically visualizing only the non-zero or actively engaged axes. This approach would provide users with a clear understanding of what movement is being applied to the object and its spatial direction.

6.2 Adaptive sensitivity may aid in balancing user performance and preference

Participants using WISDOM expressed difficulties with object misalignment due to hand instability (Section 4.4). One improvement to avoid these issues might be a proximity-dependent transitioning between modes, similar to the zoning approach of [34]. This would allow users a smoother transition from using SVH to AMP-IT as they move closer to the alignment target. This approach would leverage the rapid, broad adjustments of WISDOM's SVH mode, along with the fine-tuning and granular precision of AMP-IT, allowing users to engage with and benefit from the full spectrum of capabilities provided by these manipulation techniques while maintaining their desire for more direct manipulation. Of course, this approach relies on the alignment target being known by the system, which is true in our additive manufacturing alignment case, but may not apply to all precise manipulation tasks.

7 Limitations & Future Work

There were several limitations of our study. First, we conducted this study with a single object of one geometric complexity, did not vary complexity systematically, and compared our results to prior work in order to infer the effects of geometric complexity. While we only examined one object, our work contributes towards broadening our understanding of how complexity affects manipulation techniques. However, the object used in our study, while complex, did not represent the full spectrum of geometric properties and manipulation challenges that may be encountered with real-world objects, including irregular or non-axis-aligned objects. Expanding this work to include a wider range of geometric features may introduce additional perceptual and spatial reasoning challenges that could further impact technique effectiveness.

Individual differences in spatial visualization abilities present an additional limitation as participants' capacity to mentally visualize and reason about 3D transformations could have influenced their performance and preferences. We did not assess the' spatial ability of the participants, which may have contributed to unaccounted-for variability in task performance and technique preferences. Future work should consider explicitly measuring and controlling for these individual differences to better understand their impact on manipulation technique effectiveness.

The focus on *Hard* and *Easy* tasks may not fully represent the spectrum of real-world manipulation scenarios. An individual user's performance and preferences may vary based on experience levels, as during the training trials the participants were encouraged to take their time to familiarize themselves with the interaction techniques. Additionally, time constraints in the *Hard* trials may have influenced performance differences, as the participants could have been close to finishing the task, but simply ran out of time.

We understand that our findings may transfer differently to real-world objects of varying complexity and, based on our work, the potential for objects with distinct alignment challenges to require different manipulation approaches. Therefore,future research directions should include a direct and systematic examination of the effects of geometric complexity across multiple, distinct complexity levels, with real-world objects, to evaluate how the difference in user metrics change across the complexity to better determine the long-term viability and generalizability of newly developed techniques. Subsequent research should also explicitly explore user manipulation requirements, specifically differentiating between when users desire coarse adjustments versus fine adjustments during object manipulation, as well as their corresponding mode-switching triggers, to minimize disruptions and unintentional movements while transitioning to and from the different adjustment phases. Further work would also benefit from a more thorough examination of trade-offs between user preference and objective performance metrics, and a comparative study of simple and complex objects side by side to better understand the intricacies of geometric complexity. Finally, future work could also include implementing additional functionality into these techniques such as color-mapped or numerical deviation notifications similar to [49] or the inclusion of locking and unlocking modes as described in [33].

8 Conclusion

In this study, we re-examined user performance, usability, workload and user preference of two high-precision VR manipulation techniques, AMP-IT and WISDOM, in the context of precise alignment tasks. The originality of our work lies not in the development of new techniques, but in understanding how existing manipulation techniques perform under more rigorous conditions, which brings us closer to practical adoption. Through our comparative study of these techniques, we partially validated previous findings but also identified important distinctions that emerge when users interact with the complex geometry of a real-world object rather than a simple geometric shape. The transition from a simple to complex object exposed limitations in WISDOM's hybrid approach while highlighting AMP-IT's adaptability to challenging geometric complexities. Our findings help to establish how performance and preference metrics of precise manipulation techniques shift when used with complex objects compared to simple ones, informing VR manipulation technique choice and design.

The most significant distinctions appeared in the *Hard* trials, in which the introduction of a geometrically complex object greatly impacted user performance. Our evaluation revealed that AMP-IT's continuous scaled approach proved unexpectedly effective for high-precision alignment of complex objects. However, WISDOM's hybrid approach, despite showing lower objective performance, remained the preferred technique among users, affirming the need for balance between technical capability and user experience.

These findings contribute to the larger body of knowledge on VR interaction design, offering valuable insights for developers working on precise manipulation tasks. Our research particularly emphasizes the importance of considering both performance metrics and user experience when designing VR interaction techniques for complex 3D object manipulation. While our work only examines two levels of difficulty when manipulating a complex object, it gets at an important concept in that user performance with some precise manipulation techniques in VR is dependent on object task and complexity. Furthermore, the reproducibility aspect of our work further validates the benefits and drawbacks of the AMP-IT and WISDOM techniques, providing insights that can inform future design decisions within the field.

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