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SIT6: Indirect touch-based object manipulation for DeskVR

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ABSTRACT

Virtual reality (VR) has the potential to significantly boost productivity in professional settings, especially those that can benefit from immersive environments that allow a better and more thorough way of visualizing information. However, the physical demands of mid-air movements make it difficult to use VR for extended periods. DeskVR offers a solution that allows users to engage in VR while seated at a desk, minimizing physical exhaustion. However, developing appropriate motion techniques for this context is challenging due to limited mobility and space constraints. This work focuses on object manipulation techniques, exploring touch-based and mid-air-based approaches to design a suitable solution for DeskVR, hypothesizing that touch-based object manipulation techniques could be as effective as mid-air object manipulation in a DeskVR scenario while less physically demanding. Thus, we propose Scaled Indirect Touch 6-DOF (SIT6), an indirect touch-based object manipulation technique incorporating scaled input mapping to address precision and out-of-reach manipulation issues. The implementation of our solution consists of a state machine with error-handling mechanisms and visual indicators to enhance interaction. User experiments were conducted to compare the SIT6 technique with a baseline mid-air approach, revealing comparable effectiveness while demanding less physical exertion. These results validated our hypothesis and established SIT6 as a viable option for object manipulation in DeskVR scenarios.

1. Introduction

Virtual Reality offers its users unique capabilities by immersing them in a realistic and detailed environment. It allows physical-like interactions with virtual entities, encouraging users to use natural gestures for object selection and manipulation. Additionally, it presents a better and more thorough way of visualizing information by allowing the user to move freely around it in a 3D setting. These advantages of being within a virtual environment, which are impossible to obtain in a regular desktop experience, might help ease professional work. As such, they mainly benefit jobs that require either interaction with 3D content, such as architecture and content creation, or that demand a comprehensive look at information, which is the case for data analysis and medicine [1]. However, VR often requires tiring and extensive movements to function due to many applications requiring mid-air movements similar to natural gestures, making its use hard in work environments for prolonged periods. With this in mind, DeskVR comes as a solution [2,3]; it allows users to be fully immersed in Virtual Reality while sitting at an office desk without needing exhausting and prolonged movements. Therefore it seamlessly integrates a virtual environment into a user's workflow and workplace, potentially increasing productivity. Considering this and the many advancements in virtual reality technology for DeskVR, in both price and performance, the potential for this concept to become a viable option for professional work settings might already be present.

Since many existing VR techniques are primarily designed for users in a standing position and rely on physically demanding mid-air movements for interaction, it is challenging to find practical VR solutions for a seated context. Hence, the requirements of DeskVR demand the exploration of alternative approaches that enable comfortable and efficient movement, object selection, and object manipulation within the virtual space. The complexity of developing such techniques arises from the challenge of achieving natural and intuitive interactions while being imposed by the limitations of a seated position. Unlike standing-based VR experiences, DeskVR users have restricted physical mobility and may have limited space to perform large-scale movements. Thus, techniques must be carefully designed, considering the range and intensity of movements required and the ergonomics of the user's seated position [4]. Ultimately, these techniques must integrate seamlessly into the user's workflow, providing an immersive experience without requiring extensive physical effort. It is also necessary that the approaches' gesture mappings

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maintain a straightforward, user-friendly interface that can still provide all the necessary functionality.

In this paper, we focus on the challenge of object manipulation, more specifically on translation and rotation transformations, the main manipulation tasks [5]. Although a manipulation operation can only be applied after a selection [6], this is considered a different challenge that has also been the subject of previous research for DeskVR settings [BFRP]. Therefore, in this work, we assume that selection is made automatically or has already been made previously. Considering the previously specified challenge and the established goals, we put forward the following research question:

RQ *Can touch-based object manipulation be as effective as mid-air object manipulation in a DeskVR scenario while being less physically demanding?*

To tackle this question, we propose and evaluate SIT6, a touch-based technique composed of undemanding and intuitive gestures for translation and rotation operations while in a seated position. The proposed approach also aims to address precision and out-of-reach manipulation issues by employing distance and velocity-based input mappings.

2. Related work

Throughout our research and analysis of existing techniques, we follow a taxonomy parallel to the one defined in a survey by Mendes et al. [7], in which they presented, reviewed, and discussed several object manipulation approaches. Thus, we first examine touch-based methods, which include direct, widget-based, and indirect approaches, and then analyze mid-air techniques, which can be within arm-length or designed to solve precision and out-of-reach manipulation issues. In this study, we focus on finding gesture dictionaries and input mapping strategies that can be adapted to suit a DeskVR context.

2.1. Touch-based interactions

Regarding a touch-based object manipulation paradigm, several approaches have been proposed and evaluated, with efforts being made to create physically undemanding content interactions that are more natural and can effectively outperform mouse-based inputs [8]. We first delve into direct touch approaches, which involve physically touching the object through the display to initiate manipulations. Initially, studies proposed approaches that could control multiple DOFs simultaneously, with Hancock et al. [9,10] and Reisman et al. [11] both proposing methods that could manipulate 6 DOFs at once. Nevertheless, since solutions that can execute distinct transformations simultaneously often cause unintentional operations to occur [7], several approaches with DOF separation were proposed. In this context, techniques by Martinet et al. [12], and Liu et al. [13] were proposed, requiring distinguishable gestures in order to activate the different types of transformations.

As for widget-based approaches, which involve using virtual widgets and directly touching them for manipulations, several methods have been developed for a touch-based paradigm. For instance, the tBox [14] and Gimbalbox [15] techniques utilize box-shaped widgets around the object to perform transformations. Alternatively, widgets can be implemented outside the object in the form of menus, as demonstrated by TouchSketch [16]. Furthermore, techniques such as LTouchIt [17] combine both direct touches with the object and interaction with widgets, offering a mixed approach.

Indirect touch object manipulation comprises techniques that can be performed through an external touch surface, therefore not needing to touch the object directly for manipulations. Many relevant techniques in this paradigm are employed with stereoscopic tabletops and make use of cursors, which is the case for the Balloon Selection [18] and Triangle Cursor [19] techniques. On the other hand, Simeone et al. [20] proposed techniques that provide indirect touch interaction by using an external multi-touch surface. The presented techniques, Indirect4 and Indirect6, can control 4 DOFs and 6 DOFs, respectively. Indirect4 employs a touch from the dominant hand for horizontal movement and a touch from the non-dominant hand for either adjusting the object's vertical position or rotating around a vertical axis. Indirect6 controls the object's position similarly but can manipulate an additional 2 DOFs by using two touches from the non-dominant hand to perform rotations. Horizontally moving two fingers controls yaw, while vertically moving them controls pitch. Driving the two fingers in opposite directions controls roll.

2.2. Mid-air interactions

Mid-air-based interactions commonly perform inputs in a spatial 3D environment, allowing them to manipulate objects with potentially more natural gesture dictionaries. However, although a straightforward approach such as a Simple Virtual Hand [6] can perform translations adequately, it does not offer an efficient solution regarding rotation and scaling. Therefore, several authors have conducted research to propose practical solutions for mid-air manipulation metaphors. Some of these techniques expand upon the 2D interactions on a tabletop, utilizing the space above it, as demonstrated by the approaches developed by Hilliges et al. [21] and De Araújo et al. [22]. Nevertheless, most mid-air techniques such as Spindle [23], Handlebar [24], and Spindle+Wheel [25] solely track both user's hands in 3D space, using depth cameras and sensors. Two other distinct mid-air manipulation techniques were proposed by Bossavit et al. [26], providing users widget-like elements, such as a crank handle metaphor, for performing transformations.

One of the challenges regarding object manipulation in immersive virtual environments is the interaction with objects that are out of the users' reach. Several solutions have been designed to mitigate this problem, such as the Go-Go [27] technique, which uses the metaphor of interactively extending the user's arm. Bowman et al. [28] proposed HOMER, a hybrid 3D manipulation technique that uses ray-casting for selection and a virtual hand for manipulation, which is placed in the object upon selection. In this approach, the distance between the user's torso and the object is directly mapped to the distance separating the user's torso and the controller (the user's physical hand) at the time of selection. The following equation calculates this mapping:

$$D_{virthand} = D_{currhand} * \frac{D_{object}}{D_{hand}} \tag{1}$$

Where $D_{virthand}$ is the distance of the virtual hand from the user's body, $D_{currhand}$ is the current distance between the user's torso and hand, D_{object} is the initial distance between the user's torso and the selected object, and D_{hand} is the initial distance between the user's torso and hand.

Mossel et al. [29] extended HOMER to HOMER-S by adapting HOMER for selection in a smartphone/tablet AR context, and use the phone's orientation and movement to manipulate the selected object.

Another common problem with object positioning techniques in immersive virtual environments is the need for more precision. There have been solutions for this issue based on discrete placement constraints (snapping) and collision avoidance mechanisms [30]. However, Frees et al. [31] introduced PRISM, a technique that does not restrict the placement of objects, scaling hand movements down to enable precise control over objects. Auteri et al. [32] demonstrated the integration of PRISM's precise mapping with long-reach approaches, incorporating the scaling factor of the technique along with Go-Go. Moreover, Wilkes et al. [33] proposed Scaled HOMER, an evolution over the HOMER technique that also adds PRISM's velocity-based scaling to provide more precise object control. Thus, when the hand is moving quickly, the scaled hand distance will be equal to or greater than the actual distance; when the hand is moving slowly, the scaled hand distance will be less than the actual distance, providing fine-grained control of the object's position. The scaled distance is obtained through the following equation:

$$SD_{hand} = min(\frac{Velocity_{hand}}{SC}, 1.2) * D_{hand} \tag{2}$$

Where SD_{hand} is the hand's scaled distance, $Velocity_{hand}$ is the current hand velocity, SC is a predefined scaling constant, and D_{hand} is the initial distance between the user's torso and hand.

2.3. Discussion

While the presented object manipulation techniques were not designed for DeskVR, they provide important insights into the specific characteristics suitable for a seated-position scenario. Regarding the interaction paradigm, **touch-based** techniques do not usually require tiring motion gesture-wise since most rely on simple touch inputs, reinforcing their suitability for a seated desk context. As for mid-air techniques, these approaches do not particularly fit the seated desk experience since they often demand exhausting movements or even require the user to stand up.

As for the suitable type of contact in touch-based interactions, we can conclude that both the direct touch and widget-based approaches are unsuitable for DeskVR since it is impossible to touch an object or widget within a VR environment directly. On the other hand, it is trivial to implement **indirect touch** techniques in VR since the inputs are performed outside the object (e.g., Indirect6 [20]). Additionally, an external touch frame can reasonably emulate a desk surface, which means that the approaches that employ this input device fit the DeskVR experience well.

Furthermore, having 3 DOFs for both translation and rotation is essential for effectiveness in a seated-desk scenario. Thus, only gesture dictionaries from approaches that allow **6 DOFs** are suitable. Although some widget-based approaches allow more than 6 DOFs by adding object scaling operations, implementing widgets in an indirect touch context would be challenging due to the direct interaction required. Furthermore, DOF separation would also be preferred to avoid unintentional operations, which are more likely to happen in VR since users cannot see their movements.

In order to address precision and out-of-reach issues, it would be beneficial to take advantage of the distance and velocity-based mappings of some mid-air techniques, such as Scaled HOMER [33], adapting them to a touch-based technique for a seated desk scenario. This **N:1 and 1:N mapping** would make it so that when the user wants to move an object precisely, the object should move slower than the user's hands [31]. Conversely, precision may not be a priority when relocating an object from one remote location to another, and the user may move relatively quickly [28].

3. SIT6

In light of the lack of object manipulation techniques designed for a DeskVR environment, our objective was to develop a viable solution tailored to this setting that could also effectively handle precise and out-to-reach object placements. Consequently, drawing inspiration from some of the examined approaches outlined in Section 2, we created Scaled Indirect Touch 6-DOF, or SIT6, an indirect touch object manipulation technique with distance and velocity-based scaling.

3.1. Gesture dictionary

Our solution incorporates a gesture dictionary adapted from Indirect6 [20], offering the advantages of touch-based interaction, indirect manipulation, and 6 DOF. With the goal of enhancing the intuitiveness and natural feel of the input, several modifications to the original technique were integrated into the motion dictionary of SIT6, aligning the object's movement with the same plane as the user's hand rather than with the screen's plane. These changes ensure that the user's gestures have the intended effect in a three-dimensional VR space, aligning with the immersive nature of VR technology. Fig. 1 illustrates the solution's gesture dictionary.

In our approach, one-finger gestures translate the object across the XZ-plane, as seen in Figs. 1(a) and 1(b). To translate the object along the Y-axis, the user applies a second touch, moving the finger forward and backward on the touch surface to translate the object up and down (Fig. 1(c)). Regarding rotations, vertical and horizontal movement with two touches activates either X-axis (Fig. 1(d)) or Z-axis (Fig. 1(e)) rotation, respectively, with two touches in circular motion activating rotation along the Y-axis (Fig. 1(f)).

3.2. Input mapping

Moving away from Indirect6, SIT6 explores distance and velocity-based scaling to facilitate precision and out-of-reach placements. For this, we adapted the mapping approach from Scaled HOMER. Regarding the distance-based scaling implementation, we faced challenges in accurately estimating the distance between the user's hand and torso within a touch-based context. As a result, we relied exclusively on the distance between the user and the object in the virtual environment, multiplied by a predefined coefficient, for the calculation process. Regarding the computation of velocity-based scaling, we employ the finger velocity divided by a scaling constant. Our implementation limits the value of this scaling factor to 1.2 because, similarly to Scaled HOMER, it becomes challenging for users to control the object when using higher values. Ultimately, by integrating both distance-based and velocity-based scaling approaches, the calculation of object translation in SIT6 is determined by the following equations:

$$T_{object} = ST_{touch} * min(\frac{Velocity_{touch}}{SC}, 1.2) \tag{3}$$

$$ST_{touch} = T_{touch} * c * D_{object} \tag{4}$$

Where T_{object} is the object translation distance, ST_{touch} is the scaled translation of the touch, $Velocity_{touch}$ is the current touch velocity, and SC is a predefined scaling constant. To calculate ST_{touch}, T_{touch} is the touch translation distance, c is the fixed coefficient, and D_{object} is the distance between the object and the user. Considering the scale of the environment of the test application and the order of magnitude of the input readings from the touch surface, the value for the predetermined coefficient (c) was empirically defined as 0.001. As for the scaling constant (SC), we decided on an empirically chosen value of 3000, corresponding to a 1:1 input mapping when the user's finger is moving at a velocity of 1.1 m/s.

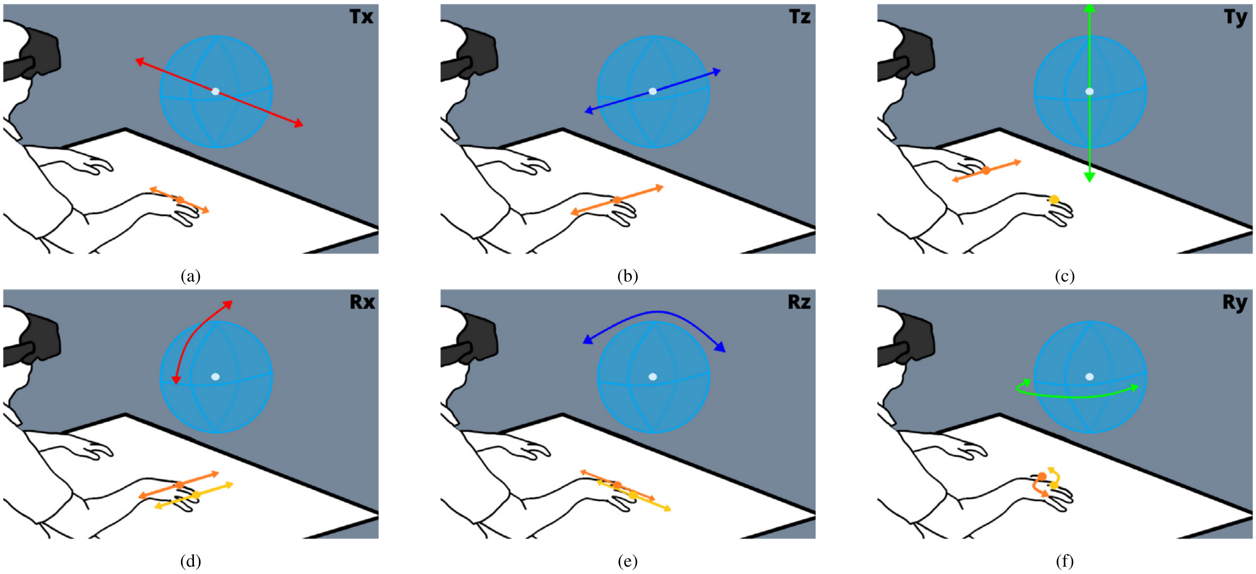


Fig. 1. Gesture dictionary for SIT6. Movements of a single touch move the object horizontally (a and b). While having a stationary touch, back and forth movements of another translate the object vertically (c). Two simultaneously moving touches rotate the object, one axis at a time (d, e, and f). Stationary and moving touches can be done in any order and with either hand.

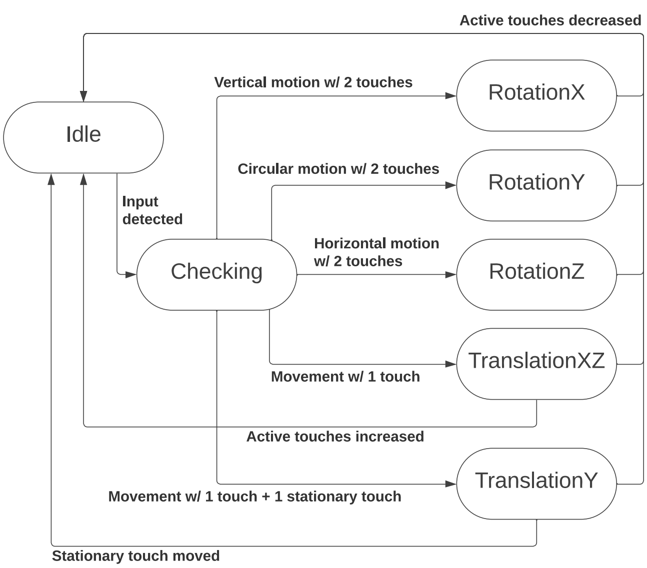


Fig. 2. Simplified state-machine diagram of our SIT6's implementation.

3.3. Implementation

We used an HTC Vive Pro 2 HMD and a 32-inch infrared multi-touch frame for our solution's hardware, allowing interaction with the VR environment and enabling gesture input. Regarding software, we leveraged the Unity game engine as our development platform, specifically employing its Touch API, which allowed us to retrieve the necessary information from the touch input to identify and enable our approach's gestures.

3.3.1. State machine and error handling

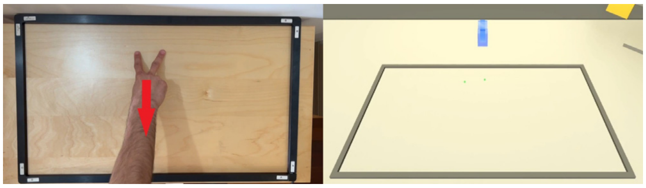
At the core of our approach's controller component, we have employed a state machine, with each state representing a specific phase or gesture detected during user interaction. The state machine diagram displayed in Fig. 2 illustrates a simplified version of how the controller operates.

Our implementation contains two control states and five gesture states. The control states include the *Idle* state, where the controller waits for user input, and the *Checking* state, where the controller conducts continuous checks on touch inputs for a fixed period to determine the type of gesture the user performs. As for the gesture states, these group the *TranslationXZ*, *TranslationY*, *RotationX*, *RotationY*, and *RotationZ* states, which handle the transformation operations for each corresponding gesture. Notably, a state check function is invoked at a fixed update interval of 0.02 s, evaluating various conditions to trigger the previously mentioned states. These conditions include changes in touch input, the detection of specific gestures, or the absence of touches.

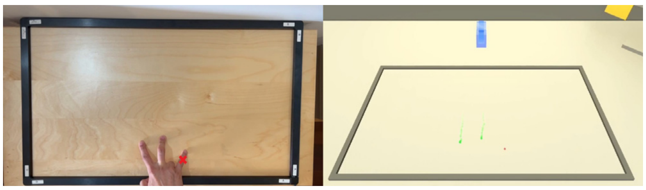
This state-based implementation also integrates error-handling mechanisms that ensure the proper functionality of gestures even in the presence of unexpected inputs. This error-handling is crucial due to the touch frame's high sensitivity and limited precision, which frequently cause accidental touches by users and loss of valid touches. One of the mechanisms utilizes a threshold variable to monitor consecutive updates of touch input that do not meet the conditions for a specific gesture state. This variable acts as a countdown, decrementing each update when the current state's conditions are not satisfied. When the threshold variable reaches zero, indicating a significant deviation from expected motion, the system transitions back to the *Idle* state. This feature guarantees that the system does not abruptly switch states when a valid touch is temporarily not detected. Furthermore, we have implemented a mode-locking mechanism for gesture states that require two touches. Upon entering one of these states (*TranslationY*, *RotationX*, *RotationY*, and *RotationZ*), the system remains locked in that state even if the user introduces additional touches. The two original touches retain control over the transformations, disregarding any subsequent touch inputs. The state can only be changed when the total touch count drops below two, thus preventing the transformations from stopping if the user inadvertently adds more touches.

3.3.2. Visual indicators

To aid users in performing and distinguishing gestures within the VR environment, our implementation of SIT6 incorporates two distinct visual indicators. The first indicator tool utilized

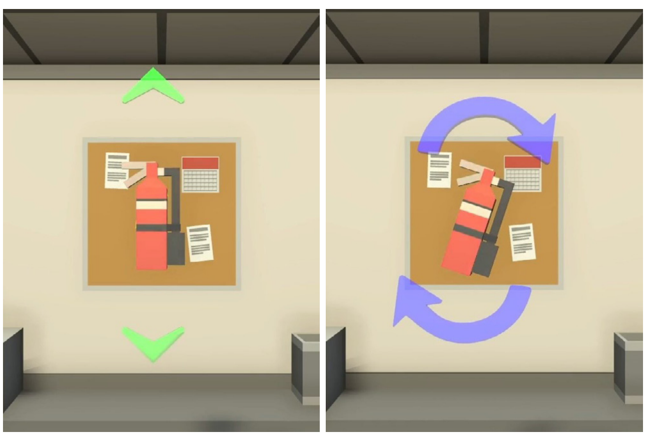


(a)



(b)

Fig. 3. Virtual touch frame indicator in action. (a) The two green points on the virtual touch frame (right) represent the position of the fingers (left). (b) The invalid third touch, marked with a cross, is represented in red on the virtual frame.



(a) (b)

Fig. 4. Axis indicator arrows: (a) Y-axis translation. (b) Z-axis rotation.

in our system consists of a virtual representation of a multi-touch frame. Whenever the user makes contact with the touch surface, the virtual representation displays the precise position of their fingers, as observed in Fig. 3. This visual mechanism enables users to consistently track the placement of their fingers, addressing the inherent challenge of not being able to see their hands physically in virtual reality.

Additionally, we incorporated an indicator tool that utilizes arrows to represent the axis along which the object is undergoing translation or rotation, illustrating the direction and orientation of the object's movement. The shape of the arrows dynamically changes based on whether the user is performing a rotation or a translation, while their color depends on the specific axis on which the operation is being executed, as depicted in Fig. 4. These arrow indicators give users a visual aid that enables a clearer understanding of the specific axis involved in the transformation, which is especially beneficial during rotations.

4. User evaluation

A series of experiments were conducted to assess our solution's effectiveness. Participants were assigned specific tasks to perform, allowing us to collect the necessary quantitative and qualitative data for evaluating the proposed method's performance and usability. To facilitate a comprehensive comparison, we implemented an alternative method already explored in the previous analysis, Scaled HOMER [33]. Additionally, to further test SIT6 and better answer our research question, we devised the following hypotheses:

- **H1** SIT6 can achieve an equal or greater success rate at object manipulation tasks than a state-of-the-art mid-air baseline.
- **H2** SIT6 can be as fast as a state-of-the-art mid-air baseline at completing object manipulation tasks.
- **H3** SIT6 is less physically demanding than a state-of-the-art mid-air baseline.

4.1. Baseline

The comparison baseline should be composed of techniques that, although not specifically designed for a DeskVR scenario, have characteristics that qualify them to be implemented in this context, allowing us to test our solution's performance against them. Based on the analysis presented in Section 2, the only technique with the necessary features to be included in this baseline is Scaled HOMER. Although mid-air, this approach attempts to tackle the same precision and out-of-reach problems as SIT6, making it a solid ground comparison in terms of effectiveness. Indirect6, while being our reference for the gesture dictionary, is not suited for manipulations at different distances as it uses a fixed input mapping. Therefore, it was not included in this evaluation.

While Scaled HOMER was designed to work in VR environments and was employed for object manipulation (through a virtual hand), it was also meant to be used in object selection (through raycasting). Therefore, we had to adapt the method to restrict it to work only for manipulation to make it an acceptable comparison method for SIT6. With this in mind, we made it so that the manipulable object is selected when the user presses and holds the controller's trigger button, with the manipulation process starting immediately. The implemented technique then works exactly as Scaled HOMER, with the object following the user's hand input as long as the trigger is held. The raycasting selection is not needed, as the object is automatically pre-selected in our tasks.

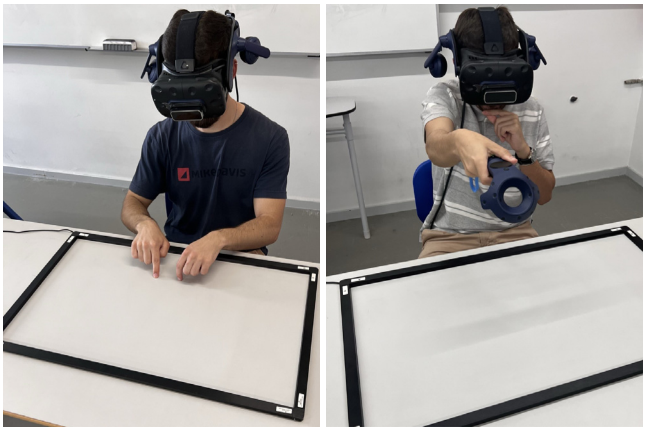
4.2. Setup and test environment

For the experiment's setup, we employed the HTC Vive Pro 2 virtual reality HMD, the complementary controllers, and a 32-inch infrared multi-touch frame. Throughout all experiments, participants were seated at a desk with the touch frame and VR controller on top, as seen in Fig. 5. Considering the high sensitivity of these devices, we deactivated them when not in use to prevent interference with the testing software and methods.

The test environment for the user study consisted of an office setting, which would later expand to include the outside city streets as the experiment progressed. Within this environment, participants were seated at a desk with a timer and computer monitor. The monitor displayed vital information, including details about the current task, the docking status, and any position and rotation mismatches between the object and the docking point.

4.3. Methodology

The experimental procedure for the user study consisted of three phases, carried out sequentially and repeated once for each tested method, alternating the tested technique order among



(a) (b)

Fig. 5. Some participants of the experiments. (a) Setup for the SIT6 tasks. (b) Setup for the Scaled HOMER tasks.

participants. Before starting the experiments, participants were asked to complete a profiling questionnaire and provide consent for data sharing. Following that, they received a brief video presentation that provided an overview of each object manipulation technique and outlined the objectives of the tasks they would be undertaking. The first phase of the procedure allowed participants five minutes to practice the input mappings until they became comfortable with the experimented method. The second stage comprised a sequence of eight timed trial docking tasks, described in the next section. For the third phase, once all tasks were completed, participants were asked to fill out a questionnaire about their experience with the tested technique.

4.4. Tasks

Each task consisted of a 6-DOF 3D docking mission, which involved moving a single object from one position to another. In order to focus exclusively on the manipulation process in the user experiments, each task began with the manipulable object preselected. We established a distance and rotation threshold when evaluating whether or not the object was in its final position, particularly to facilitate placements involving distant objects. When the manipulable object fell within the specified threshold of the docking point, the task would be deemed successful after a 5-second countdown, provided the object did not leave its position. Furthermore, each task had a time limit of 2 min, a boundary necessary to keep the duration of the study manageable.

The experiment encompassed eight docking tasks, each featuring a distinct combination of sizes, positions, and rotations for both the manipulable object and the docking point. These varied configurations were designed to assess the effectiveness of the approaches in scenarios involving out-of-reach and precision manipulations. The eight tasks are categorized into four classes based on the distance between the user and the docking point or the user and the initial object position, with the object size increasing proportionally with distance in each class.

Additionally, within each class, there are two tasks comprising different difficulty levels. While both tasks require translation movement in 2 DOFs (XZ-plane) or 3 DOFs, the first task is more straightforward and solely requires rotation along a single axis. In contrast, the second task entails a more intricate rotation involving multiple axes. To maintain consistency among participants, the order of the tasks remained fixed and identical throughout every experimental procedure, starting with the closer classes of objects and gradually transitioning to the more distant classes. Notably, the simple task was always presented first within each class. All tasks are depicted in Fig. 6.

4.5. Participants

A total of 26 individuals participated in the experiments, with 6 of them being female. All participants were right-handed, and their ages ranged from 16 to 50 years old, with the majority (88%) falling between the ages of 21 and 25 (avg. = 24, SD = 7.43). Most participants (77%) held a bachelor's degree, and a substantial portion (85%) were students. When asked about previous experience in Virtual Reality, 54% reported having none, with 39% reporting a one-time usage.

5. Results

During the experiments, we gathered quantitative data through system logs for each task and qualitative data through questionnaires. While both techniques achieved a success rate of 100% across all tasks, the system also logged data on completion time, idle time, active time, total object translation, and total hand movement. These quantitative metrics allow us to evaluate the techniques' effectiveness and efficiency in executing tasks. As for the questionnaires, these logged user feedback on comfort, perceived physical and mental demand, ease of use, ease of learning, and DeskVR context suitability, allowing us to gain valuable insights into the user experience and their overall satisfaction with the techniques. To analyze and draw conclusions from these metrics, several statistical tests were conducted. On these tests, we utilized the conventional alpha-value of 5% ($\alpha = 0.05$) to determine whether or not the results had a statistically significant difference.

5.1. Objective results

To ensure the reliability of our quantitative metrics, we first identified and removed any outliers through descriptive data analysis. Subsequently, we applied the Shapiro–Wilk test to determine whether the remaining data adhered to a normal distribution. We then employed either the paired-samples t-test when the data followed a normal distribution or the Wilcoxon signed-rank test when it did not. Results of this statistical analysis are reported in Table 1.

For the completion time results, we found that Scaled HOMER was statistically significantly faster than SIT6 in most tasks (Task 2: 13.01 ± 3.29 s vs. 40.25 ± 11.78 s; Task 3: 12.98 ± 2.57 s vs. 18.36 ± 0.97 s; Task 4: 14.69 ± 3.25 s vs. 39.44 ± 8.48 s; Task 5: 18.45 ± 4.65 s vs. 29.28 ± 8.71 s; Task 6: 17.35 ± 4.99 s vs. 42.39 ± 11.45 s; Task 8: 15.81 ± 5.00 s vs. 31.05 ± 11.98 s). The techniques remained comparable in simple tasks 1 and 7. This metric, recorded in seconds, is displayed in Fig. 7.

Regarding the idle time results, Scaled HOMER had statistically significantly lower values than SIT6 in most tasks (Task 2: 6.45 ± 1.35 s vs. 13.98 ± 2.90 s; Task 3: 6.93 ± 1.06 s vs. 8.97 ± 1.51 s; Task 4: 7.40 ± 1.14 s vs. 15.82 ± 3.74 s; Task 5: 7.04 ± 0.85 s vs. 11.28 ± 2.64 s; Task 6: 7.67 ± 1.25 s vs. 15.58 ± 3.94 s; Task 8: 6.87 ± 1.06 s vs. 12.97 ± 4.51 s). The methods had comparable results in simple tasks 1 and 7. Fig. 8 presents this metric, recorded in seconds.

As for the active time metric, Scaled HOMER had statistically significantly lower values than SIT6 in most tasks (Task 2: 6.83 ± 2.54 s vs. 24.15 ± 8.76 s; Task 3: 7.23 ± 2.98 s vs. 9.88 ± 2.31 s; Task 4: 7.57 ± 2.96 s vs. 26.85 ± 10.28 s; Task 5: 11.56 ± 3.72 s vs. 17.52 ± 5.87 s, Task 6: 9.30 ± 3.33 s vs. 26.18 ± 7.15 s; Task 8:

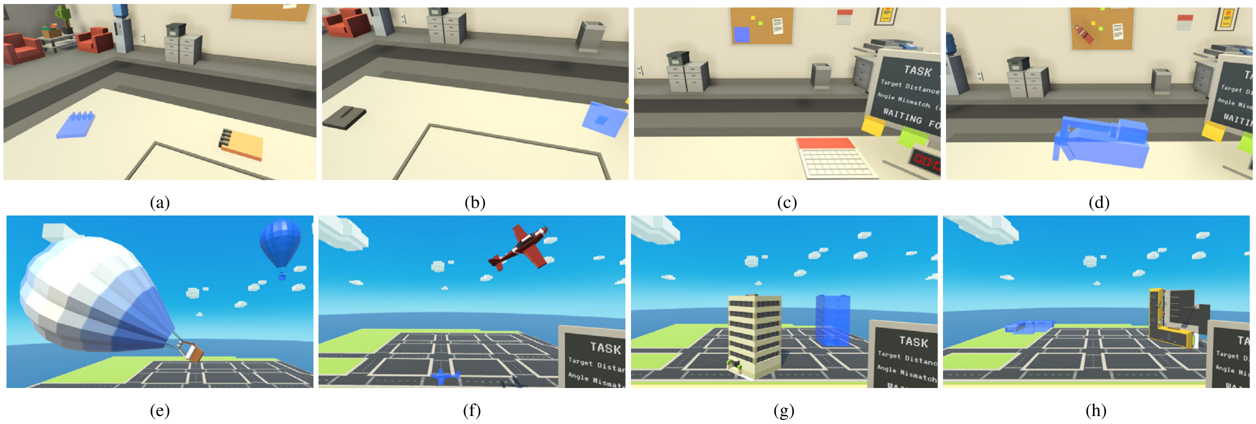


Fig. 6. The experiment's docking tasks. (a) Task 1: Ultra-Close Simple (Notepad). (b) Task 2: Ultra-Close Complex (Photograph). (c) Task 3: Close Simple (Calendar). (d) Task 4: Close Complex (Fire Extinguisher). (e) Task 5: Medium Simple (Hot Air Balloon). (f) Task 6: Medium Complex (Airplane). (g) Task 7: Far Simple (Building). (h) Task 8: Far Complex (Shopping Mall).

Table 1
Results of the objective results' statistical analysis.

Completion time	
Task 1	$Z = -0.049, p = 0.961$
Task 2 *	$t(22) = 10.128, p < 0.001$
Task 3 *	$t(10) = 6.459, p < 0.001$
Task 4 *	$t(17) = 11.025, p < 0.001$
Task 5 *	$t(22) = 4.638, p < 0.001$
Task 6 *	$t(23) = 11.368, p < 0.001$
Task 7	$Z = -1.195, p = 0.232$
Task 8 *	$t(20) = 5.161, p < 0.001$
Idle time	
Task 1	$Z = -0.896, p = 0.370$
Task 2 *	$Z = -3.920, p < 0.001$
Task 3 *	$t(19) = 5.017, p < 0.001$
Task 4 *	$t(18) = 9.191, p < 0.001$
Task 5 *	$t(21) = 6.940, p < 0.001$
Task 6 *	$t(18) = 8.843, p < 0.001$
Task 7	$t(18) = -0.396, p = 0.697$
Task 8 *	$Z = -3.883, p < 0.001$
Active time	
Task 1	$Z = -0.629, p = 0.530$
Task 2 *	$t(23) = 8.666, p < 0.001$
Task 3 *	$t(17) = 2.771, p = 0.013$
Task 4 *	$t(21) = 8.602, p < 0.001$
Task 5 *	$t(21) = 3.644, p = 0.002$
Task 6 *	$t(23) = 11.413, p < 0.001$
Task 7	$Z = -0.370, p = 0.711$
Task 8 *	$t(21) = 4.513, p < 0.001$
Total hand movement	
Task 1 *	$Z = -3.337, p = 0.001$
Task 2 *	$t(22) = 5.555, p < 0.001$
Task 3 *	$t(19) = -4.473, p < 0.001$
Task 4 *	$t(18) = 5.808, p < 0.001$
Task 5	$t(22) = 1.793, p = 0.087$
Task 6 *	$t(21) = 7.491, p < 0.001$
Task 7 *	$t(16) = -7.525, p < 0.001$
Task 8	$t(17) = -1.147, p = 0.267$
Total object translation	
Task 1 *	$Z = -2.749, p = 0.006$
Task 2	$t(17) = -1.126, p = 0.276$
Task 3	$t(21) = -0.486, p = 0.632$
Task 4 *	$Z = -3.623, p < 0.001$
Task 5 *	$Z = -3.574, p < 0.001$
Task 6	$Z = -1.686, p = 0.092$
Task 7 *	$t(15) = -2.316, p = 0.035$
Task 8 *	$t(18) = -3.493, p = 0.003$

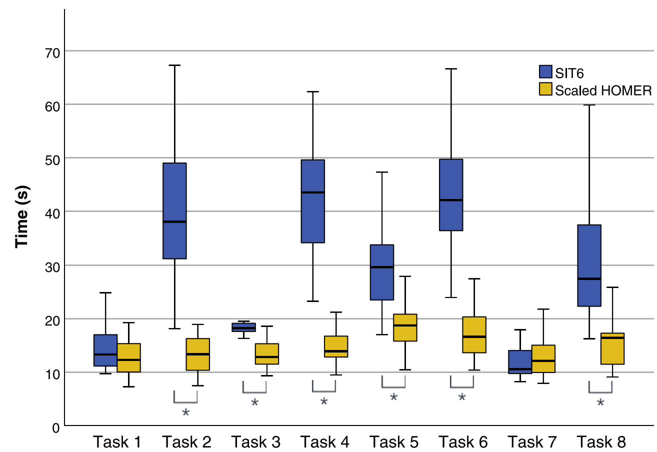


Fig. 7. Box-plot of completion time per task by technique. * indicates statistical significance.

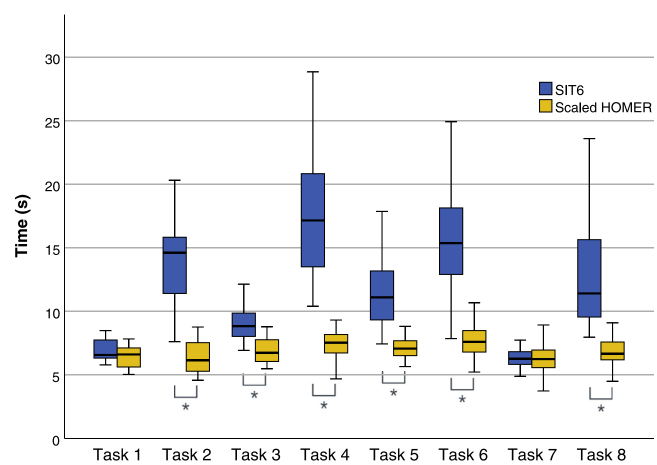


Fig. 8. Box-plot of idle time per task by technique.

9.00 ± 4.11 s vs. 18.67 ± 8.25 s). The techniques remained comparable in simple tasks 1 and 7. The recorded metric, expressed in seconds, is presented in Fig. 9.

For the total hand movement metric, SIT6 had statistically significantly lower values than Scaled HOMER in tasks 1 (2.35 ± 0.82 m vs. 3.89 ± 0.50 m), 3 (3.70 ± 0.60 m vs. 5.06 ± 1.00 m)

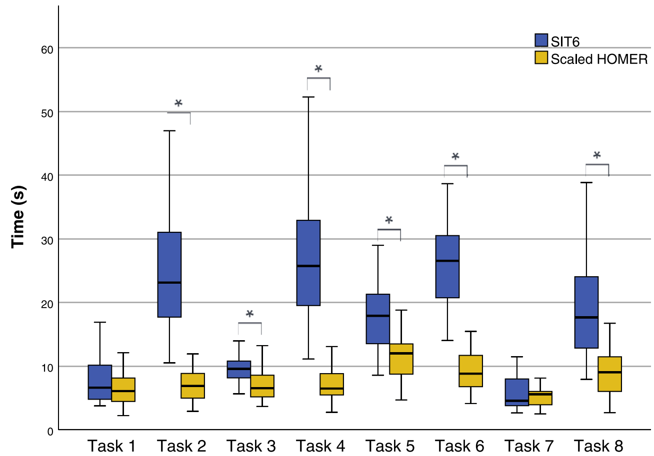


Fig. 9. Box-plot of active time per task by technique.

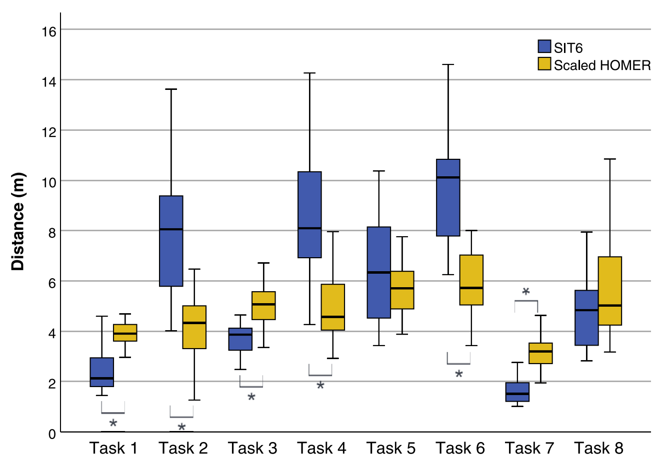


Fig. 10. Box-plot of total hand movement per task by technique.

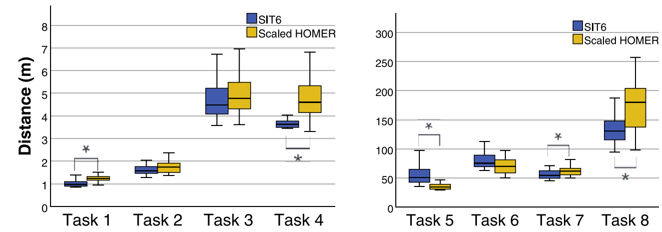
and 7 (1.60 ± 0.53 m vs. 3.10 ± 0.79 m). Conversely, Scaled HOMER had statistically significantly lower total values than SIT6 for tasks 2 (4.27 ± 1.30 m vs. 7.85 ± 2.39 m), 4 (4.90 ± 1.24 m vs. 8.66 ± 2.33 m) and 6 (5.70 ± 1.27 m vs. 9.85 ± 2.50 m). The techniques had comparable results in tasks 5 and 8. Fig. 10 depicts the metric, recorded in meters.

The total object translation results display SIT6 with statistically significantly lower values than Scaled HOMER in tasks 1 (1.02 ± 0.16 m vs. 1.23 ± 0.14 m), 4 (3.66 ± 0.18 m vs. 4.83 ± 0.96 m), 7 (56.03 ± 7.62 m vs. 63.98 ± 10.59 m) and 8 (126.74 ± 22.69 m vs. 170.05 ± 45.44 m). On the other hand, Scaled HOMER had statistically significantly lower total values than SIT6 for task 5 (35.65 ± 5.57 m vs. 56.08 ± 16.88 m). The approaches remained comparable in tasks 2, 3, and 6. The data for this metric, which is measured in meters, is presented in Fig. 11.

5.2. Subjective results

For the analysis of the qualitative results, we assumed a non-normal distribution of the data. Consequently, we used the Wilcoxon Signed Ranks test to assess whether there were any statistically significant differences between the methods.

The subjective results demonstrated that SIT6 had statistically significantly higher value answers than Scaled HOMER for comfort ($Z = -2.277, p = 0.023$, with 4.42 ± 0.76 vs. 3.81 ± 1.06) and DeskVR suitability ($Z = -3.018, p = 0.003$, with 4.81 ± 0.49 vs. 3.85 ± 1.22). Contrarily, Scaled HOMER had statistically significantly higher value answers than SIT6 for physical demand



(a) (b)

Fig. 11. Box-plot of total object translation per task by technique, split into two graphs due to scale differences. (a) Tasks 1-4. (b) Tasks 5-8.

Table 2
User questionnaire answers: Median (IQR).

Question	SIT6	Scaled HOMER
Q1 — Comfortable*	5 (1)	4 (2)
Q2 — Physically demanding*	1 (1)	4 (1.25)
Q3 — Mentally demanding	3 (1)	2 (2)
Q4 — Easy to use	4 (2)	4 (1.25)
Q5 — Easy to learn*	4 (2)	5 (1)
Q6 — Suitable for DeskVR*	5 (0)	4 (2)

* Indicates statistical significance.

($Z = -4.095, p < 0.001$, with 3.62 ± 1.27 vs. 1.50 ± 0.65) and ease of learning ($Z = -2.996, p = 0.003$, with 4.69 ± 0.55 vs. 4.08 ± 0.80). The answers revealed comparable results for mental demand ($Z = -1.852, p = 0.064$) and ease of use ($Z = -0.294, p = 0.769$). Further results of this analysis are presented in Table 2.

5.3. Discussion

With the data from the objective and subject metrics analyzed, we can now interpret and discuss the obtained results. First, upon analyzing the results for completion time, idle time, and active time, it becomes apparent that these three metrics exhibit a consistent pattern, with SIT6 consistently demonstrating statistically significantly higher values than Scaled HOMER across most tasks (2, 3, 4, 5, 6 and 8). The superior performance of Scaled HOMER is probably caused by its inherently natural manipulation, as the object follows the user's hand movements. On the other hand, in SIT6, participants spent a significant amount of time either engaged in the thought process of axis selection during rotations or making repeated attempts when gestures failed to activate the intended state, raising the total idle time and, consequently, the completion time. These results match what we observed during the experiments and the subjective results, where users reported that Scaled HOMER was the easier technique to learn. Interestingly, although Scaled HOMER had higher values across all time metrics compared to SIT6 in most complex tasks (2, 4, 6, and 8) and some simple tasks (3 and 5), the techniques show no significative performance difference in basic tasks 1 and 7, which solely required rotation along the Y-axis. These particular results are likely due to the challenging nature of executing Y-axis rotation gestures in Scaled HOMER, which frequently places considerable strain on the user's wrist, thus slowing down the rotation movement. The exertion Scaled HOMER demanded during tasks, especially in those involving Y-axis rotation movement, possibly justifies the observed subjective results, where users reported that SIT6 was the more comfortable and less physically demanding technique. Furthermore, this physical demand could have negatively influenced the user's perception of Scaled HOMER's ease of use, making users indicate that the technique was as easy to use as SIT6, despite the latter being harder to learn.

Regarding total hand movement, we can see that, for most tasks, SIT6 shows either no statistically significant difference or higher total hand movement than Scaled HOMER. However, as mentioned previously, participants' feedback indicated that SIT6 was the more comfortable and less physically demanding technique. These contradicting results from the objective and subjective metrics are likely explained by the fact that while SIT6 may involve more hand movement in specific tasks, its gestures are executed in just two dimensions and allow for resting the hands on the desk. On the other hand, Scaled HOMER requires movements to be performed in three dimensions, demanding the user to elevate the controller in the air, which places additional strain on the user and contributes to the perceived discomfort, despite the potential for reduced hand movement. Thus, it is inappropriate to directly compare the required physical effort for a given total of hand movements between the two techniques.

As for total object translation, in most cases, SIT6 achieved task completion with either no statistically significant difference or lower total object translation values than Scaled HOMER. This outcome can be attributed to the precise manipulation enabled by our solution's input mapping, allowing users to perform accurate movements at short and long distances. In contrast, experiments revealed that Scaled HOMER's input scaling, combined with the non-separation of degrees of freedom, often led to unintended translations while users attempted to rotate objects. This issue was further exacerbated during out-of-reach manipulation (e.g., tasks 7 and 8) due to the technique's distance-based scaling, increasing total object translation. This inability to effectively isolate transformations in Scaled HOMER might have also negatively impacted some users' perceived mental demand for the technique, thus explaining why the approach has no statistically significantly different results to SIT6 in this subjective metric.

5.4. Hypotheses and research question

With all the results interpreted and discussed, it is now possible to assess if our hypotheses were validated and to answer the proposed research question.

H1 (*SIT6 can achieve an equal or greater success rate at object manipulation tasks than a state-of-the-art mid-air baseline*) was **validated**. The objective results showed a 100% task success rate for both SIT6 and Scaled HOMER, indicating that both techniques were equally effective in enabling users to accomplish the assigned tasks. Furthermore, as the tasks were subject to a 2-minute time limit and the majority of participants were able to finish each task within that timeframe comfortably, it is evident that both techniques can complete object manipulation tasks within a reasonable time frame.

H2 (*SIT6 can be as fast as a state-of-the-art mid-air baseline at completing object manipulation tasks*) was **not validated**. Scaled HOMER was statistically significantly faster than SIT6 for most tasks, especially those requiring more complex rotations involving multiple axes. Nevertheless, SIT6 does not demonstrate significantly different performance to Scaled HOMER in specific simple tasks, mainly those where rotation can be easily executed.

H3 (*SIT6 is less physically demanding than a state-of-the-art mid-air baseline*) was **validated**. From the qualitative results, we can conclude that SIT6 was statistically significantly more comfortable and less physically demanding than Scaled HOMER. This outcome also holds in tasks where our solution demands more hand movement than Scaled HOMER. Since this additional movement comes from the additional rotation motion and is performed in two dimensions, it is still less physically exhausting than the three-dimensional movement required in Scaled HOMER.

With the hypotheses analyzed, we can now answer our **RQ** (*Can touch-based object manipulation be as effective as mid-air object manipulation in a DeskVR scenario while being less physically demanding?*). The answer is **yes**. The findings from the conducted user evaluation prove that although our solution was not as efficient at most object manipulation tasks, it was consistently as effective as the mid-air baseline while requiring less physical effort from participants.

6. Conclusions and future work

Virtual Reality (VR) offers immersive experiences and improved visualization capabilities, potentially benefiting various professional settings. However, the utilization of VR for extended periods is limited by the need for physically demanding mid-air movements. DeskVR addresses this issue by allowing users to fully immerse themselves in VR while sitting at a desk, enabling seamless integration into their workflow. Nevertheless, designing suitable techniques for this context is challenging due to limited physical mobility and space. Considering this, we proposed a novel object manipulation method tailored for DeskVR, employing undemanding and intuitive gestures while also addressing precision and out-of-reach manipulation issues. The proposed solution, SIT6, incorporates an indirect touch-based paradigm, with distance and velocity-based input mappings adapted from mid-air approaches. To implement this approach, we developed a state machine that converts the performed gestures into specific states, containing several error-handling mechanisms. We also included visual indicators to assist users in object manipulation tasks.

User experiments were conducted to assess the effectiveness of SIT6 compared to the chosen baseline, Scaled HOMER. The experimental process involved various docking tasks with varying difficulty levels and was categorized based on the distance between the user and the object/docking point. The results showed that SIT6 showed longer task completion times than Scaled HOMER in most tasks. However, when considering task success rate and user feedback, SIT6 was equally effective as the mid-air approach while being less physically demanding. These results validate the hypothesis that while SIT6 may be less efficient, it remains suitable for DeskVR scenarios without compromising effectiveness.

As for future work, although our solution has comparable effectiveness to the selected baseline, there is room for further improvement in terms of efficiency. By rethinking the gesture dictionary for rotation movements and incorporating more distinct and easier-to-execute gestures, users would spend less time trying to repeatedly engage in rotation movement. Optimizing implementation components like the state machine and the gesture detection controller could also improve the technique's swiftness by enhancing the system's motion detection. Similarly, upgrading touch-detection equipment to a touch surface with lower sensitivity and higher precision would also increase efficiency. On the other hand, while our solution provides object manipulation in 6 DOFs, enabling translation and rotation along every axis, there is an opportunity to expand its functionality to include object-scaling capabilities. Implementing this feature would likely require introducing additional gestures, increasing the complexity of the technique's motion dictionary. However, it would further enhance the versatility and flexibility of our solution, enabling users to interact with virtual objects in a more customizable manner.

CRediT authorship contribution statement

Diogo Almeida: Conceptualization, Software, Writing – original draft, Investigation, Formal analysis, Visualization. **Daniel Mendes:** Writing – review & editing, Supervision, Validation, Project administration. **Rui Rodrigues:** Writing – review & editing, Supervision, Validation, Project administration.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Appendix A. Supplementary data

Supplementary material related to this article can be found online at https://doi.org/10.1016/j.cag.2023.10.013.

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