ManiLoco: A VR-Based Locomotion Method for Concurrent Object Manipulation

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The use of virtual reality (VR) in laboratory skill training is rapidly increasing. In such applications, users often need to explore a large virtual environment within a limited physical space while completing a series of hand-based tasks (e.g., object manipulation). However, the most widely used controller-based teleport methods may conflict with the users' hand operation and result in a higher cognitive load, negatively affecting their training experiences. To alleviate these limitations, we designed and implemented a locomotion method called ManiLoco to enable hands-free interaction and thus avoid conflicts and interruptions from other tasks. Users can teleport to a remote object's position by taking a step toward the object while looking at it. We evaluated ManiLoco and compared it with state-of-the-art Point & Teleport in a within-subject experiment with 16 participants. The results confirmed the viability of our foot- and head-based approach and better support concurrent object manipulation in VR training tasks. Furthermore, our locomotion method does not require any additional hardware. It solely relies on the VR head-mounted display (HMD) and our implementation of detecting the user's stepping activity, and it can be easily applied to any VR application as a plugin.

CCS Concepts: • **Human-centered computing** → **Interaction techniques**; *User studies*; • **Computing methodologies** → **Virtual reality**.

Additional Key Words and Phrases: Locomotion, Teleportation, Object Manipulation, Room-scale VR, Virtual Reality Training

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1 INTRODUCTION

Virtual Reality (VR) has been widely used in laboratory skill training because it provides users with an immersive environment with hands-on experience [Freina and Ott 2015; Suh and Prophet 2018; Xie et al. 2021]. Users often need to complete a series of training tasks in a large virtual laboratory scenario in a limited physical space, either by the constraints of indoor space or of a tracked area [Bozgeyikli et al. 2019; Langbehn et al. 2018]. Currently, the most popular approach to overcome

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such physical limitations is Point & Teleport [Bozgeyikli et al. 2016], which enables users to teleport to the target destinations via hand-held controllers.

However, laboratory skills training typically requires the user to interact with the controller using their hands (sometimes both hands) to complete the corresponding hand-based operations in the virtual training scenario [Jensen and Konradsen 2018]. For example, in CryoVR [Dong et al. 2022], a VR training system for hands-on CryoEM (Cryogenic Electron Microscopy) experimental operations, users need to move around to reach specific objects or devices and use both hands to hold and transfer the devices between different workbenches. In such a situation, if the user needs to activate teleportation using their hand on the controller, it may cause physical and cognitive stress and negatively impact their training experience.

Fig. 1. Example of two-hand interactions in a scientific laboratory skill training system when interacting with CryoVR.

In this case, prior studies have explored the alternative approaches that control the teleport destination by users' gaze [Habgood et al. 2018; Linn 2017; Piumsomboon et al. 2017]. Although these approaches can free users' hands, they lack precision and is likely to induce motion sickness since the user remains passive while the virtual world moves [Zhang 2021]. Another alternative approach is foot-based teleport techniques that enable localization and teleport through different foot postures and orientations [Müller et al. 2019; Velloso et al. 2015; von Willich et al. 2020]. However, such foot-based methods usually require additional and expensive hardware. Bolte et al. [Bolte et al. 2011] combined eye- and foot-based interactions. This approach supports real walking for short distances and utilizes users' gaze to locate the destination point while detecting jumping actions to trigger larger-distance teleportation. However, they found that jumping, as an intense foot action, increased the activity of the whole body, thereby affecting the accuracy of eye-based localization [Spurgeon 2018]. Furthermore, it has not been demonstrated to be applicable to room-scale tracking space. Although these locomotion methods allow users to free up their hands, they are either expensive, inflexible, or lack specialization, and therefore have not been utilized in current VR training applications.

To address these challenges, in this paper, we present an easy-to-use and implement locomotion technique, naming ManiLoco. Firstly, ManiLoco utilizes the headset's direction to locate the target and simple foot actions to activate the teleport, naturally distributing the movement task to the users' interaction habits and allows for hand-based interactions for the primary training task. Furthermore, ManiLoco is suitable for continuously tracking room-scale areas in VR within a boundary of a small physical space by introducing a specific offset to guide users back to the center of the space.

We conducted a user study to compare ManiLoco with the most widespread controller-based teleportation method, Point & Teleport [Bozgeyikli et al. 2016]. In particular, we examined the task completion time, errors, perceived usability, movement trajectory, and participants' subjective feedback for performing a laboratory skill training task with intensive hand-based interactions. We found that ManiLoco led to significantly less effort than Point & Teleport and also led to a significantly higher perceived sense of control and presence. Besides, ManiLoco caused fewer errors in the task by allowing users to focus more on the main training tasks. Meanwhile, the introduction of the foot action in ManiLoco led to decreased motion sickness. Research on novel hand-free locomotion methods will become more important due to the proliferation of VR training applications. Thus, we think that our proposed work can serve as a useful springboard for future investigations.

The remainder of this paper is structured as follows. In Section 2, we discuss previous work on locomotion methods in VR. In Section 3, we describe in detail ManiLoco in terms of the design considerations and implementation. In Section 4, we explain the user study. In Section 5, we summarize the results, which we discuss in Section 6. In Section 7, we summarize the limitations and provide an outlook on potential future work directions. Finally, we draw conclusions from our work in Section 8.

2 RELATED WORK

In a VR application, a user often needs to navigate a virtual environment. Various locomotion methods with different characteristics have been developed and evaluated so far. At a one-to-one physical/virtual scale, **natural walking** is undoubtedly the most realistic and immersive method [Usoh et al. 1999]. However, this method is unsuitable for navigating a large virtual environment when physical space is limited. Several specific hardware devices have been explored to simulate natural walking in VR. Such hardware allows the user to walk in a virtual environment with limited physical motion while preserving immersion. Typical examples are the omnidirectional treadmill [Darken et al. 1997; Iwata 1999] and the ball bearing-based concave surface [Huang 2003; Suryajaya et al. 2009].

An alternative is the **Walking in Place (WiP)** method. The WiP is a pose-based locomotion method that aims to imitate walking without changing position. The direction of the user's movement in the virtual environment is determined by the user's head orientation, while the forward speed is determined by the arm [Slater et al. 1995] or leg [Templeman et al. 1999] swinging speed, or stepping speed [Tregillus and Folmer 2016]. WiP leaves the hands free for interaction; however, with the contract of the physical motion and virtual motion, the user may experience motion sickness with walking in place [Bozgeyikli et al. 2019; Kolasinski 1995; LaViola Jr 2000; Mousas et al. 2021].

Redirected walking (RDW) is a locomotion method that leads the user to walk in circles in the room by translating, rotating, or curving the path in the user's field of view [Razzaque et al. 2002], which allows the user to walk naturally in the virtual environment [Langbehn et al. 2017; Rietzler et al. 2020]. However, this method is particularly suitable for large open scenes, making path distortions small enough to be unnoticeable to the user.

Step scaling is another effective method for the limited space. This method changes the original distance mapping by introducing a scale factor [Interrante et al. 2007] or enlarging the user's avatar relative to the virtual environment [Abtahi et al. 2019]. As a result, it can produce a broader range of locomotion depending on the degree of scaling. However, the scale factor has an upper limit. The virtual space cannot be scaled up indefinitely. When the scaling degree is too large, the difference between the actual action and the motion results in the virtual world will become too large, increasing the risk of motion sickness. Also, a large scale makes the user hard to estimate and control the moving distance.

Then, the **teleport** technique was proposed, allowing users to travel arbitrary virtual distances without moving in the real world [Bozgeyikli et al. 2016]. The dominant teleport method relies on interacting with the handheld VR controllers [Bozgeyikli et al. 2016; Funk et al. 2019; Griffin and Folmer 2019]. Users often trigger teleport functions via specific buttons or joysticks, then point to a destination and jump to the place. The benefit is that it can be effortless and easy to learn [Høeg et al. 2017]. However, current approaches for teleportation rely on the users' hands for input and thus may hinder other hand-based interactions, such as grasping. Therefore, researchers have recently started exploring eyes- and foot-based locomotion methods to release hands from locomotion.

Researchers have shown that interaction using eyes in a head-mounted display (HMD)-based VR environment is more efficient than using hands [Tanriverdi and Jacob 2000]. The idea of the **eye-based** approach is the selection according to the users' gaze [Habgood et al. 2018; Piumsomboon et al. 2017], which can be applied to locate the destination, thus enabling the locomotion function. Furthermore, the users' gaze time can be used to determine their intention; thus, avoiding unintentional scanning. Linn [Linn 2017] used this approach to develop a gaze-based teleport method. When the users continuously gazed at a location for 200 ms, pressing a button would teleport them to that point. The experiment has shown that gaze can be used in VR teleport as a novel, fun, and easy way to interact. However, the biggest problem with these eye-based methods is accuracy, as it is difficult for people to keep their heads or eyes stable due to physiological reasons [Zhang 2021]. Moreover, the noise can pose a precision challenge for eye-based localization, especially considering the other inevitable physical movement [Bolte et al. 2011].

Foot-based locomotion methods were introduced to leave the user's hands free for other interactions. The advantage of using the foot is to enhance the users' understanding and perception of the interactions while reducing the stress of their hands [Velloso et al. 2015]. LaViola et al. [LaViola Jr et al. 2001] displayed a top-view map under the users' feet. The users could step towards a specific location on the map, triggering step-by-step movements in the virtual environment. Then an entirely foot-based VR teleport method was developed [von Willich et al. 2020]. The users wore a unique device on their feet that enabled localization and teleport through different foot postures and orientations. This method completely avoids hand manipulation, leaving more space for hand interaction. However, the disadvantage is that it is not as accurate and convenient as the hand-based teleport method, considering that the feet are much less flexible than the hands. While these methods are effective, the expensive and bulky hardware devices are not suitable for general home users and severally limit the adaptation of these approaches.

In recent years, there has also been an increasing number of researchers trying to combine **eye- and foot-based** interactions—using eyes to locate while feet to trigger actions [Müller et al. 2019; Xu et al. 2019]. Compared with commonly-used hand controller-based teleport methods, the eye-foot combination has the advantage of being hands-free. Therefore, the users can perform other hand operations during teleport without intervention. For example, "jumping" has been used to trigger the teleport [Bolte et al. 2011]. Based on users' gaze location, the method could judge whether they wanted to trigger the teleport by detecting their instantaneous acceleration. However, researchers found that when the users performed intense physical actions, it would increase the movement of the whole body, thus, severely affecting the eye-based localization accuracy [Spurgeon 2018]. Therefore, one critical point is how to eliminate the localization error due to the eye's focal point and the physical body movement (e.g., jumping) caused by feet. In addition, when the feet begin to move, the method may no longer apply to room-scale compared to traditional teleport methods. The user may run out of the physical boundary when navigating the large virtual environment. ManiLoco aims to address these two issues.

3 MANILOCO METHOD

3.1 The ManiLoco Technique

The aim of ManiLocois to enable users to move around in a virtual training environment without interrupting their primary hand-based tasks while being able to be achieved limited physical space. This is accomplished by transferring the hand-teleport interaction to head and foot. Based on reviewing the pros and cons of previous locomotion methods, we list the following design considerations (DCs):

- **DC1**: The aim of ManiLoco is to provide an easy-to-use and affordable method of room-scale movement for VR training. Eye-based methods are often technically complex and require expensive setups. Instead, we utilize the HMD and head orientation to control positioning, a more accessible alternative with similar effectiveness. Previous studies have found that both head orientation and gaze can be used to predict the target motion destination [Holman et al. 2021]. Furthermore, research has demonstrated that head and eye orientations are coordinated when individuals are observing their environment or walking, and that eye orientation can be inferred from head orientation [Grasso et al. 1998; Holman et al. 2021; López et al. 2019; Pozzo et al. 1995].
- **DC2**: The user should easily select and maintain the target location during movement. It is crucial to ensure the accuracy of head localization. To achieve this goal, we must take into account two factors that affect head or eye-based motion methods. Firstly, we need to minimize the impact of the normal physiological jitter of the user's head-on head localization accuracy, as highlighted in previous research [Spurgeon 2018]. Secondly, we need to avoid the influence on the accuracy of head localization caused by foot activity [Zhang 2021].
- **DC3**: Avoid mistakes e.g. accidental trigger of the locomotion. In typical VR experiences, users often scan the environment to locate target objects and naturally take some foot actions [Majaranta and Räihä 2007]. Therefore, to enhance the triggering accuracy of ManiLoco, it is crucial to differentiate between the user's intent to scan the environment and their intent to trigger teleportation.
- **DC4**: ManiLoco is aimed at a locomotion method that can be used in a limited physical space. Therefore, it is essential to ensure that the user does not exceed the room-scale space even when they perform foot-based actions [Bolte et al. 2011].

3.2 Implementation

ManiLoco was developed in Unreal Engine (UE)[1] version 4.22 and only relies on the HMD device. The head orientation was obtained through the virtual camera. Therefore, ManiLoco does not require additional specialized hardware. This could make this method easily accessible and be utilized on a broad range of applications as a plugin (**DC1**).

3.3 Activation and Teleportation

ManiLoco can be divided into three steps. These steps implement the specific functionality while overcoming the above design challenges.

3.3.1 Step A: View Localization. Accurately locating the destination is always the most essential subtask within a VR teleport method. ManiLoco destination allocation is based on the object the

[1]https://www.unrealengine.com/

user intends to interact with. We use a simple algorithm instead of an expensive eye tracker to let users locate objects. We give every interactive object two bounding volumes, a small inner volume, and a large outer volume. The inner volume works when switching another object, while the outer volume works when maintaining the same object, as shown in Algorithm 1.

Algorithm 1 Object Locate Algorithm

```
global variable targetObject;
global variable interactiveObjectList;
hit = RayCast(Camera.position, Camera.forward);
Sort(interativeObjectList) by Distance(interativeObject.position, hit.position);
viewObject = NULL;
flag = False;
for all interativeObject do
   if hit.position in interactiveObject.outerBounding then
      viewObject = interactiveObject;
      flag = True;
      if viewObject != targetObject then
         if hit.position in interactiveObject.innerBounding then
            targetObject = viewObject;
            break;
         end if
      end if
   end if
end for
if Distance(targetObject.position, user.position) ≤ d or !flag then
   targetObject = NULL;
end if
Highlight(targetObject);
return targetObject.position;
```

On the one hand, a large outer bounding volume allows the user to locate objects more easily, solving the problem that the eyes or head often slightly jitter due to physiological reasons. It also overcomes the challenge of locating small or far objects. On the other hand, a small inner bounding volume can make the users feel a little resistance when switching objects, alleviating the situation that the locating object is shifted due to the large step and head movement in the next step (**DC2**).

The objects that are too close (within the arm's reach distance, we consider it to be .50 m) to the users will be ignored. The purpose is to prevent the users from selecting objects right next to their hands; thus, ensuring the highlight effect will not appear in their normal operating space and interrupt the immersion. Eventually, the algorithm returns the object's position for the next steps.

3.3.2 Step B: Stepping Activity Detection. After identifying the object the users are looking at, ManiLoco starts detecting the users' foot activities. Teleport will be triggered if the users accumulate a certain distance towards their sight directions within a given time. The detection for triggering is based on the following condition:

$$\begin{cases} \text{if } \left((p_{(t+\Delta t_W)} - p_t) \cdot \boldsymbol{v_{forward.xy}} \geq d_W\right) & \text{trigger teleport} \\ \text{else} & \text{do nothing} \end{cases},$$

where t represents the current timestamp, p represents the users' position in the virtual environment, and $\boldsymbol{v_{forward.xy}}$ is the camera's forward vector in the horizontal plane (unit vector), representing the head orientation. Δt_W is a time threshold, and d_W is a distance threshold. The above-mentioned condition determines whether the users have taken a step toward the looking object. If the method detects the foot action, it triggers teleport. Such distance and time thresholds allow ManiLoco to judge whether the users want to take a teleport or whether they are normally scanning the environment (**DC3**).

We conducted a preliminary study to identify the appropriate setting of the time and distance thresholds. Four participants (two male and two female graduate students) with an average age of 23.50 (SD = 3.11) volunteered for this study. Their heights are typical heights that range from 162cm to 181cm. All four participants were students in STEM fields. All of the participants had previously used VR applications and were aware of teleportation-based locomotion in VR. In total, there were five testing trials (Δt_W was set to .20 s, .40 s, .60 s, .80 s, and 1.00 s) for each participant. We used the same virtual laboratory scenario as the formal experiment, which included four tables (A, B, C, and D) placed side-by-side. The participants started the testing trials in front of Table B. For each trial, participants performed three teleportation actions with different locomotion distances (spanning 1, 2, or 3 tables). The whole testing lasted no more than 30 minutes. We interviewed these participants about their preferences for the thresholds. Participants were asked to indicate which condition they appreciated the most in terms of efficiency, ease of use, lack of mental and physical demand, absence of frustration, and helpfulness for teleportation. Three of the four participants clearly indicated that they felt best in the Δt_W = .40s condition. One participant noted that both the Δt_W = .40s and .60s conditions had an equal effect on them. Based on the participants' suggestions, we set the Δt_W = .40 s, which can effectively alleviate the localization bias caused by the head movement due to foot actions. We further set the d_W = .15 m to trigger the transmission by measuring these participants' nature step length.

3.3.3 Step C: Position Restoration. After Stepping Activity Detection (B), the user is no longer at the center of their physical tracking space because they have moved to a distance in the chosen direction. Therefore, to solve the room-scale problem (DC4), ManiLoco offsets the users' teleport destination in the virtual environment to implicitly guide them back to the center. This design considered that the users typically stand directly in front of the target object and they naturally adjust their position to the desired position once they are in an offset position. Specifically, ManiLoco recalculates the offset teleport position according to the user's current position in the physical tracking space instead of teleporting the users directly in front of the target object in the virtual environment. The offset of the virtual position is computed based on the physical distance of the user's current position to the center of the physical tracking space.

In detail, considering that the teleportation is only happening along one axis, we have the following equation to calculate the new position:

$$p = p_{object} + (p_{tracking} - o_{tracking}), \tag{1}$$

where p_{object} represents the world position of the object in view localization (A), $p_{tracking}$ represents the position of the user in the physical tracking space, $o_{tracking}$ represents the center of the tracking space. Since the virtual world has the same scale as the real world, therefore, $(p_{tracking} - o_{tracking})$ indicates the offset of the virtual position, which can be obtained through the HMD.

As Figure 2 shows, if the user's current physical position has a certain distance to the right of the center, then the user's teleportation location in the virtual space will be accordingly offset to the right side (relative to the location directly in front of the interacting object). In this way, the user needs to move to the left (the direction of the center of the tracking space) in order to be in front of

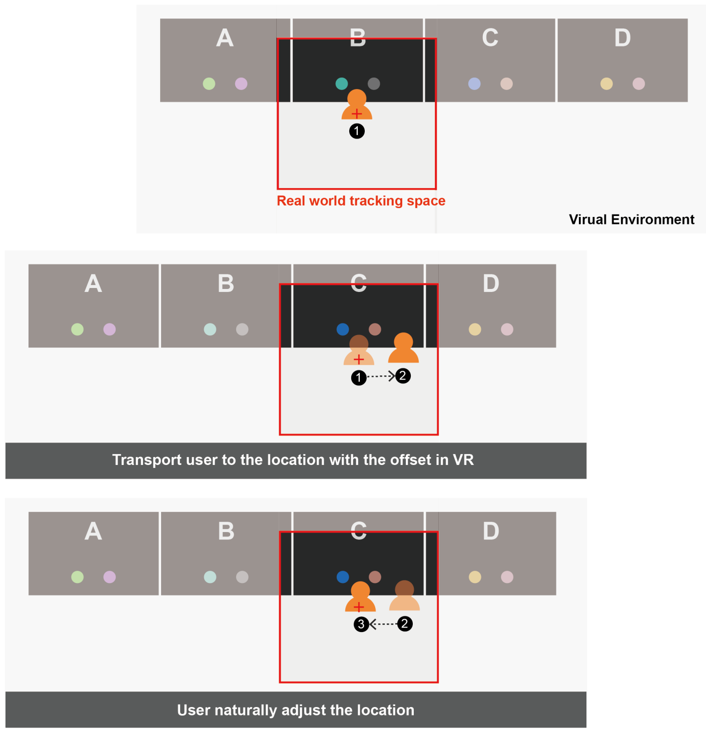

Fig. 2. Position restoration process. Step 1: The user starts at Table B (the tracking space center). Step 2: The user goes to Table C to get the containers (moves to the right side in the real world). In this step, the user is transported to the location with the offset in the VR environment. Step 3: The user naturally moves toward the targeted area that is good to get both containers (moves back toward the tracking area center.)

the interacting object. Sometimes the user may not need to move to the desired position (right in front of the interacting object). Alternatively, the offset might be too small to notice if the users are close enough to the room center. Under such situations, users may not take any adjustments back to the tracking area center. After several rounds of ManiLoco, the offset might become large enough to be noticed by the user.

4 EVALUATION OF MANILOCO

4.1 Experimental Design

In this experiment, we compared the ManiLoco with Point & Teleport, which is commonly used in a large virtual space within a limited physical space. We adopted the default Point & Teleport [Bozgeyikli et al. 2016] method in the Unreal Engine version 4.22 VR template project. In the Point & Teleport method, users can press the joystick on the controller to activate the user interface that guides the locomotion destination. The user controls the locomotion destination by pointing the controller to the desired position. Transportation is achieved by releasing the joystick. We aim to create an accessible locomotion method that can be easily applied and implemented in existing applications as a plugin. Therefore, although some gaze-based locomotion methods are also useful for the room-scale VR experience, we did not include them in our comparison due to their requirement for eye-tracking capability in the HMD.

We conducted a within-subjects controlled laboratory experiment. With each locomotion method, participants completed a task that included 15 interaction steps in a virtual laboratory scenario. The order of the locomotion methods was counterbalanced across all participants. Based on the review of existing research, we build the following four research hypotheses for the experiment:

- **RH1**: ManiLoco will result in lower number of errors.
- **RH2**: ManiLoco will result in less effort than the Point & Teleport.
- **RH3**: ManiLoco will be the better technique in terms of enjoyment.
- **RH4**: ManiLoco will provide lower motion sickness ratings.

4.2 The Testing VR Application

We used Unreal Engine version 4.22 to implement the testing VR application. A high-resolution HTC Vive Cosmos was used to immerse participants in the virtual environment. Referring to the study of room-scale locomotion methods [Bozgeyikli et al. 2016], we set the tracking area as 2×2 m as shown in Fig. 3.

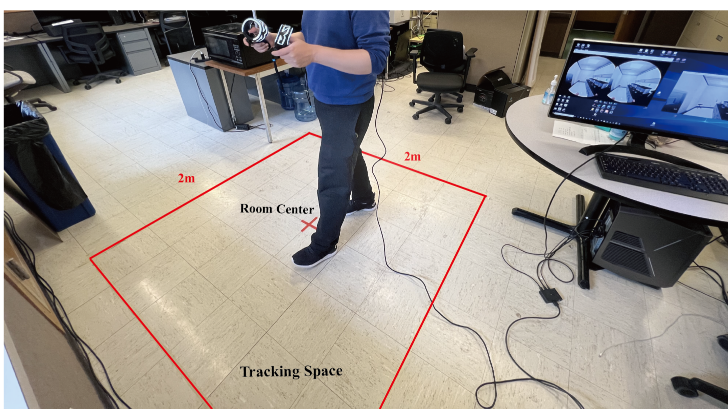

Fig. 3. Tracking area (2×2 m) for the testing.

4.2.1 Scenario. We created a virtual laboratory scenario for the user study. As Fig. 4 shows, the size of the scenario was 3×8 m and included a workbench in a chemistry lab that contained four tables (A, B, C, and D) placed side-by-side (identical across conditions). A whiteboard was in front of each table to display textual instructional information. The width of each table was 1.80 m, and there were two containers (beakers or flasks) with different colored liquids placed in the middle of each table. This means that if participants rely only on natural walking within the limited tracking space 2×2 m, they cannot move from the current table (e.g., Table B) to the desired location where they can acquire the target container on the other three tables (e.g., Tables A, C, and D).

4.2.2 Instruction. The participants were asked to finish all steps following the instruction. The application used audio and text-based instructions to guide the participants. Specifically, the instructional audio was played to inform participants of the required actions at the beginning of each step. Additionally, an instruction board in front of each table showed the textual instruction. Moreover, visual cues with red arrows and outlines guided the participants to find the target containers in each step.

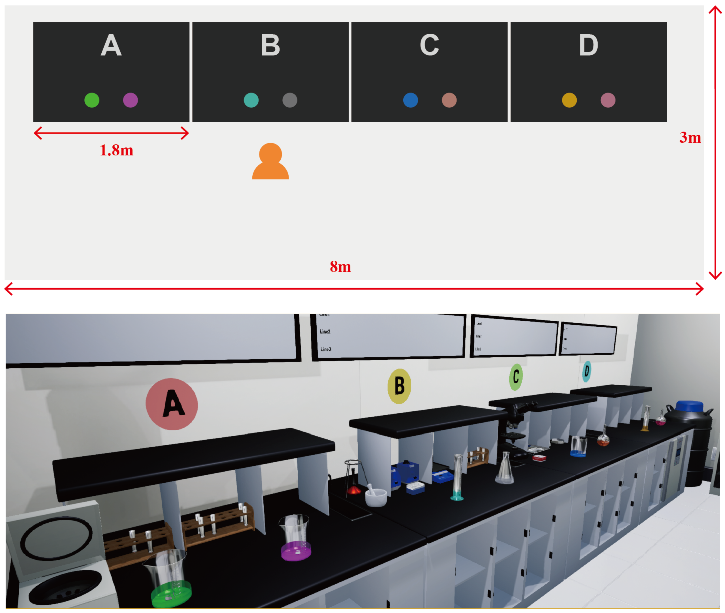

Fig. 4. Designs of the virtual scene and the final effect in VR. Top view (up) and perspective view (bottom). Participants started at Table B.

4.2.3 Hand Interaction. All hand interactions for the task only relied on the index finger trigger on the controller, which ensured that the hand interaction would not conflict with the Point & Teleport method. For example, the participants can press the trigger to pick up the object and release it to drop. Besides, the interaction between the objects simulated real-life interaction and scenarios. For example, to transfer liquids between two containers, participants needed to align the mouths of both containers and perform a pouring action for a few seconds.

4.3 The User Task

After consulting with chemistry experts, we designed the VR tasks to simulate real-life tasks that require simultaneous hands-operation and locomotion. In the task, participants need to manipulate beakers and flasks containing chemical liquids and transfer them between different tables. There are different types of containers on different tables and different colors, as shown in Fig. 4. Moreover, the user should handle the container carefully to simulate a real-life situation. Therefore, we designed the liquid to spill out when the container tilted to a certain angle.

For the task, there were a total of 15 steps (see Table 1) which can be classified into three categories based on the interaction types involved: (1) *Hand-only Step* (**H**) including garb the target containers or mixing different liquids; (2) *Locomotion-only Step* (**L**) including moving to another table; and (3) *Hand and Locomotion Step* (**H&L**) where to have two interaction types at the simultaneous existence (e.g., carrying a beaker with liquids from table A to table B). The participants had to complete the locomotion assignment in this step while maintaining their hand interaction. Furthermore, we distinguished the steps according to hand involvement (one hand **H1** or both hands **H2**) and locomotion distance (**L1**, **L2**, and **L3**). For example, a **H2L2** step required participants to use their two hands to grab the large beaker and transfer it to a distance table on their left/right side. The process comprised ten **H&L** steps, including five two-hand involvement steps and five one-hand involvement steps. The other five **H** and **L** steps were designed to balance the workload of the participants. One example of the 15-step task is shown in Table 1. We designed the tasks with different sequences but the same number of interactions and locomotion.

Table 1. The 15 steps of the user testing task. T denotes Table. The task begins with T_B. The targeted transport table for each step was changed in each condition.

Index	Description	Type
1	Go to T_C	**L1**
2	Transfer 1 Container to T_B	**H**
3	Transfer 1 Container to T_A	**H1L1**
4	Mix the liquid in the two Containers at T_A	**H**
5	Transfer 1 Container to T_C	**H1L2**
6	Transfer 2 Container to T_B	**H2L1**
7	Transfer 2 Container to T_D	**H2L2**
8	Mix the liquid in the two Containers at T_D	**H**
9	Transfer 1 Container to T_A	**H1L3**
10	Transfer 2 Container to T_C	**H2L2**
11	Transfer 1 Container to T_A	**H1L2**
12	Go to T_B	**L1**
13	Transfer 2 Container to T_C	**H2L1**
14	Transfer 1 Container to T_D	**H1L1**
15	Transfer 2 Container to T_A	**H2L3**

4.4 Data Collection

We collected task completion time and errors during the execution of the study to assess users' performance. Specifically, each step's task completion time (CT) was recorded through an integrated logging function of the Unreal Engine. The start and end of each step are indicated by activating the instruction of the steps. The participant's dwell time (including the time for watching instructions) in each step was counted in the CT. The errors were recorded manually and documented with pictures after the completion of the procedure. An error was counted when the transfer location did not match the target table or the liquid in the container was spilled in the interaction process.

We further collected participants' subjective experience data using questionnaires. Inspired by the similar research [Bozgeyikli et al. 2016], we used a modified version of Loewenthal's core elements of the gaming experience questionnaire [Loewenthal and Lewis 2018] to measure the usability of different locomotion methods. The questionnaire has eight subcategories relevant to our evaluation. Additionally, we used a modified version of the Pensacola Diagnostic Criteria survey [Lawson et al. 2002] for measuring motion sickness. To measure the presence, we used a modified version of Witmer and Singer's questionnaire [Witmer and Singer 1998]. All the questions had answers on a 5-point Likert scale (1: not at all, 5: very much). Additionally, to verify whether users could perform the task in the room-scale tracking space, we tracked the participants' positions in the tracking space.

To enrich the collection and for triangulation, we also video-recorded the task's execution and audio-recorded a follow-up discussion carried out as a closing interview. This discussion followed a predefined interview guideline. The audio recordings were fully transcribed and coded using a deductive coding system which was derived from the interview guideline.

4.5 Participants

We recruited 16 participants (nine male and seven female) ranging between 21-30 years old ($M = 23.50$, $SD = 3.01$) from our university. All participants were students that have or will have scientific experiment training. As the scenario is for scientific training, the target users often are not VR experts. Concerning their VR experience, four participants reported to be experts, two considered their experience as above average, four as average, five as below average, and one participant used VR for the first time.

4.6 Procedure

Instruction. We began our study by informing participants about the overall goal and the procedure. All participants signed a consent form informing them about their right to stop participating in the study at any time without any consequences. We also informed that the session would also be video- and audio-recorded. The participants had sufficient time to read the consent form and ask questions before signing it.

Pre-training Session. Next, we adjusted the VR device and instructed each participant on how to use the VR controller. Participants then experienced a VR training scenario. The goal was to enable participants to learn the basic interaction methods (e.g., manipulation and selection), the testing application, and the instructions. We explicitly notified the participants of the liquid being spilled on the ground and the consequences. Then, all participants completed the training session that included two VR scenarios for the two locomotion methods (ManiLoco and Point & Teleport). Participants were allowed to experience our VR training session as much as they wanted until they thought they were familiar enough with all the locomotion methods. The process lasted until we were sure the participants had mastered the most important interactions. After the training section, we briefly explained the general task and let the participants take a minute break until they were comfortable continuing the next test sessions.

Test Session. Each participant experienced the two experimental conditions (locomotion methods). The order of the two conditions was counterbalanced using a Latin square design. For each condition, the participants were required to complete a task (15 steps; see Table 1) of the chemistry experiment with instructions. These tasks are slightly different to avoid the participants learning from previous sessions. Participants were asked to complete the task as quickly as possible while avoiding errors. After completing each condition, the participants were asked to take off the HMD and complete the questionnaires. Then, the participants were allowed to take a three-minute break to relieve fatigue and continue to the next condition. The entire procedure was recorded with a video camera.

After all two conditions were completed, there was a closing semi-structured interview. The interview specifically asked the participants whether they liked or disliked any aspect of locomotion and what they might do to improve them. The interview was audio-recorded. Overall, the procedure lasted no more than 45 minutes.

5 RESULTS

5.1 Objective Measures

5.1.1 Task Completion Time (TCT). To analyze the average time it took to complete the task with different locomotion methods, we divided the data into two groups according to the number of hands involved in the steps since the two hands involved may have caused a longer time (see

Fig. 5). A Shapiro-Wilk test showed that the data is normally distributed ($p > .05$). Then, a paired samples t-test indicated that the average time of the Point & Teleport ($M = 48.82$, $SD = 8.97$) and ManiLoco ($M = 47.67$, $SD = 6.73$) did not reveal a significant difference in one-hand steps ($t[15] = -.363$, $p = .722 > .05$). However, the paired samples t-test indicated there is a significant difference between Point & Teleport ($M = 59.76$, $SD = 24.83$) and ManiLoco ($M = 48.44$, $SD = 9.02$) in two-hand steps ($t[15] = -2.366$, $p = .032 < .05$).

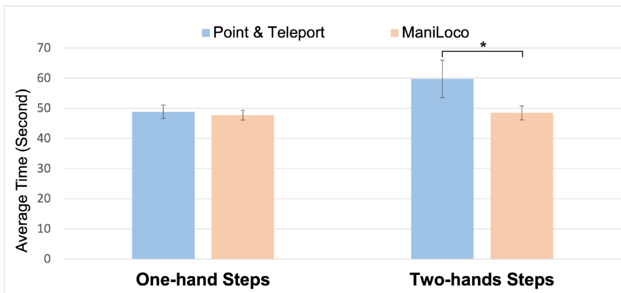

Fig. 5. The average completion time using the different locomotion methods. Error bars in all charts are standard errors of the mean.

5.1.2 Errors. We looked at participants' errors as a measure of their control over the locomotion methods (see Fig. 6). A Shapiro-Wilk test showed that the data is normally distributed ($p > .05$). Results of the paired samples t-test show that there is a significant difference ($t[15] = -2.786$, $p = .014 < .05$) between the errors made when using Point & Teleport ($M = 3.25$, $SD = 1.82$) and ManiLoco ($M = 1.81$, $SD = .77$) methods.

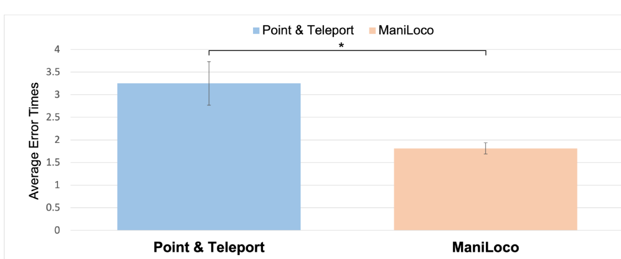

Fig. 6. The average number of errors using the different locomotion methods. Error bars in all charts are standard errors of the mean.

5.2 Subjective Measures

5.2.1 Perceived Usability. A Shapiro-Wilk test proved that the data is normally distributed ($p > .05$). Then, eight paired samples t-tests were employed to compare the different perceived usability items between the two locomotion methods (see Fig. 7).

Difficulty of Understanding and Operating the Technique. The result of paired samples t-test shows there is no significant difference between the two techniques ($t[15] = -.251$, $p = .806 > .05$) for the difficulty of understanding the locomotion methods. Similarly, no significant difference ($t[15] = -1.861$, $p = .083 > .05$) was found in the difficulty of operating the two locomotion methods.

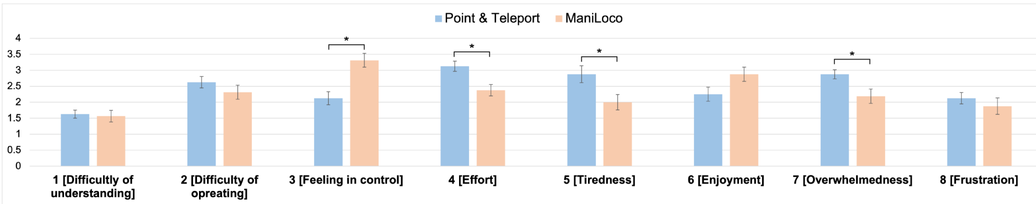

Fig. 7. The results of perceived usability questionnaire of using different locomotion methods. Error bars in all charts are standard errors of the mean.

Feeling in Control. As we conducted paired samples t-test analysis, a significant difference was observed in feeling in control when using the techniques ($t[15] = 3.033$, $p = .008 < .05$). Here, perceived feeling in control was reported to be significantly higher when using the ManiLoco ($M = 3.31$, $SD = .87$) than using Point & Teleport ($M = 2.37$, $SD = .80$).

Perceived Effort and Tiredness. The analysis of paired samples t-test also resulted in significant differences between the two locomotion methods in terms of the effort it took to use them ($t[15] = -2.440$, $p = .028 < .05$) and the perceived tiredness ($t[15] = -2.458$, $p = .027 < .05$). Descriptive statistics show that the perceived effort was significantly lower when using ManiLoco ($M = 2.37$, $SD = .71$) than using Point & Teleport ($M = 3.00$, $SD = .63$). Similarly, the tiredness was reported as lower when using ManiLoco ($M = 2.00$, $SD = .96$) than using Point & Teleport ($M = 2.93$, $SD = 1.06$).

Perceived Overwhelmedness. A significant difference was observed in the level of overwhelmedness between the two locomotion methods ($t[15] = -2.666$, $p = .018 < .05$). Here, participants' reported overwhelmedness was significantly lower using ManiLoco ($M = 2.18$, $SD = .91$) than using Point & Teleport ($M = 2.91$, $SD = .57$).

Enjoyment and Frustration. The finding shows no significant difference in the perceived enjoyment ($t[15] = -2.45$, $p = .027 < .05$) when comparing using ManiLoco and Point & Teleport method. Similarly, there was no significant difference found between the two techniques in terms of perceived frustration ($t[15] = -1.168$, $p = .261 > .05$).

5.2.2 *Presence and Motion Sickness.* The paired samples t-tests revealed no significant difference between Point & Teleport and ManiLoco ($t[15] = 1.616$, $p = .127 > .05$) in the presence score. However, a significant difference was found for the motion sickness data ($t[15] = 2.873$, $p = .016 < .05$). Table 2 presents the results for the presence and motion sickness scores.

Table 2. The results of presence and motion sickness scores.

	Point & Teleport		**ManiLoco**	
	M	**SD**	**M**	**SD**
Presence	2.64	.84	3.10	.95
Motion Sickness	1.77	.36	1.48	.47

5.3 Qualitative Feedback

In addition to the quantitative data, we gathered comments from every participant about anything they liked or disliked and suggestions about each locomotion method. As one of the most popular and commonly-used VR locomotion methods, Point & Teleport only received positive feedback from a few participants (3/16). Most participants stated that it was a bit challenging using Point & Teleport in a task with intensive hand interactions and expressed discomfort when mentioning the steps where they needed to use both hands to hold two containers while performing Point & Teleport. As P10 noted, "I needed to press the joystick, control the position, and then release the joystick with one hand. Meanwhile, both my hands needed to continuously press the trigger to grab the objects, while I also had to pay attention to the liquid not spilling, which made me exhausted." Or, as P4 said, "When releasing the joystick, I always felt like I was to release the trigger as well." Besides, some participants (4/16) mentioned that Point & Teleport tended to cause vertigo.

Compared with Point & Teleport method, ManiLoco was a completely new technique for the participants, even though some of them are experts in VR. Some participants (3/16) were uncomfortable with object-based localization. P7 said, "Locating some small objects far away was a little difficult for me. I must rotate my head carefully." P8 also explained, "Unlike the Point & Teleport method, the visual feedback for object-based localization was intermittent, and it only appeared when looking at objects, making me upset." However, many participants (9/16) also gave their acceptance and felt that the design idea of ManiLoco and this experiment was intuitive and interesting. They thought ManiLoco could likely be a better solution to the locomotion problem when the hands needed to manipulate objects. Especially when both hands were holding objects, ManiLoco made their hands feel much more comfortable. P10 and P11 mentioned that "After getting used to this method, it became beneficial." and "It can directly lead you to the target object, and you no longer have to worry about hand movements." respectfully. P1 also stated that "ManiLoco is very suitable for this type of VR application requiring much hand interaction. It made me feel more comfortable and focused on the training." P4 said, "Looking at an object and walking towards it is very natural, as we do in real life."

5.4 Trajectories in Tracking Space

ManiLoco is designed to enable participants to navigate a bigger space within a limited area. Therefore, it is essential to ensure ManiLoco can be used for room-scale tracking space. Our experiments recorded the participants' real-time positions in the tracking space to verify whether they could perform multiple rounds of ManiLoco and finish the task in the tracking space. We did not record in Point & Teleport method as it did not need the participants to move. The trajectories of 16 participants' movement in the tracking space are shown in Fig. 8. By dividing the tracking space into a grid with cells that were sized 10×10 cm, we calculated overall tracking space utilization using the collected positional tracking data. The results show that no participants had been out of bounds and used tracking space with .78 m^2 on average (SD = .24, Min = .48, Max = 1.28), with an average width of 1.47 m (SD = .23, Min = 1.16, Max = 1.74), and an average height of .53 m (SD = .13, Min = .38, Max = .75). This means all the participants could explore the scene with ManiLoco in a 2×2 m room-scale virtual space.

6 DISCUSSION

When we examined the task completion time, we found the two locomotion methods took similar times in completing one-hand steps. However, in the two-hand steps, we found that participants significantly took less time with the ManiLoco method. When holding an object in one hand, the participants with VR experience chose to hold the object in one hand and control the teleport with the other, which did not cause conflict. Therefore, similarities in completion times between the two methods are expected in these steps. However, performing the Point & Teleport method when holding the object with both hands further burdens the hand operation of participants, which leads to a significant increase in completion time for the Point & Teleport for two-hand steps compared to

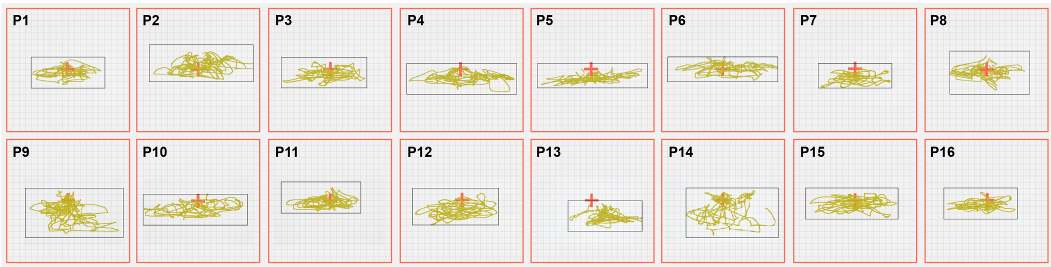

Fig. 8. Tracking trajectories of 16 participants using ManiLoco.

one-handed steps. ManiLoco method did not exert further cognitive load, which can be reflected in the fact that no significant difference was found between one-hand and two-hand steps in terms of task completion time. Besides, we found that the participants could finish the hand-only interaction tasks after each locomotion in a shorter time in the ManiLoco condition. We argue that it may be because ManiLoco allows the participants to focus on their hand interaction better. Therefore, the participants can jump out of the locomotion operation and quickly return to the hand interaction.

ManiLoco resulted in a significantly lower number of errors than Point & Teleport, which supports **RH1**. We interpret this as the ManiLoco method allows participants better focus on their training tasks. When using Point & Teleport method, some participants spilled the task liquid or dropped the container onto the ground. We consider this can measure how stable the participants' hands were, and the failures can represent a sign of conflict between locomotion methods and hand interactions. Although there is no conflict in the buttons, this unsynchronized operation does not allow the participants to control their hand actions well, thus producing the above failures.

Another type of error we found when participants were using Point & Teleport was being moved to the wrong location. We interpret this as participants had to pay attention to the liquid in the container and thus could not control the location of the teleport very well. As a result, they always teleported too far or too close to the target, thus adjusting position with a second or more teleport. This error also occurs in a few cases in the ManiLoco method, where some participants tend to move their bodies quickly and intensively, thus shifting the target object and reaching an adjacent position. When using the ManiLoco method, more errors occur in activating the transition. This is because ManiLoco is a parameter-based detection method and thus may have sensitivity issues.

In addition, when using the Point & Teleport method, some participants triggered the transport when they did not intend to. Such problems mainly occurred when participants manipulated the objects with both hands. We found that sometimes the participants' fingers unconsciously pressed the button and triggered the teleport again, even though the first teleport had already let them reach the destination. We think this also represents the conflicts between the locomotion method and the hand interaction.

No differences were found between the ManiLoco and Point & Teleport methods in terms of difficulty to understand and operate. We interpret this as ManiLoco not exerting significant cognitive load for learning how to use it. The ManiLoco got a significantly higher score for feeling in control. ManiLoco required fewer efforts than the Point & Teleport method, which supported **RH2**. Despite introducing a specific walking action, ManiLoco did not require the participants to exert more effort. These results can be explained from two perspectives. First, performing Point & Teleport while holding an object in both hands caused pressure on the hands, thus increasing the overall physical demand. Second, feet are naturally mapped to movement, and the speed needed for walking is the daily walking speed that did not cause too much physical pressure on the participants

[Howard et al. 2016]. Moreover, the cognitive process is a combination of internal processes and bodily manipulation of environmental structure [Rowlands and Mark 1999]. ManiLoco separates the locomotion operation from hand to the participant's head and foot, thereby reducing the expenditure of internal information-processing resources during the participant's perception and action of hand operations.

The tiredness results also reveal that ManiLoco could successfully release the stress on the hands. Regarding the feeling of enjoyment, our findings show the mean score for ManiLoco was higher than for the Point & Teleport. However, a significant effect could not be found. Hence, **RH3** cannot be confirmed. However, we received positive feedback about the ManiLoco being fun and intuitive. Point & Teleport caused participants to have a feeling of being overwhelmed. These results may be because participants were more prone to the error of having been transported to the wrong location when using the Point & Teleport method. They needed to adjust the position by making additional teleportation, a process that could overwhelm the participants. Both techniques got a low score for feeling frustrated, which makes us think that ManiLoco is a user-friendly locomotion method.

The results show that motion sickness is significantly lower for using the ManiLoco method, which confirms **RH4**. The results can be explained by the larger discrepancy between visual and vestibular, and proprioceptive cues, which occur when VR users are physically stationary while they navigate and move with a joystick only. While using ManiLoco, participants were moving physically and thus able to recover during the task. We didn't observe any significant effect of the two locomotion methods on the level of presence.

To sum up, the experiment results and the participants make us think that ManiLoco is easy to learn and user-friendly. It has a high potential to be a locomotion method in VR training applications with intensive hand-based interaction tasks.

7 LIMITATIONS AND FUTURE WORK

As a method based purely on VR HMD and stepping activity detection, ManiLoco inevitably introduces many parameters, e.g., the time and distance to detect foot activities. These parameters may significantly affect the users' experience. If they are set too large, the users will have to rigger through strenuous physical movement, but if they are set too small, they are likely to trigger it when they do not want to mistakenly. It can be a trade-off between sensitivity and body load. We think each person should have their settings reflecting their height and stepping habits for better results. We used a universal number in the current experiment, but in the future, users could be allowed to customize these parameters to actual use to improve efficiency and lower errors.

In addition, ManiLoco is an object-based locomotion method requiring the user to focus on the object first. Object detection might become a burden when the object is far away or too small. In addition, occlusions between objects can also lead to increased difficulty in positioning the target object. ManiLoco introduces a range search to reduce this problem. However, users may encounter difficulties in assigning these objects in a scenario where things are dense.

Finally, in the current virtual laboratory scenario, the users' locomotion is in 1D, i.e., the targets are all in their horizontal direction. Returning to the tracking space center is an essential step of ManiLoco to ensure the user does not go out of the boundary. For full-functional 2D locomotion, ManiLoco may make the user feel unnatural since the user may be placed after the object in the virtual space so that the user can move back to the center of the physical room.

8 CONCLUSION

We design and develop a new VR locomotion method, ManiLoco, intended to effort of locomotion from hand to head and foot, and thus make it more suitable for VR training applications where hand interaction is dominant. A task in a virtual laboratory room with a horizontal layout was created and performed with 16 participants to compare ManiLoco with the most commonly used locomotion method, Point & Teleport. The results show that ManiLoco required less effort for the users by not relying on the controllers while maintaining efficiency and presence. Besides, ManiLoco caused fewer errors in the task by allowing users to focus more on their hand interactions and aided them in object manipulation. Meanwhile, the introduction of the foot action in ManiLoco leads to decreased motion sickness. Our experiment proves that users can explore the 3×8 m VR environment within a physical space of 2×2 m, demonstrating the feasibility of ManiLoco to adapt to typical laboratory activities that the users use locomotion in 1D with targets in their horizontal direction. Furthermore, we hope to provide more research ideas for future VR locomotion methods by describing the design ideas and details.

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