Comparative Analysis of Artefact Interaction and Manipulation Techniques in VR Museums: A Study of Performance and User Experience

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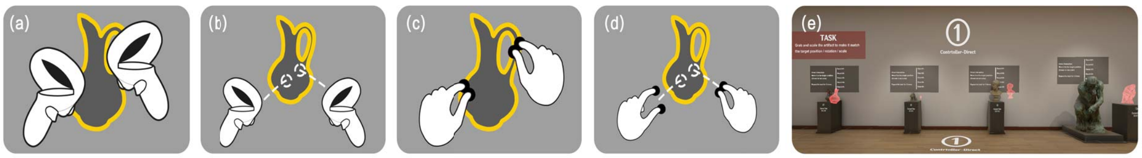

Figure 1: Illustrations of the (a) controller-based direct manipulation, (b) controller-based indirect manipulation, (c) hand-tracking direct manipulation, and (d) hand-tracking indirect manipulation. (e) The experimental scene for the manipulation tasks.

Abstract

For museums in Virtual Reality (VR), various interaction and manipulation techniques could be employed for users to engage with artefact interactions. This study examined four combinations of interaction (controller-based and hand-tracking) and manipulation (direct and indirect) techniques, assessing user performance and experience with these interaction techniques in a virtual museum environment. We conducted a within-subjects experiment and asked participants to perform a series of transform manipulation tasks using the four techniques. Participants' task completion time was measured. They also provided feedback on acceptance, learnability, presence, sickness, and fatigue, and gave an overall ranking through post-experiment questionnaires and interviews. The results revealed that controller-based direct manipulation outperformed the other techniques in terms of task performance and user experience, with hand-tracking indirect manipulation being the least efficient and the least preferred option. The study offers insights for future research and development in refining interaction and manipulation techniques and designing more user-friendly VR museum experiences.

Index Terms: Human-centered computing - Human computer interaction (HCI) - Interaction paradigms - Virtual reality Human-centered computing - Human computer interaction (HCI) - Empirical studies in HCI Human-centered computing - Human computer interaction (HCI) - Interaction techniques - Gestural input

1 Introduction

Virtual Reality (VR) has brought opportunities to various traditional industries, including the museum sector, by providing more immersive and interactive experiences of culture and history. It enables visitors to engage with cultural heritage and perceive artefacts in new ways, offering unique interactions and opportunities that are otherwise impossible in the physical museum spaces [31]. Studying artefact interactions in virtual environments is essential for optimising user experiences and enhancing users' interest and learning motivation in VR museums.

In VR museums, visitors can interact with artefacts in ways that are not possible in the real world. For instance, virtual artefacts can be manipulated without being influenced by gravity or fragility, allowing for more convenient observation from various angles without occlusion from hands. Such contrast of feasibility between the virtual and physical world reflects the concept of affordance [3]. Additionally, visitors can scale artefacts as desired for a clearer observation, leading to improved user experiences in virtual environments [34]. Therefore, the objective of this study is to systematically investigate interaction and manipulation techniques for artefacts in VR museums, and to identify the optimal technique within this context. Specifically, we explore affordances in VR museums where virtual artefacts can be free from external forces and scalable for enhanced observation.

Hand-held controllers are common input devices that have been employed to simulate virtual hands in VR environments. However, as users maintain the posture of holding the controller, the shape of the virtual hands may not align with that of the real hands, reducing the sense of immersion [23]. Recent advancements in head-mounted displays (HMDs) have introduced hand-tracking techniques as an alternative to controllers [36]. Hand-tracking technology, such as that used in Microsoft HoloLens and Meta Quest 2, does not require additional devices like tracking gloves, resulting in hands-free inputs [9]. Hand-tracking interactions foster a more realistic connection between the real and virtual hands, making them more intuitive for users unfamiliar with VR controllers and allowing for more natural user experiences [26].

In this work, we implement both controller-based and hand-tracking methods for artefact interactions, allowing users to transform a virtual object (i.e., position, rotation, and scale). For each interaction method, we examined both direct and indirect manipulations (see Figure 1). With direct manipulations, users are allowed to manipulate an artefact by attaching it to the hand and letting it follow the hand positions and rotations. Indirect manipulations enable users to manipulate the artefact at a distance, mediated by two rays pointing to the target artefact. The need for indirect manipulation is mainly motivated by the fact that in a museum environment, artefacts are often displayed at a distance, and many of them are of a large size, in which case direct manipulations can be obtrusive. Through controlled user studies, we found that participants had the overall best task performance and user experience with the controller-based direct manipulation technique. Specifically, participants found controller-based interactions more acceptable and less tiring than hand-tracking interactions. In addition, compared to indirect manipulations, direct manipulations were found to be more acceptable and learnable, better contribute to presence, and cause less sickness and fatigue. Participants' overall rankings for the four techniques

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from the highest to the lowest were controller-based direct manipulation, hand-tracking direct manipulation, controller-based indirect manipulation, and hand-based indirect manipulation.

Our work demonstrates three main contributions. First, we detailed the design of artefact interactions based on two mainstream approaches: controller-based and hand-tracking. To complete the VR museum experience, we also implemented the locomotion in VR using the same techniques and introduced the design of interactive user interfaces for museum artefacts. These are necessary components for a virtual museum design, which can also be easily adapted in other application domains such as education and games. Second, we conducted a comprehensive comparative study to evaluate task performance and user experience with four different techniques in the virtual museum context. The results and discussions show the explicit strength and limitations of controller-based and hand-tracking interactions, as well as direct and indirect manipulations. Finally, the insights gained from this research contribute to a better understanding of 3D object interactions and user experiences in VR. The design implications offer valuable takeaways for researchers and practitioners and identify areas of improvement to foster more acceptable and engaging designs of VR interactive systems.

2 Related Work

2.1 Artefact Interaction in Virtual Museums

There have been various previous works related to virtual artefacts and virtual museums. Early in 2006, Walczak et al. [37] pointed out that the application of virtual and augmented reality in museums would transform visitors from simply passive viewers and readers into active actors and players. Other than the museum itself, some projects aimed to provide experience of the past, in which virtual environments were created to reconstruct historical scenes [12, 13, 29]. There have been other projects which introduce gameplay features on simulating archaeological works [2, 22, 30]. General application scenarios of these projects are education and entertainment.

Numerous studies have delved into virtual museums, yet a systematic investigation of artefact interactions in VR museums remains sparse. The interactivity of virtual artefacts stands out as a pivotal digital affordance in these settings. A range of interaction techniques, from controller-based [13] and hand-tracking interactions [8, 16] to direct [21] and indirect manipulations [11], have been explored in prior works. While researchers have identified that direct manipulation can become disruptive with larger objects [20], there's a consistent user inclination towards interacting with artefacts, irrespective of their size. Notably, enhanced interactivity correlates with heightened user engagement in the virtual museum [21]. The following sections provide a detailed overview of these techniques, discussing their applications, advantages, and disadvantages.

2.2 Controller-Based and Hand-Tracking Interactions

Controller-based interactions utilise physical input devices, such as handheld controllers, to interact with virtual objects and environments [17]. These controllers typically have buttons, joysticks, and touchpads for input and are tracked in 3D space to allow for accurate interaction. Despite the ease of use and intuitiveness of controller-based interactions, they may not always provide the most natural experience, as users may need to learn how to operate the controllers and remember the button mappings [35].

In the context of VR museums, controller-based interactions have been used for navigation and object manipulation [13, 14]. Controller-based interactions have been widely used in various VR applications and demonstrated strength in its highly accurate operations. Despite its precise control, the interactions are mediated by the hand-held device, and the operations are not as natural as hand-tracking interactions.

Hand-tracking interactions involve tracking users' hand movements in real-time, allowing them to interact with virtual objects and environments using natural hand gestures [28]. These interactions do not require any physical input devices, offering more intuitive controls. In the meantime, precise and responsive hand-tracking can be challenging as it often relies on real-time recognition of users' hands and gestures. Individual differences, lighting conditions, and camera motions may cause variances, delay, and imprecision in the recognition of gestures. Users may also experience difficulties performing precise manipulations due to the lack of tactile feedback [19].

While hand-tracking promotes natural interactions with artefacts [16], much of the research has focused on demonstrating its feasibility without extensively exploring its specific advantages or limitations compared to other methods. With the advent of recent advancements in VR HMDs, such as the Meta Quest 2 which incorporates embedded hand-tracking, an opportunity arises to more comprehensively compare hand-tracking with the widely adopted controller-based approach in VR museum experiences.

2.3 Direct and Indirect Manipulations

Direct manipulation techniques involve users physically interacting with virtual objects as if they were real-world objects, using their hands or input devices to grab, move, rotate, or scale them [27, 40]. This technique is widely adopted, as it closely resembles real-world manipulations of objects and maps well with users' existing mental models. However, direct manipulation may not be suitable for all scenarios, especially those involving large or distant objects.

Direct manipulation techniques in virtual environments have been extensively studied in the related work [5, 33]. A comprehensive evaluation of techniques for grabbing and manipulating remote objects in immersive virtual environments was conducted [5], focusing on assessing the performance of various direct manipulation techniques, such as the *Go-Go* technique and the *HOMER* (Hand-centered Object Manipulation Extending Ray-casting) technique. These techniques attach virtual objects to the virtual hand, thus facilitating natural and intuitive object manipulations within virtual spaces by closely mimicking real-world interactions. Steed and Parker [33] found that for both HMDs and immersive projection, raycasting is preferable for selection, and the virtual hand is preferable for manipulation. Nevertheless, when an object is too close to the user, direct manipulation, especially the scaling operation, may face the issue of occluding the camera and blocking the user's first-perspective view.

Indirect manipulations involve the use of intermediary devices, controls, or representations to interact with objects in virtual environments [32]. With these techniques, users do not interact with the objects directly, but instead utilize other means, such as raycasting, to manipulate them [25]. This approach is more suitable for scenarios where direct manipulation is not feasible, such as manipulating large or distant objects. Chan et al. [11] designed a spherical display system based on a crystal ball that allows users to manipulate a virtual artefact appearing inside the transparent sphere using barehands. However, as reported by the authors, users felt uneasy before they realised the correct way to operate. Indirect manipulations may be less intuitive as they require users to learn specific gestures or actions and acquire a new mental model to perform the desired interactions.

3D object manipulations are also closely related to the selection techniques. Argelaguet and Andujar [1] conducted a comprehensive survey of 3D object selection techniques in virtual environments. The authors highlighted various indirect techniques that are widely used to interact with objects in virtual environments, among which ray is the most used selection tool. Raycasting is particularly suitable for grabbing virtual objects placed at a distance [5]. The raycasting metaphor is intuitive and thus has been adopted by default in many VR applications. While direct and indirect manipulation techniques have been extensively researched, empirical studies directly comparing them, especially in the context of controllers versus hand-tracking, remain scarce. This underscores a significant void in the literature concerning VR museum interactions.

3 System Implementation

We implemented the virtual museum environment and the four techniques in Unity (version 2021.3.6f1c1). This project was developed and run on a laptop with an i7-9750H CPU, 16 GB RAM, and the NVIDIA RTX 2070 GPU. We used a Meta Quest 2 HMD, with a resolution of 1832 * 1920 per eye, and a refresh rate of 72 Hz.

3.1 Virtual Museum Environment

The virtual museum developed for this project is illustrated in Figure 2. It comprises basic components such as 3D models of the environment, 3D photogrammetric artefacts, lighting, and object materials. We included artefacts of different shapes and sizes, ranging from 36 cm to 182 cm. The 3D models of the artefacts along with their corresponding materials were sourced from public free model libraries. We used mesh colliders that closely matched the geometry of the models to ensure accurate interactions. The Universal Render Pipeline (URP) was employed to achieve more realistic graphics.

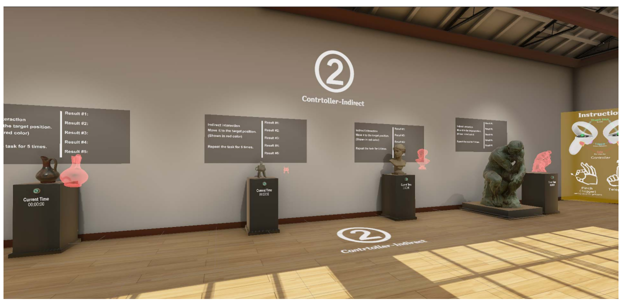

Figure 2: The virtual museum environment showing four artefacts. From left to right, the artefact sizes are (30 cm, 45 cm, 30 cm)[1], (22 cm, 36 cm, 21 cm)[2], (52 cm, 80 cm, 32 cm)[3], and (146 cm, 182 cm, 116 cm)[4] in width, height, and depth.

3.2 Interactive Functions

Within the virtual museum, users can interact with virtual objects and move around within the scene. Two core functions have been implemented for interactions with artefacts: grabbing and scaling. In addition, teleporting was implemented to enable users to move freely within the virtual museum and view different cultural relics. The Mixed Reality Toolkit (MRTK) [24] was utilised to implement interactive functions including grabbing, scaling, and teleporting for both controller-based and hand-tracking interactions (see Figure 3).

With controller-based interactions, users can use the controller buttons to confirm the selection. For direct manipulation, users need to move close to a virtual artefact in order to grab and scale it. The selection is confirmed by pressing the grab button using the middle finger. For the indirect manipulation, two parabola curves are cast from the two controllers and participants can grab and scale the object at a distance by pressing the trigger buttons using their index fingers. Users can teleport to move by pushing the thumbstick forward (see Figure 3).

With hand-tracking interactions, users can pinch their thumb and index finger to confirm the selection. Similar to the direct manipulation for controller-based interactions, users need to touch the virtual artefact with their virtual hands to perform manipulation operations. The operations for indirect manipulations are mediated by the two parabola curves connecting users' virtual hands and the

[1] Mexico jug: `https://skfb.ly/6TBnQ`
[2] Fangjia wine vessel: `https://skfb.ly/6YOnz`
[3] Sculpture "Bust of Róża Loewenfeld": `https://skfb.ly/ZMvC`
[4] The thinker: `https://skfb.ly/6YwPH`

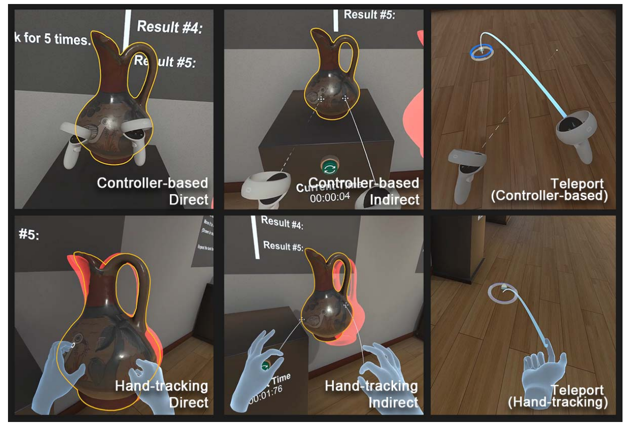

Figure 3: An overview of interactive functions.

selected artefact. Users can grab an object using one hand and scale an object with two hands. By pointing the index finger towards the floor, users can teleport to move around in the virtual museum.

Moreover, as an essential part of artefact interactions in VR museums, we also designed interactive user interfaces (UI) to present artefact information (see Figure 4). Three different schemes were considered for displaying the historical information of artefacts: static labels, floating tags, and audio guides. In the implemented example, the UI system includes elements of a static label, floating tags, a reset button, and an audio guide button with a progress bar below it. We also include two toggle switch buttons so that users can enable or disable the gravity effect and floating tags.

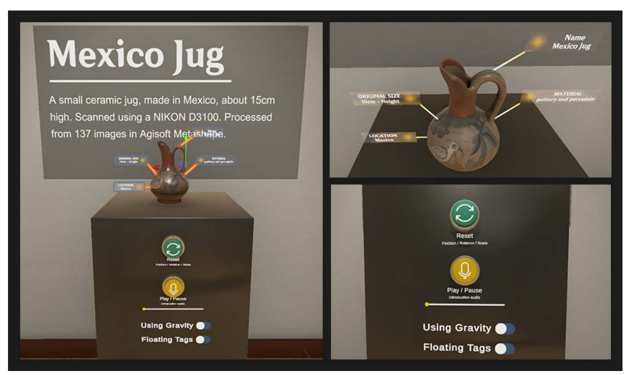

Figure 4: The interactive user interfaces for artefact information: a static label, floating tags, a reset button, and audio guides.

4 Study Design

In our study, we employed a within-subjects experimental design to measure the performance and user experience with four different interaction techniques in a VR museum setting: Controller-based Direct (CD), Controller-based Indirect (CI), Hand-tracking Direct (HD), and Hand-tracking Indirect (HI). Drawing inspiration from studies on freehand grasping and docking tasks in VR [4], participants were asked to complete transform manipulation tasks involving the selection, grabbing, and scaling of virtual artefacts using each of the interaction techniques. To balance between accuracy and task difficulty, we introduced a threshold of 10% in the object's transform position, rotation, and size (see Figure 5). Participants voluntarily signed up for the study and there was no monetary incentive. This study is approved by the University Ethics Committee at Xi'an Jiaotong-Liverpool University.

Figure 5: Illustration of the transform manipulation task. The orange area indicates the target location, and the colour will change to green if there is a match.

4.1 Research Questions

The study aims to answer two research questions (RQs):
RQ1: Do users' task performances (speed) differ when using different techniques for artefact interaction and manipulation in VR museums?
RQ2: Do user experiences vary when using different techniques for artefact interaction and manipulation in VR museums?

4.2 Experimental Procedure

The general procedure of the experiment is illustrated in Figure 6. At the beginning of each experiment, we introduced the study purpose and collected informed consent and demographic information from participants. An instruction tutorial was provided to all participants for them to get familiar with the four interaction techniques prior to the task trials. The experiment included four sessions, one for each interaction technique (CD, CI, HD, and HI). To counterbalance any order effects and minimise potential learning or fatigue biases, the session order of the interaction techniques was determined by following a Latin Square Design. For each experimental session, participants need to complete transform manipulation tasks, where they manipulate a virtual object by moving, rotating, and scaling it to match the target position, orientation, and size. There were five repetitive trials for each of the four artefacts (see Figure 2), resulting in 20 task trials in total for each condition. The task completion time was recorded to measure the performance of each interaction technique. Upon the completion of each session, participants evaluated the technique by filling in a post-condition questionnaire. The experiment concludes with a short interview and debriefing. The entire experiment took ∼75 minutes for each participant.

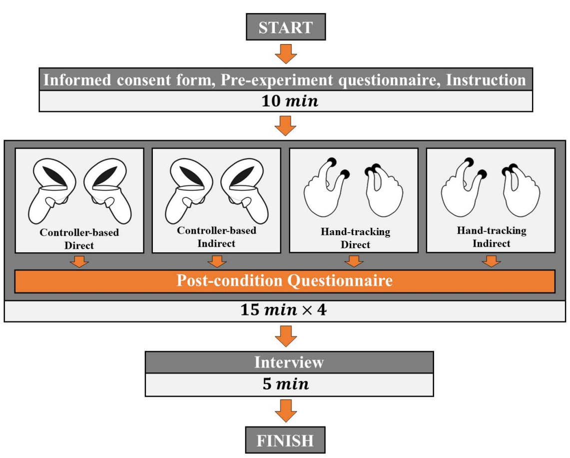

Figure 6: The experimental procedure.

4.3 Measures

The dependent variables are task performance and user experience. We recorded system timestamps to collect objective performance data and used questionnaires to collect participants' self-reported user experience.

4.3.1 Task Performance

We measured the time participants spent for each trial of transform manipulation tasks. Given that participants were asked to conduct five repetitive trials for each artefact, we excluded the maximum and minimum completion time for each artefact and calculated the average time of the remaining three trials, mitigating the impact of extreme values on the results. The overall average completion time for each interaction technique was then determined by calculating the mean value of the task completion time for all four artefacts.

4.3.2 User Experience

We included a 28-item questionnaire to measure the explicit user experience of artefact interactions in VR museums. All questionnaire items were rated on a 5-point Likert scale, where 1 denotes strongly disagree, 3 signifies neutrality, and 5 indicates strongly agree. The full questionnaire details are shown in Table 1. Some questions were designed in an opposite way and were reverse coded in the analysis.

Acceptancen (A1-A6). Participants' acceptance regarding the interaction techniques in the VR museum consists of an important part of their user experience. We include six questions adapted from the scale items for perceived usefulness and perceived ease of use [15]. These are classic constructs that determine user acceptance.

Learnability (L1-L6). As a critical aspect of user experience evaluation, learnability assesses the ease with which users understand and learn the interaction techniques in the VR museum. We include six items that measure learnability, based on the System Usability Scale [6]. This helps us understand how easily users can grasp and use the interaction techniques.

Presence (P1-P6). Presence is a vital component of the user experience in VR. It focuses on users' feeling of being there in the virtual environment, which entails the realism, immersion, and the sense of control. Five questions were derived from the Presence Questionnaire [39]. This indicates how effectively users feel present and engaged in the virtual environment.

Sickness (S1-S5). Sickness evaluates users' feelings of discomfort, such as dizziness and eye discomfort, during their VR museum experience. This evaluation utilized five questions adapted from the Simulator Sickness Questionnaire [18]. Simulator sickness was measured between each condition to understand the potential negative effects of the different interaction techniques.

Fatigue (F1-F5). Fatigue gauges users' feelings of tiredness and relaxation when interacting with artefacts in the VR museum. Five questions were adapted from the Chalder Fatigue Scale [10]. This helps us understand how different techniques might influence users' physical comfort levels.

4.4 Participants

The study involved twenty participants, consisting of 12 males and 8 females aged between 19 and 28 ($M = 22.6$, $SD = 2.24$). Eleven participants had prior experience with VR devices, while nine did not. Participants' self-reported proficiency in controller-based interactions in VR was moderate ($M = 2.65$, $SD = 1.39$), whereas they were slightly familiar with hand-tracking interactions ($M = 2.10$, $SD = 1.30$). Figure 7 shows two participants in the experiment using the controller-based interaction techniques and hand-tracking interaction techniques respectively.

5 Results

In total, we gathered 80 sets of task completion time data as objective performance measures (4 techniques x 20 participants), 80 sets of

Table 1: Questions to measure explicit user experience of artefact interactions in VR museums. *Italic items* are reverse coded.

#	Question
A1	I liked this form of interaction with artefacts.
A2	It was comfortable for me to explore VR museum with this technique.
A3	I would like to interact with more artefacts with this technique.
A4	I was in favour of interacting with artefacts in this way.
A5	*I found it not suitable for me to interact with artefacts in this way.*
A6	*I disliked interacting with artefacts in this way.*
L1	It takes me a short time to understand and learn how to interact with artefacts properly.
L2	I found it easy to learn how to grab the object.
L3	I found it easy to learn how to scale the object.
L4	I would imagine that most people would learn to use this interaction method very quickly.
L5	*It takes me a long time to understand and learn how to interact properly.*
L6	*It was hard to learn this interaction method.*
P1	I felt natural using my hands to interact with artefacts.
P2	I had a sense of "being there" in the VR museum.
P3	*I didn't think that I was interact with the artefact with my own hands.*
P4	I felt consciously aware of being in the real world whilst playing.
P5	I felt I was in good control of the artefact.
P6	The virtual hands were felt like my real hands.
S1	I felt dizzy while doing the tasks.
S2	I felt sick during the experiment.
S3	I felt uncomfortable with my eyes.
S4	*I did not feel dizzy during the experience.*
S5	*I did not feel sick while doing the tasks.*
F1	I felt tired while trying to fit the object to the target position.
F2	*It was not tiring for me to finish the task with this type of interaction.*
F3	*This experience was relaxing for me.*
F4	I suffered from fatigue during my interaction with the virtual environment.
F5	I felt tired with the overall experience in the VR museum.

subjective ratings for preference, learnability, immersion, sickness, and fatigue (4 techniques x 20 participants), and 20 sets of subjective rankings from the interview (20 participants). Data analysis was performed using IBM SPSS Statistics. We conducted one-way repeated measures ANOVA to study the effect of the four techniques on task performance, given that time is a continuous measure. User experience variables were measured on a 5-point Likert scale, so we used the non-parametric alternative, Friedman tests. In addition, we conducted two-way repeated ANOVA to further examine the effects of interaction technique (IT, i.e., controller-based and hand-tracking) and manipulation technique (MT, i.e., direct and indirect) on the examined dependent variables. This dual analysis approach ensured a comprehensive understanding of both overall technique impact and the nuances between IT and MT.

5.1 Task Completion Time

To answer **RQ1**, we processed the collected time data from the transform manipulation tasks to calculate the average time for completing the task per artefact for each participant. A box-plot diagram, shown in Figure 8, visualises the distribution of the processed time data.

A repeated measures ANOVA with a Greenhouse-Geisser correction showed statistically significant differences in task completion time, $F(2.496, 47.424) = 21.308$, $p < 0.001$. Significant differences were found in task completion time between CD-CI ($Z = 2.95$, $p = 0.003$), CD-HD ($Z = 3.40$, $p < 0.001$), CD-HI ($Z = 3.92$, $p < 0.001$), CI-HI ($Z = 3.73$, $p < 0.001$), and HD-HI ($Z = 3.29$, $p = 0.001$). However, no significant difference in time was observed

(a) A participant using controller-based interaction techniques. (b) A participant using hand-tracking interaction techniques.

Figure 7: Participants in the experiment.

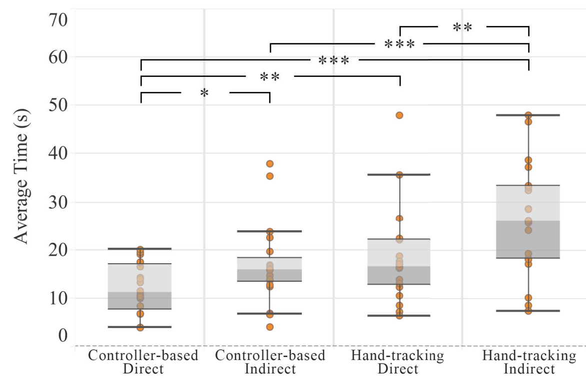

Figure 8: Task completion time using four techniques.

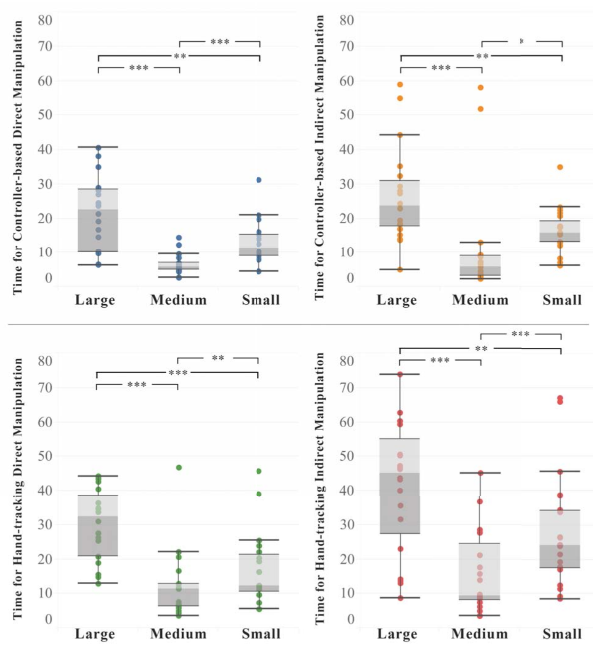

Figure 9: Task completion time with three different objects' sizes for four interaction techniques.

between CI-HD ($Z = 0.34$, $p = 0.737$).

A two-way repeated measures ANOVA showed no statistically significant interaction effect ($F(1,19) = 3.60$, $p = 0.073$). Statistically significant main effects of IT on time ($F(1,19) = 28.54$, $p < 0.001$) and MT on time ($F(1,19) = 19.97$, $p < 0.001$) were observed.

We also analysed the difference in task completion time among objects of varying sizes (large, medium, and small). The first and the third artefact shown in Figure 2 were categorised to a medium size; the second artefact was a small artefact, and the last one was a large artefact. Significant differences were found for all four techniques (see Figure 9). Notably, users required significantly more time to manipulate large-sized and small-sized artefacts compared to medium-sized artefacts.

5.2 User Experience

Participants' self-reported user experience scores in terms of acceptance, learnability, presence, sickness, and fatigue provide answers for **RQ2**. Figure 10 shows a box-plot illustrating the results of user experience.

Acceptance. A Shapiro-Wilk test showed that the distribution of acceptance data departed significantly from normality ($p < 0.001$). A Friedman test found a significant difference in user acceptance among the four techniques, $\chi^2(3) = 32.75$, $p < 0.001$. Post hoc analysis with Wilcoxon signed-rank tests was conducted with a Bonferroni correction applied, resulting in a significance level set at $p < 0.0125$. Significant differences were found in acceptance between CD-CI ($Z = 3.60$, $p < 0.001$), CD-HD ($Z = 2.62$, $p = 0.009$), CD-HI ($Z = 3.93$, $p < 0.001$), CI-HI ($Z = 3.66$, $p < 0.001$), and HD-HI ($Z = 3.21$, $p = 0.001$). The difference between CI-HD was insignificant ($Z = 0.79$, $p = 0.433$), despite the overall lower ratings for HD than CI.

A two-way repeated measures ANOVA showed a statistically significant interaction between the effects of IT and MT on acceptance, $F(1,19) = 5.28$, $p = 0.033$. Simple main effects analysis demonstrated that the ratings of acceptance for controller-based interactions were significantly higher than those for hand-tracking interactions when conducting indirect manipulations ($F(1,76) = 24.82$, $p < 0.001$). A similar significant difference occurred when conducting direct manipulations ($F(1,76) = 4.95$, $p = 0.029$). Furthermore, the ratings of acceptance for direct manipulations were significantly higher than those for indirect manipulations, both with controller-based interactions ($F(1,76) = 11.03$, $p = 0.001$) and hand-tracking interactions ($F(1,76) = 36.96$, $p < 0.001$).

Learnability. A Shapiro-Wilk test showed that the distribution of acceptance data departed significantly from normality ($p < 0.001$). A Friedman test found a significant difference in learnability among the four techniques, $\chi^2(3) = 18.26$, $p < 0.001$. Pair-wise comparisons showed significant differences in learnability between CD-CI ($Z = 3.53$, $p < 0.001$), and CD-HI ($Z = 2.97$, $p = 0.003$). No significant differences were found between CD-HD ($Z = 1.83$, $p = 0.067$), CI-HD ($Z = 0.99$, $p = 0.322$), CI-HI ($Z = 0.17$, $p = 0.868$), or HD-HI ($Z = 2.34$, $p = 0.019$).

A two-way repeated measures ANOVA showed a statistically significant interaction between the effects of IT and MT on learnability, $F(1,19) = 7.21$, $p = 0.015$. While IT showed no significant effect on learnability ($F(1,19) = 0.19$, $p = 0.672$), simple main effects analysis revealed significantly higher ratings of learnability for direct manipulation than those for indirect manipulations with controller-based interactions, $F(1,76) = 11.71$, $p = 0.001$. However, no significant difference was found between the direct and indirect manipulations with hand-tracking interactions, $F(1,76) = 1.55$, $p = 0.217$.

Presence. A Shapiro-Wilk test showed that the distribution of acceptance data departed significantly from normality ($p = 0.004$). A Friedman test revealed no significant difference in presence among the four techniques, $\chi^2(3) = 7.59$, $p = 0.055$.

A two-way repeated measures ANOVA showed no statistically significant interaction between the effects of IT and MT on presence, $F(1,19) = 1.48$, $p = 0.239$, but MT showed a significant effect on presence, $F(1,19) = 14.55$, $p = 0.001$. Ratings for presence were significantly higher for direct manipulations than indirect manipulations.

Sickness. A Shapiro-Wilk test showed that the distribution of acceptance data departed significantly from normality ($p < 0.001$). A Friedman test showed a significant difference in sickness among the four techniques, $\chi^2(3) = 17.30$, $p < 0.001$. The analysis revealed higher sickness with HI compared to CD ($Z = 2.86$, $p = 0.004$). There were no significant differences between CD-CI ($Z = 2.11$, $p = 0.035$), CD-HD ($Z = 0.27$, $p = 0.789$), CI-HD ($Z = 2.31$, $p = 0.021$), CI-HI ($Z = 1.50$, $p = 0.133$), or HD-HI ($Z = 2.45$, $p = 0.014$).

A two-way repeated measures ANOVA showed no statistically significant interaction between the effects of IT and MT on sickness, $F(1,19) = 0.95$, $p = 0.342$, while MT showed a significant effect on sickness, $F(1,19) = 14.44$, $p = 0.001$. This suggests that, regardless of the interaction technique, participants experienced less sickness when engaging in direct manipulation tasks.

Fatigue. A Shapiro-Wilk test showed that the distribution of acceptance data departed significantly from normality ($p = 0.006$). A Friedman test showed a statistically significant difference in fatigue among the four techniques, $\chi^2(3) = 23.56$, $p < 0.001$. It was highlighted that participants reported significantly higher fatigue with CI ($Z = 3.13$, $p = 0.002$), HI ($Z = 3.40$, $p < 0.001$) compared to CD, and HI ($Z = 3.15$, $p = 0.002$) compared to HD. The differences between CD-HD ($Z = 1.71$, $p = 0.087$), CI-HD ($Z = 2.02$, $p = 0.043$), and CI-HI ($Z = 2.35$, $p = 0.020$) were insignificant.

A two-way repeated measures ANOVA showed no statistically significant interaction between the effects of IT and MT on fatigue, $F(1,19) = 3.77$, $p = 0.067$. However, the effect of IT on fatigue ($F(1,19) = 5.48$, $p = 0.030$) and the effect of MT on fatigue ($F(1,19) = 21.36$, $p < 0.001$) were statistically significant. Hand-tracking induced more fatigue than controller-based interactions, and direct manipulations caused less fatigue than indirect manipulations.

5.3 Interview Findings

To obtain a holistic overview of the four techniques, participants were asked to rank the interaction techniques during the interview session at the end of the experiment. Out of the 20 participants, CD received the top rank from 12 participants. Five participants liked HD the most, with two participants voted for CI and one participant voted for HI as their favourite technique. The analysed data for their subjective ranking is shown in Figure 11.

A Friedman test revealed a statistically significant difference in the subjective ranking among the four techniques, $\chi^2(3) = 20.940$, $p < 0.001$. Median (IQR) subjective ranking for CD, CI, HD, and HI were 4 (3 to 4), 2 (2 to 3), 3 (2 to 3.75), and 1 (1 to 2), respectively, with higher scores represent higher rankings. Post hoc analysis showed significant differences in subjective ranking between CD-CI ($Z = 3.079$, $p = 0.002$), CD-HI ($Z = 3.207$, $p = 0.001$), and HD-HI ($Z = 2.973$, $p = 0.003$). No significant difference were found between CD-HD ($Z = 1.739$, $p = 0.082$), CI-HD ($Z = 1.088$, $p = 0.277$), or CI-HI ($Z = 1.891$, $p = 0.059$).

A two-way repeated measures ANOVA showed no statistically significant interaction between the effects of IT and MT on subjective ranking, $F(1,19) = 0.00$, $p = 1.000$. However, there was a statistically significant main effect of IT on the ranking ($F(1,19) = 4.65$, $p = 0.044$), and a statistically significant main effect of MT on the ranking ($F(1,19) = 18.928$, $p < 0.001$).

6 Discussion

6.1 Overall Performance and User Experience

In response to **RQ1**, participants' performance on transform manipulation tasks revealed that for artefact interactions in VR museum,

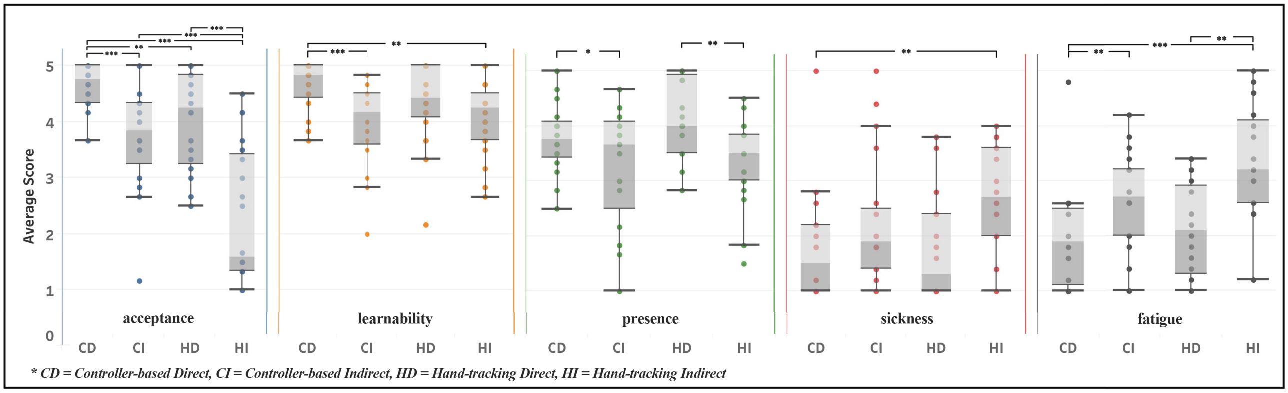

Figure 10: User experience using four techniques.

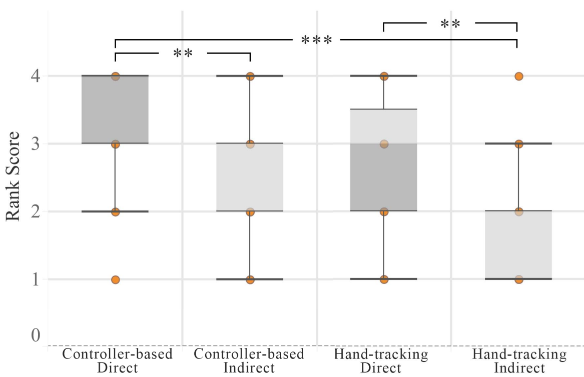

Figure 11: Users' subjective rankings of the four techniques.

(1) controller-based interaction is more efficient than hand-tracking interaction, and (2) direct manipulation outperformed indirect manipulation. This led to a significantly better task performance using controller-based direct manipulation than the other techniques, and hand-tracking indirect technique was found to be the least efficient one. One of the possible reason is that our participants were more familiar with controllers than hand-tracking gesture control. However, from participants' interview comments, it seems that the precision and sense of control provided by controllers have excelled the hand-tracking approach. Overall, the majority of participants found controller-based and direct manipulations to be the most preferred interaction technique (N=12). For future VR applications that demand efficiency in tasks, controller-based direct manipulation technique should be adopted.

In terms of user experience (**RQ2**), controller-based direct manipulation technique demonstrated the highest acceptance and learnability, and the lowest sickness and fatigue. We discuss the explicit user experience results and implications in the following two sections.

6.2 Controller-Based and Hand-Tracking Interaction Techniques

Controller-based interaction techniques were found more acceptable and less tiring than hand-tracking techniques, but no significant difference was found in learnability, presence, or sickness. For both techniques, users reported relatively high learnability. Usually, hand-tracking techniques were deemed to be natural interaction techniques [26]. Our study showed that although participants rated higher on presence using hand-tracking interactions than controller-based interactions, the difference was statistically insignificant. We speculate that the interaction technique was not the decisive factor of users' perceived presence. There are other factors such as the visual fidelity of the VR environment, the interactivity of virtual objects, and the media richness afforded in the system, which may influence users' perceived presence in VR.

Participants' comments have identified issues of hand-tracking technique in user acceptance and fatigue. One participant (P1) mentioned that *"I felt more in control when using the controller and direct manipulation, as it felt more responsive and accurate."* On the other hand, participants raised issues such as *"not precise enough"* and *"lost tracking"* when using hand-tracking interactions. We observed that some participants preferred to have their fists clenched over pinching their thumb and index fingers. Fatigue was notably pronounced when participants had to extend their arms to access distant artefacts. This appeared to be more pronounced in the context of hand-tracking interactions, where corrective movements were more frequently required to achieve precise control. One participant (P3) mentioned that *"My arms got tired when trying to reach artefacts directly, as I had to stretch my arms out to grab them."* Another participant (P7) shared his experience with hand-tracking, saying that *"Sometimes it was frustrating when the system didn't detect my hand movements properly, which added to the overall fatigue."* Mitigating the physical fatigue and increasing the recognition precision are two main optimisations needed for handing-tracking techniques to be more acceptable.

6.3 Direct and Indirect Manipulation Techniques

Comparing direct and indirect manipulation techniques, users found direct manipulation techniques more acceptable, easier to learn, more present, and have caused less sickness and fatigue. A participant (P10) shared that *"It took me a while to get used to the indirect manipulation, especially with hand-tracking, but the direct manipulation felt natural right away."* Direct manipulations were considered more intuitive and easier to learn by most participants, given that 17 out of 20 participants ranked direct manipulation techniques as the preferred options.

We found that users' perceived presence is affected by the manipulation technique - direct techniques have led to higher presence than indirect techniques. However, participants also reported limitations of unnaturalness when grabbing an artefact of large size with direct manipulations. One participant (P2) commented that *"When I tried to grab the large artefact directly, it felt a bit strange, like my hand should not have been able to grab it so easily."* Despite this comment, participants generally reported a more immersive experience when using direct manipulations. Sickness with direct manipulations was generally lower than indirect manipulations, with a significant difference found between CD and HI. A participant (P15) noted that *"I felt a bit dizzy when using hand-tracking with indirect manipulation. It was disorienting at times."* Thus, hand-tracking with indirect manipulation should be used with caution, as we found that it is more likely to cause discomfort and sickness. Manipulating artefacts at a distance also caused greater fatigue. With both controller-based and hand-tracking interactions, the manipulation was found more tiring when participants could not hold an object in hand. This finding is consistent with participants' overall rankings on the four techniques.

Overall, participants ranked higher on direct techniques (1^{st} CD, 2^{nd} HD) than indirect techniques (3^{rd} CI, 4^{th} HI). P4 explained that *"I liked the controller-based interactions more because they felt more precise and less tiring compared to hand-tracking."* While the other participant (P5) stated different opinions, *"I would put the rank of hand-tracking interactions ahead. That was a very novel experience for me, and it greatly enhanced my sense of immersion."* P12 provided an explanation for choosing between two manipulation techniques, *"For the transform manipulation task, I would strongly prefer direct manipulations, as I could easily complete the tasks with them. However, if I were to explore and visit a virtual museum casually, I would prefer to use indirect manipulations cause I found them more interesting, and I no longer need to frequently extend my hands and arms."* In general, participants tended to prefer controller-based interactions, but some also appreciated the novelty and immersion offered by hand-tracking interactions.

6.4 Design Implications

Our research comparing different interaction and manipulation techniques in VR has several design implications for future VR systems and applications. Based on our findings, we provide the following recommendations to improve user experience and performance with 3D virtual object interactions.

Define the context and task requirements. When designing VR applications, consider the specific tasks users will perform and the context in which they will interact with the virtual environment. For tasks requiring high precision and efficiency, direct manipulation techniques will yield significantly better performance. For scenarios that prioritise the sense of presence but not task performance, hand-tracking technique is worth trying because it has shown potential in supporting a great sense of presence.

Balance naturalness and acceptance. Hand-tracking interactions offer a more natural and intuitive method of interaction but may face challenges related to accuracy and a perceived difficulty in releasing objects [7]. Designers should strive to improve user acceptance of hand-tracking interactions by improving the reliability and responsiveness, while also providing clear feedback to users about the best practices for using such interactions. For example, visual cues can be employed to indicate the success or failure of an interaction, while haptic feedback can enhance the sense of touch and presence in VR.

Optimise physical effort. Fatigue is another limitation of hand-tracking interactions that needs to be considered. Designers may avoid using it for prolonged and frequent interactions. In the meantime, one can consider implementing ergonomic solutions to reduce the physical demand, such as providing adjustable interaction distances or incorporating assistive features such as snapping or auto-alignment.

Allow for customisation and flexibility in control. Different users may have varying preferences and abilities when it comes to interaction techniques in VR. Designers should consider providing options for users to customise their interaction preferences, such as the choice between direct and indirect manipulation or the ability to switch between hand-tracking and controller-based interactions.

6.5 Limitations and Future Work

This project has potential for expansion in both research and development directions. It also has some limitations. First, the techniques evaluated in this study are based on an existing toolkit - the MRTK. On the one hand, the techniques supported in the toolkit are representative of the mainstream approaches. On the other hand, there are other techniques that were shown effective in previous work, such as HOMER [5], which were not examined in the current work. Moreover, it is worth noting that other toolkits and implementations may yield different results, or reveal variations in user experience. Despite that it is out of the scope of this study to compare all manipulation techniques, future work could extend the study to explore more effective techniques, especially hand-tracking interactions and indirect manipulations, to obtain a more comprehensive understanding of user acceptance of the techniques in VR museums. Second, our participants are mostly young adults, which may not fully represent diverse user groups. Future studies could include a larger and more diverse participant pool to obtain more generalisable results. Third, the study was a controlled experiment and participants were asked to perform repetitive trials on transform manipulation tasks as fast as possible. However, artefact interactions are very likely to be different in an actual virtual museum visit. The manipulation of artefacts will be less frequent and the overall interactions will be less taxing. Thus, it is worth noting that user experience in this study mainly reflects that of artefact interactions. For a virtual museum experience that also involves navigation, learning, and social interactions, the effect of artefact interaction techniques on user experience may not be as significant as shown in this study.

Future work could also explore mixed interaction techniques, which combine direct and indirect manipulations, and also controllers and gestures. Additionally, investigating effective manipulation techniques for artefacts of different features may provide valuable insights. Our work shows that regardless of the technique used, participants found it difficult to manipulate small ($\sim$20 cm) and large ($\sim$1.5 m) objects. Future work should explore techniques to address this challenge. An additional avenue for future research is the exploration of pseudo-haptic weight in VR. The perception of weight, as suggested by recent work [38], can influence how users interact with virtual objects. Incorporating pseudo-haptic weight could add another layer of realism to the interaction and potentially influence user performance and experience. This aspect, while not investigated in our current study, holds promise for enhancing the immersion and realism of VR museum interactions. Finally, if hand-tracking technology advances in hardware or software, repeating the experiment with the latest techniques could yield new findings.

7 Conclusion

In this study, we designed a virtual museum system to investigate the impact of different interaction and manipulation techniques on task performance and user experience. Four techniques were implemented by combining controller-based and hand-tracking interactions with direct and indirect manipulations. The results revealed that direct manipulations were generally preferred, leading to better performance, acceptance, learnability, and less fatigue and sickness. While hand-tracking interactions showed potential in supporting presence, they were also associated with issues of user acceptance and fatigue. We suggest design implications and takeaways for future design of more effective and user-friendly VR applications.

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