Simulated Reference Frame: A Cost-Effective Solution to Improve Spatial Orientation in VR

Thinh Nguyen-Vo, Bernhard E. Riecke, and Wolfgang Stuerzlinger

Fig. 1. Left: Participant wearing an HMD (HTC VIVE) and sitting on the NaviChair locomotion interface. Middle: Visual stimuli of the virtual environment designed to eliminate all visual landmarks. Right: By approaching the box from its front side (the side denoted by a red banner), participants can make the box automatically open to see whether there is a ball inside, and collect the ball by touching it with the controller.

Abstract—Virtual Reality (VR) technology is increasingly used in spatial cognition research, as it offers high experimental control in naturalistic multi-modal environments, which is hard to achieve in real-world settings. Although recent technological advances offer a high level of photo-realism, locomotion in VR is still restricted because people might not perceive their self-motion as they would in the real world. This might be related to the inability to use embodied spatial orientation processes, which support automatic and obligatory updating of our spatial awareness. Previous research has identified the roles reference frames play in retaining spatial orientation. Here, we propose using visually overlaid rectangular boxes, simulating reference frames in VR, to provide users with a better insight into spatial direction in landmark-free virtual environments. The current mixed-method study investigated how different variations of the visually simulated reference frames might support people in a challenging navigational search task. Performance results showed that the existence of a simulated reference frame yields significant effects on participants completion time and travel distance in the task. Though a simulated CAVE translating with the navigator (one of the simulated reference frames) did not provide significant benefits, the simulated room (another simulated reference frame depicting a rest frame) significantly boosted user performance in the task as well as improved participants preference in the post-experiment evaluation. Results suggest that adding a visually simulated reference frame to VR applications might be a cost-effective solution to the spatial disorientation problem in VR.

Index Terms—Human-centered computing - Empirical studies in HCI.

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1 INTRODUCTION

Virtual Reality (VR) has been increasingly adopted in both scientific research and the entertainment/game industry in recent years. Current VR technology offers not only naturalistic stimuli in a fully immersive and interactive experience, but also physically impossible locomotion modes such as teleporting and flying. In other words, people can easily translate in the simulated world, with little or even no effort.

However, locomotion remains a challenge in VR, as people might not be able to efficiently perceive their self-motion. For instance, when traveling in immersive virtual environments people have been shown to take substantially longer time with keeping track of where they are compared to the real world [39]. Also, people learning a route by exploring a virtual building made more errors when being asked to then walk the same route in a physical building [28]. Various sources

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of disorientation, such as left-right confusion [29] or the inability to update visually-simulated rotation [2, 16] can substantially affect the effectiveness of virtual locomotion. In general, spatial disorientation happens when the immediate position and orientation cannot be correctly determined, which prevents the human brain from updating the current spatial awareness with recent self-motion [16, 33].

Spatial updating helps people to keep track of their position and orientation when they move through an environment, especially when reliable landmarks are missing [16, 33]. Inconsistencies might occur in such situations when the visual cues suggest that you are translating/rotating, whereas the vestibular system signals the opposite, which commonly happens with simulated movements, especially when stationary. In VR, the spatial updating process is affected by various visuomotor cues [16, 33, 38], and the conflicts between these cues can produce not only disorientation but also motion sickness [12, 21, 27].

Visually-induced motion sickness or simulator sickness is associated with dizziness, nausea, or fatigue of users while being immersed in the virtual world. The latency between physical movement and visual stimuli is one of the factors causing such symptoms [8]. Though recent advances in technology have decreased this latency to a level low enough that people can hardly perceive it, simulator sickness can
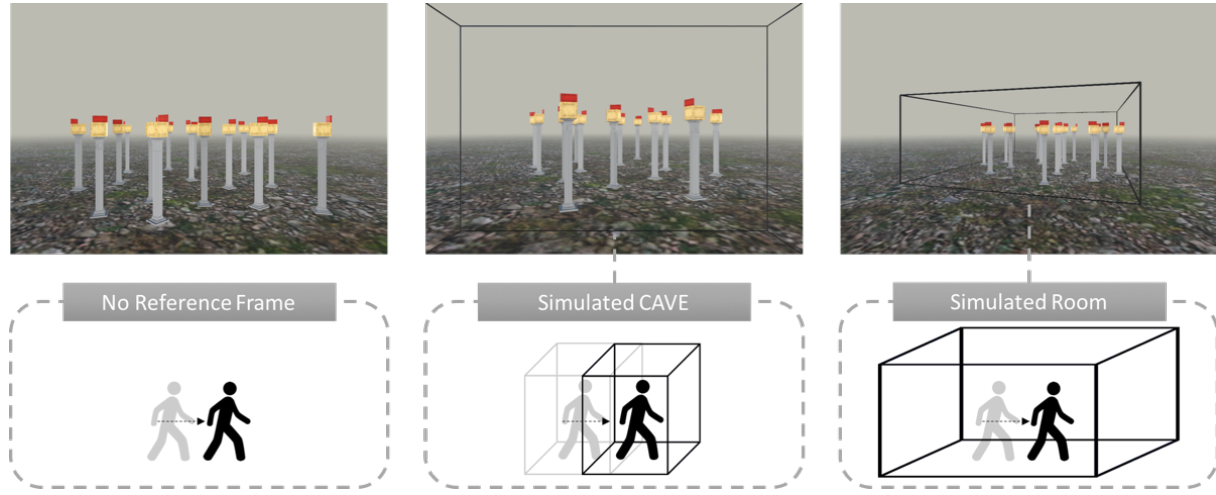
Fig. 2. Three variations of reference frames. Left: No reference frame. Middle: Simulated CAVE. Right: Simulated Room.

still occur when there are inconsistencies between the signals across sensory modalities [27]. This sensory conflict is the most widely accepted explanation of such symptoms [9]. Nevertheless, the chance that a person might get motion sickness also depends on other biological aspects such as gender, age, and prior knowledge [21]. While the tendency to get sick therefore varies from person to person [18], the severity of sickness decreases generally with better synchronization between visual and vestibular cues [21, 36].

Cognitive Reference Frames

Reference frames have long been studied in spatial cognition research, and have been shown to significantly affect spatial updating and spatial orientation [17, 23, 10]. A reference frame defines a set of parameters used to represent the immediate spatial knowledge which enables a person to maintain and update their awareness of position and direction when traveling through an environment. Different reference frames are specified by different sets of parameters, like the x and y of the Cartesian coordinate system or the r and θ of the polar system. These parameters define which kinds of frames are to be used. An egocentric frame is centered on the navigator, whereas an allocentric frame is centered at an external point in the environment [17]. Fig. 3 illustrates these two different reference frames in physics.
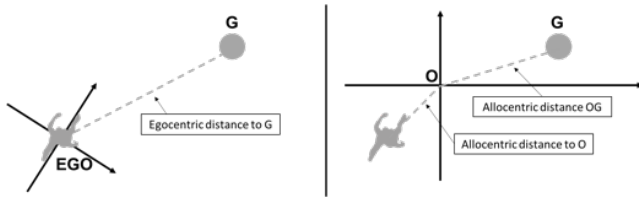

Fig. 3. Egocentric (left) and allocentric (right) reference frame

Though previous study has investigated the role of cognitive reference frames in spatial cognition and spatial orientation [17, 10], there has been little or even no effort on visualizing/simulating this cognitive concept to assist VR users in maintaining spatial orientation. In the real world, these frames are typically embedded in objects or landmarks, such as a building, a table, our shadow, or even our body components. In this study, we investigate if adding a simulated reference frame to VR could serve as a cost-effective visual cue to facilitate the human spatial orientation process.

Recent studies showed that one's orientation in a rectangular environment can lead to sensorimotor facilitation or interference when asked to imagine a different environment [31]. However, there is still

little knowledge of how the presence of a rectangular reference frame actually affects the way people retain their spatial orientation and act on it in a non-trivial spatial orientation task. This unclear relationship exists in a CAVE, where people are frequently aware of the edges forming the display. This question leads to the need for precise and careful exploration of the effects of the rectangular reference frame for all kinds of VR displays. Towards that goal, we designed a study to investigate the spatial behaviors of participants when doing a navigational search task in virtual environment with or without the presence of an additional simulated reference frame.

Simulating reference frames in immersive VR

Simulated CAVE: Although one could consider using an actual CAVE for the study, we decided to instead simulate the rectangular frame of a CAVE using a head-mounted display (HMD) to avoid possible confounds, i.e., visibility of edges and corners of a CAVE, display resolution, distortion, and brightness, which could affect the performance of the participants [37, 32]. We call this reference frame "simulated CAVE", because the rectangular frame mimics an actual setup of a six-side CAVE.

Simulated Room: To investigate what aspects of a simulated reference frames really matter for spatial cognition, we designed another simulated reference frame that provides only allocentric cues, i.e., whose position and orientation are independent of the observer. This concept has long been studied and referred to as rest frames [26]. Previous research has also shown that rest frames can help reduce motion sickness and increase the sense of presence in VR [7].

To sum up, we propose using a simple overlaid wireframe of a rectangular box as a frame of reference for participants for VR locomotion. While the simulated CAVE (whose wireframes made users feel like they were at the center of a CAVE) always followed participants, but does not rotate with them, the simulated room was stationary regardless of participants movement and rotation, just like when moving in an actual room. Both simulated reference frames are tied to the ground, which reflects the planar nature of the physical world, where people mostly locomote on 2D surfaces. In this study, we aim to investigate if and to what degree simply adding a visual representation of a fictitious rectangular box to virtual scenes might improve users spatial orientation. We hypothesize as follows:

H1: Both kinds of reference frames improve participants' performance in a navigational task compared to the no reference frame control condition (e.g. shorten completion time, travel distance, and reduce revisits), because environmental geometry can be used as an orientation cue [11] and both egocentric and allocentric reference frames are known to enhance spatial orientation [16].

H2: The simulated room is the most preferred condition, while the simulated CAVE might disturb participants when they are doing the
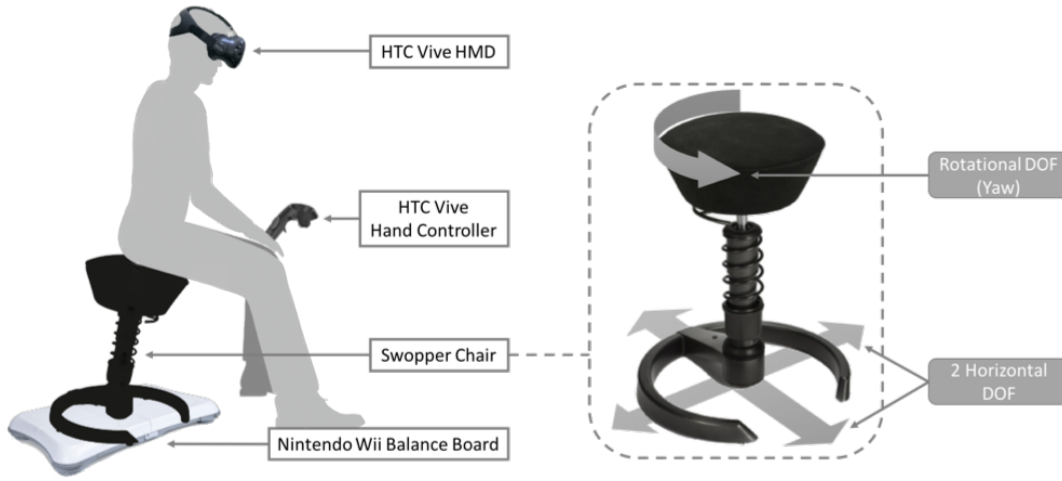
Fig. 4. Left: Sketch of the setup including HMD, interaction and NaviChair locomotion interface. Right: NaviChair's DOFs

task, as a stable room has higher ecological validity than a box moving with the observer. In other words, we predict that the CAVE-like moving reference frame yields lower preference and usability ratings.

H3: Both the simulated CAVE and room can help reduce motion sickness, because both frames provide participants with additional orientation and self-motion cues.

2 STIMULI AND APPARATUS

2.1 Virtual Environment

Participants wore a head-mounted display (HMD) displaying a virtual environment consisting of a large grass-textured ground and 16 identical wooden boxes placed on 16 pedestals, as depicted in Fig. 1. Each of these boxes was randomly positioned and rotated for each trial to avoid learning effects. Boxes were always positioned within a circular area of 5 meter diameter.

Eight of these 16 boxes contained green balls as target objects and participants had to search for and collect all these eight balls to complete a trial. To eliminate potential "cheating" strategies, ball targets were guaranteed to be only visible when the user approached the box from the side with the red board. Environmental fog was added to cancel other visual cues that could guide or re-orient participants.

A HTC Vive HMD was used to binocularly present the virtual environment. The HTC VIVE provides a per-eye resolution of 1080 x 1200 pixels and a binocular Field-Of-View (FOV) of 110 diagonally. Stimuli were generated in real time at 90Hz using Unity3D. There was no noticeable latency of rendering/tracking during the experiment. The head tracking embedded in the HMD was enabled. When they saw a ball inside a box, participant could simply touch the ball with the wireless hand controller to "collect" it (see Fig. 1).

To reduce any effect of noise in the real world that could be used as spatialized auditory cues for orientation in the virtual world, noise canceling headphones were used. In addition, a notification sound was played via the headphones whenever a ball was collected successfully.

2.2 Locomotion Interfaces

In order to effectively compare our simulated reference frames, we consider several locomotion interfaces that have been proposed previously. Walking is probably one of the most common modes of transportation for humans. It enables people to remain oriented in their immediate environment with little cognitive effort even with closed eyes [33, 25]. Thus, walking is a desirable locomotion mode in VR. However, allowing for actual walking requires tracked free-space walking areas which can be costly, especially when virtual environments are larger than normal room scale. A variety of alternative solutions have been proposed, including walking-in-place and redirected walking. While many of these approaches are promising, they require

significant technical, financial, and safety efforts to be implemented, and often become unaffordable or unfeasible for a wider adoption on the market. In this study, we used a leaning-based interface called NaviChair [15, 3] and Joystick as a standard locomotion interface.

NaviChair: This locomotion interface uses the human upper body as a joystick for navigational control in VR [15, 3, 4]. The idea of using embodied interaction to control VR locomotion has appeared repeatedly in various forms. Recent research has shown that locomotion interfaces that allow physical rotation alone (without physical translation/walking) can achieve comparable performance to actual walking in a similar navigational search task [30]. As illustrated in Fig. 4, the NaviChair interface consists of a commercially available Swopper stool [1] placed on top of a Wii Balance Board to measure users weight shifts. In the actual design, a foam slab and a circular wooden plate were placed between the WiiBoard surface and the stool to stabilize the chair as illustrated in Figure 1 (left). The NaviChair offered three degrees of freedom (DOFs): Participants controlled simulated yaw rotations in VR by simply physically rotating with the NaviChair. Translations (left-right and front-back) were controlled by participants leaning or otherwise shifting their weight in the desired translation direction, which was tracked by the Wii Balance Board underneath the Swopper stool. That is, the Wii Balance Board measured changes in the location of the center of pressure, which were linearly mapped to translation speed in the virtual scene.

Joystick: In this navigation interface, a wireless Logitech Freedom 2.4 joystick was used. Participants tilted the joystick to translate (in two dimensions) and rotated it to rotate their virtual body in the scene.

2.3 Experiment Task: Navigational Search

In order to evaluate how well people can maintain spatial orientation for the different reference frame condition, we used a navigational search task in which participants are placed in an environment consisting of 16 boxes, and tasked to find eight target objects hidden in these 16 boxes [22, 34]. Initially, participants are located outside of the target area. They had time to plan their path to optimally visit all boxes. We also told them to complete the task in the most effective way which might require them to do the task not only as quickly as possible, but also in a strategic way to avoid errors and to minimize distances traveled. Whenever they were ready, participants pressed the trigger on the controller in their hand to start a trial.

During each trial, participants used the provided locomotion interfaces to navigate through the virtual world. Only when they came close enough to a box and looked at its front side (indicated by a red banner, see Fig. 1), that side disappeared and showed a target ball, if it existed. Participants were asked to collect all balls by touching them with the controller, which made them disappear. Any touched

ball was never shown again, even if its box was revisited so that participants were unable to use it as a navigational cue.
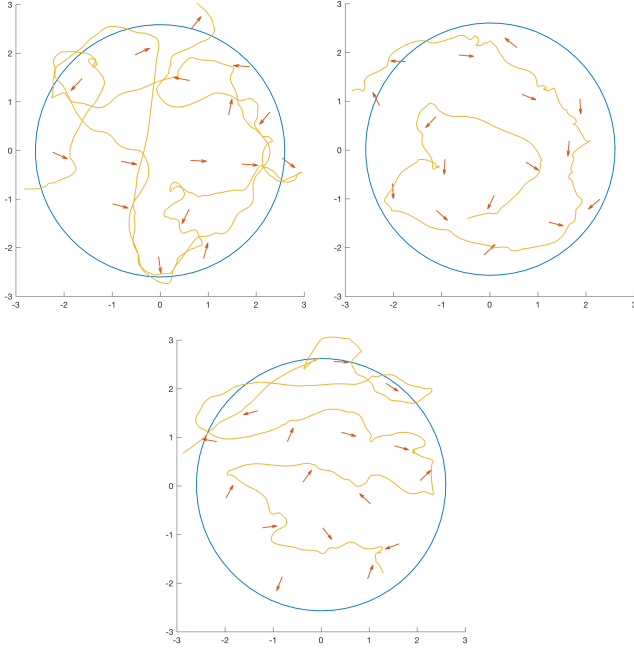

Fig. 5. Three examples of trajectory plots per trial. Top-Left: (Seemingly) random search without strategy (PT #9, trial #1). Top-Right: Spiral search (PT #5, trial #3). Bottom: Zig-zag search (PT #13, trial #3)

Fig. 5 shows exemplar trajectory plots for three typical trials from different participants using the NaviChair. The red arrows illustrate the boxes location and direction. Whereas the position of a box is exactly at the origin of an arrow, its front direction is indicated by the direction of the arrow. While most participants used either a spiral search or seemingly random search pattern, a few people tried to arrange all the targets by rows in their minds and then systematically scanned through all the targets in zig-zag trajectories.

The number of balls that had already been collected was displayed at the bottom of the screen, so that participants could focus on their search. A trial was ended when either all eight balls had been collected or the allowed period of 3 minutes had expired.

Though the task might not seem to be harder than a normal video game, it actually requires quite high cognitive load, as the task itself requires fast translation, combined with rotation in a very limited time. Moreover, the environment was designed not to provide additional orientation cues such as landmarks or directional lights. Participants had to build up the spatial awareness based on the boxes locations, and maintain it during the task. Most participants could find the first three balls easily, however, as the ratio of balls to boxes decreases over the task, those who do not maintain good spatial orientation and memory found it increasingly difficult.

2.4 Simulated Reference Frame

As a studied phenomenon, simulated reference frames were designed following previous theories which consider the center of reference as the most important attribute of a reference frame [17, 23]. As depicted in Fig. 2, we compared two variations of reference frames and a baseline condition of no reference frame:

No reference frame: This is a normal condition like any other VR game or simulation. Participants were expected to do the task in a landmark-free environment, so that they had to maintain their spatial orientation without any additional visual cue. The environment was designed to avoid both intrinsic and extrinsic reference frames. This condition, therefore, was ideal to be used as the baseline for assessing the other conditions that included a simulated frame of reference.

Simulated CAVE: A 3D rectangular box of 3 x 4 x 2 meters centered around the user was added to investigate if it might help participants to remain oriented during the task (Fig. 2). Note that the only visible components of the box were its edges, and the edges did not significantly hide any part of the virtual scene. We deliberately used a rectangular box as we expected that the difference between shorter and longer edges would enhance participants spatial orientation (e.g., they could easier distinguish different sides of the frame). In this condition, the frame translated with participants, and they were always positioned at the center of the frame. However, the orientation of the frame stays constant; participants thus feel like they were using an actual six-sided CAVE, which is a classic virtual environment setup that (unintentionally) provides users orientation cues with its edges and corners.

It is important to mention that the simulated CAVE reference frame does not behave exactly like an actual CAVE in the real world. In a CAVE, user can move his or her own head to adjust their relative point-of-view to the frame. However, in the simulated CAVE, the frame is always center-aligned with user's point-of-view. This characteristic emphasized the egocentric reference cues in the simulated CAVE.

Simulated Room: A 3D rectangular box of 5 x 6.6 x 2 meters, which fully covered the area of target objects, was added in this condition (Fig. 2). The most important difference compared to the Simulated CAVE was its stationary behavior. That is, neither the position nor orientation of the simulated room reference frame changed with participants movement, thus mimicking the cues provided by an actual room or rest frame [26]. The simulated room in this condition can be considered as an additional object in the scene, albeit one that has a clearer intrinsic reference frame than the randomly scattered target objects. Another difference is that the size of simulated room is bigger than a simulated CAVE, as we want it to fully cover the whole area of the navigational search task, a circular area of 5 meter diameter. However, the 3:4 ratio of the simulated CAVE was maintained, and the area of simulated room is hence 5 x 6.6 meters.

The height of both simulated frames is relatively shorter than actual CAVE or room in the real world. We made this choice to fit the HMD's FOV so that the frames are always visible to observers, no matter in which direction they are looking. The ultimate goal is that user can passively refer to the frames to maintain spatial orientation with less or even no cognitive load, like how we do in the real world.

3 EXPERIMENTS

Participants began the study by reading and signing an informed consent form. Then they read printed instructions explaining the task as well as the use of the equipment. Each participant completed a single practice trial in the training section to get familiar with the interface and then one trial for each condition. Order of conditions were balanced across participants to account for potential order effects. Each trial lasted three minutes on average.

After each trial, participants were asked to fill out a questionnaire on a computer. They rated the previously experienced condition using visual analog ratings with a scale ranging from 0 to 100, on aspects such as ease of use, learnability, comfort, usability, controllability, enjoyment, motion sickness, and preference (different from other ratings, preference was rated using a Likert scale from 0 to 10). This evaluation section was also a chance for the participants to take a break between different conditions, which helped to prevent motion sickness. Breaks lasted from one to ten minutes up to participants, we only started next trials when participants were ready. After the last trial, participants also completed a short exit survey in addition to their previous evaluation and were thanked for their participation.

On average, the study took 30 minutes to complete. The studies had approval of the SFU Research Ethics Board (#2012c0022) and all participants signed an informed consent form prior to participating.

3.1 Experiment 1: Pilot Study

We ran a pilot study to evaluate the experiment design in general so that we could adjust the main experiment if needed. Pilot testers (PT) were treated exactly the same as participants in the main study.

3.1.1 Participants

Nine volunteers (4 female, 5 male), aged 12-39 years old ($M = 24.33, SD = 6.39$), took part in the pilot experiment. While three of them were graduate students who had significant experience with VR, the other six were undergrad students and naive to VR.

3.1.2 Experiment Design

A 2 x 3 repeated-measures experiment was conducted. The independent variables were locomotion interface (2 levels: NaviChair and joystick) and simulated reference frame (3 levels: no reference frame, simulated CAVE, and simulated room). Every participant was supposed to take part in all six conditions, in balanced order. Qualitative data was collected by debriefing and analyzed to investigate potential factors causing motion sickness.

3.1.3 Results

A large portion of participants (4 out of 9) got motion sick and could not finish all six conditions. Thus, only part of their performance data was usable. To investigate, we asked participants several questions. When being asked *"Is there anything annoying or too difficult in this experiment?"*, some participants reported motion sickness as an issue but did not identify the cause (PT #2, 6, 7). Others mentioned difficulties in using locomotion interfaces (PT #1, 8, 9). In their feedback on locomotion interfaces, most participants preferred NaviChair (PT #4: *"The NaviChair was easier to use because it is more intuitive/natural"*. PT #6: *"The NaviChair helped my body feel the motion in real time and I would prefer to use that in a long term scenario"*.). Three participants even identified the joystick locomotion interface as the cause of their motion sickness (PT #5: *"Joystick made feel sick when I was rotating it to one side and move my head to another"*.).

In conclusion, different individuals provided different ideas on how the experiment could be improved, however, the general theme showed that locomotion interfaces and in particular the joystick might have contributed to the issue of motion sickness in this experiment. On the other hand, when comparing between the two interfaces, most participants preferred the NaviChair even though the joystick was more standard and known. This might be related to upper-body leaning being able to facilitate self-motion perception in VR [20, 19].

3.2 Experiment 2: Main Study

Based on the pilot study results, we reduced the number of experimental trials from six to three and removed the joystick condition as it seemed like it might be more prone to motion sickness.

3.2.1 Participants

Twenty-one volunteers (13 female, 8 male), aged 18-41 years old ($M = 22.06, SD = 5.01$), took part in the main experiment. Most of them were undergrad students and naive to VR. Twelve participants reported playing computer games weekly, or even daily. The other nine participants did not play computer games at all.

3.2.2 Experiment Design

Based one the pilot study results, the main study was reduced to a one-way repeated-measures design, where the only independent variable was the simulated reference frames (3 levels: no reference frame, simulated CAVE, and simulated room, as before). The reason to drop the joystick condition was to firstly shorten the overall length of the experiment and secondly to prevent motion sickness and increase the chance that participants can complete all conditions. Therefore, even though there were only three conditions in the main study, we decided not to increase the number of trials per condition. Each participant was supposed to complete three trials relevant to three conditions of simulated reference frames, in balanced order.

Though there were still 28% (6 out of 21) participants who could not finish all three conditions because of motion sickness, this was significantly less than the pilot study. To increase power without having to run more participants, we included the performance data of the two pilot testers (#4, 8) who started with the NaviChair and completed all trials in this locomotion condition without getting motion sick. In

other words, their performance had not been affected by the subsequent joystick condition at all, and the experimental procedures in the pilot and main experiment were otherwise identical. Eventually, data from 17 participants were used for analysis.

3.2.3 Results: Objective Behavior (Performance)

Data of multiple dependent variables for user performance are summarized in Fig. 6 and were analyzed using repeated-measures ANOVAs and LSD post-hoc tests in SPSS Statistics.

Simulated room helped participants reduce their completion time (Fig. 6A). ANOVA revealed a significant effect of reference frame on completion time, $F(2, 32) = 3.582, p = 0.039, \mu_p^2 = 0.183$. LSD's pairwise comparisons showed that simulated room helped participants to complete the task significantly faster ($M = 94.166, SD = 35.372$), compared to the simulated CAVE ($M = 119.763, SD = 39.514$), $p = 0.031$, and no reference frame condition ($M = 118.011, SD = 39.514$), $p = 0.008$. No significant difference was found between the presence and the absence of a simulated CAVE, $p = 0.893$. This result partially supports our hypothesis **H1** that simulated reference frames can help user improve their performance, although only the rest frame of the simulated room (but not the simulated CAVE) provided a significant reduction in task completion time.

Simulated room helped participants reduce their travel distance in the virtual world (Fig. 6B). Mauchly's test was significant, $\chi^2(2) = 9.638, p = 0.008$. The assumption of sphericity, therefore, was violated. The Greenhouse-Geisser correction was used to analyze the travel distance. It showed that using reference frames resulted in a marginal effect on travel distance, $F(1.357, 21.709) = 3.721, p = 0.056, \mu_p^2 = 0.189$. LSD post-hoc tests revealed that participants significantly traveled shorter in the condition of simulated room ($M = 33.549, SD = 2.274$) as compared to no reference frame ($M = 45.865, SD = 4.484$), $p = 0.004$ and the simulated CAVE ($M = 44.391, SD = 3.977$), $p = 0.025$. No significant difference was found between the presence and the absence of the simulated CAVE, $p = 0.820$. To some extent, this result also supports our hypothesis **H1**.

Participants revisited fewer boxes when using simulated room (Fig. 6C). As Mauchly's test showed that the assumption of sphericity was violated, $\chi^2(2) = 11.523, p = 0.003$, the Greenhouse-Geisser correction was used. Analysis showed that the presence of a reference frame marginally affected the number of box revisits, $F(1.302, 20.831) = 3.617, p = 0.062, \mu_p^2 = 0.184$. LSD post-hoc tests also pointed out that participants made smaller numbers of revisits with the support of a simulated room ($M = 3.412, SD = 0.758$) compared to the baseline condition of no reference frame ($M = 9.000, SD = 1.811$), $p = 0.009$ and the other reference frame, simulated CAVE ($M = 8.412, SD = 1.875$), $p = 0.012$. No significant difference was found between the rest pair of conditions, $p = 0.847$. Similar to previous conclusions, this result also shows that only the simulated room could improve performance, while the counterpart (simulated CAVE) yielded no significant benefits.

Simulated room helped increase the numbers of targets found before the first revisit (Fig. 6D). Though ANOVA revealed no significant difference between the three conditions in terms of the number of targets found before the first revisit, $F(2, 32) = 2.019, p = 0.149, \mu_p^2 = 0.112$, LSD pairwise comparisons showed that participants found more balls before their first revisit in the simulated room condition ($M = 5.882, SD = 0.410$) relative to the condition of no reference frame ($M = 4.706, SD = 0.444$), $p = 0.046$. Simulated CAVE ($M = 4.94, SD = 2.10$) did not differ from the other conditions, $p's > 0.287$. This suggests that it took longer for participants in the simulated room to make the first error, than in other conditions. The result hence partially supports hypothesis **H1**.

No order effect was revealed. Though we counter-balanced the order of conditions to eliminate systematic effects of order on condition, the limited number of participants and the high drop-out rate might affect the balancing. For this reason, we conducted several ANOVAs to analyze if there were any overall order effects. Analyses revealed no significant effect of the order of trials on completion time, $F(2, 32) = 2.424, p = 0.105$; travel distance, $F(2, 32) = 2.835, p = 0.074$; revis-
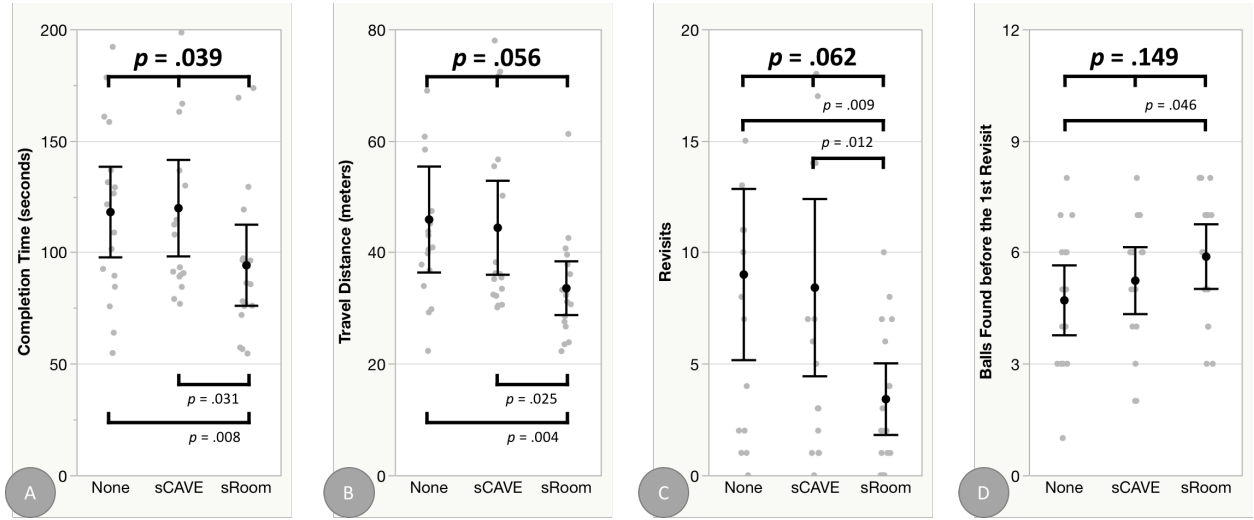
Fig. 6. Mean data of different dependent measures for performance. Error bars indicate confidence intervals ($CI = 0.95$), gray dots indicate individual participants' data

its, $F(2, 32) = 1.495, p = 0.239$; or the number of balls found before the first revisit, $F(2, 32) = 1.795, p = 0.182$.

3.2.4 Results: Subjective Evaluation

Data for the different subjective measures are summarized in Fig. 7 and analyzed using repeated-measures ANOVAs and LSD post-hoc tests. Analyses was done using SPSS Statistics. In general, user evaluations showed that the interface was easy to use ($M = 80.039, SD = 19.048$), highly learnable ($M = 87.392, SD = 12.052$), comfortable ($M = 67.020, SD = 27.091$), usable ($M = 74.275, SD = 19.477$), controllable ($M = 72.529, SD = 20.563$), and enjoyable ($M = 77.137, SD = 26.586$). Yet, there were no significant effects of simulated reference frame on any of the subjective measures apart from the preference rating and simulator sickness discussed below.

Simulated room was slightly more preferred. As denoted in Fig. 8A, most participants rated the simulated room condition as their highest preference ($M = 7.938, SD = 0.496$). Though preference was collected as Likert data, previous studies has shown its feasibility to be analyzed as parametric statistics, even with small sample sizes, unequal variances, and non-normal distribution [5, 24]. ANOVA revealed that reference frame had no significant effect on user preference, $F(2, 30) = 2.071, p = 0.144, \mu_p^2 = 0.121$. LSD post-hoc tests showed that the simulated room achieved marginally higher preference ($M = 7.938, SD = 0.496$) compared to the simulated CAVE ($M = 6.375, SD = 0.569$), $p = 0.064$, and the condition of no reference frame ($M = 6.375, SD = 0.688$), $p = 0.095$. To some extent, this trend partially supports our hypothesis **H2** that the simulated room is the most preferred condition, even though the simulated CAVE did not yield lower preference than the baseline condition.

Simulated CAVE helped reduce the level of visually-induced motion sickness. In this study we were only interested in overall motion sickness. Thus, we used only a single question rather than the SQS [13] to assess participants' simulator sickness. A single question can be sufficient, if the components of visually-induced motion sickness are not of interest [14]. Though Fig. 8B suggests that the presence of both the simulated CAVE and simulated room decreased the amount of motion sickness, ANOVA revealed no significant effect of reference frame on motion sickness, $F(2, 32) = 2.382, p = 0.109, \mu_p^2 = 0.130$. LSD post-hoc tests showed that simulated CAVE ($M = 50.824, SD = 8.310$) significantly reduced the level of motion sickness, compared to no reference frame ($M = 62.882, SD = 7.877$), $p = .029$. This result partially supported our hypothesis **H3** that the proposed visual cue could reduce users motion sickness.

A separate ANOVA was run to investigate potential effect of order on reported motion sickness. Yet, there was no significant result,

$F(2, 32) = 0.751, p = 0.480$. The high rates of reported motion sickness can be explained by the fact that the navigational search task was designed to be fast and challenging, which required participants to pay close attention to their spatial orientation; while simultaneously building up the spatial awareness of visited boxes; optimizing their path; and traveling fast and effectively. Yet, many participants initially underestimated the task difficulty, and (seemingly) randomly traveled from box to box at high speed. Motion sickness started before they actually recognized the symptoms and slowed down.

4 DISCUSSION

Though previous work has shown that the egocentric reference frame is dominant in spatial updating [23], our simulated CAVE, which adds an egocentric frame of reference (at least for translation, but not for rotation), did not show any significant difference compared with the baseline condition of no added reference frame. However, an allocentric frame of reference, mimicking a simulated room acting as a rest frame [26], seemed to be helpful in the navigational search task. Analyses revealed significant benefits in a variety of behavioral measures. In terms of user performance, our hypothesis **H1**, which predicted both kinds of reference frame would improve performance, was partially supported. In fact, only the allocentric frame (simulated room) improved user performance. In terms of usability, hypothesis **H2**, which predicted that the simulated room would be preferred, was partially confirmed, as the differences were not significant. Regarding motion sickness, hypothesis **H3** which predicted that adding reference frames can reduce user motion sickness, was also partially supported, as only simulated CAVE significantly reduced sickness, compared to the baseline condition. These mixed results suggest the potential of a simulated reference frame in enhancing VR locomotion, but also require further study with larger participant numbers for more firm conclusions.

What makes the difference between Simulated CAVE and Simulated Room? Although both kinds of reference frames brought a visual cue into the virtual environment to help participants remain oriented, the synchronization between the simulated CAVE and participants translation might not have improved participants' sense of position. That is, with the simulated room, participants could always easily identify the relative position between themselves, the boxes, and the room so that they could recognize not only how much they rotated, but also where they were in the virtual environment. The simulated rooms behavior is after all a more natural cue due to our experience with rooms in the real world, whereas the simulated CAVE, which translates (but does not rotate) with the user, can seem strange, unless users were very familiar with CAVEs (which they were not). The simulated CAVE hence might require more cognitive load for the spatial updat-
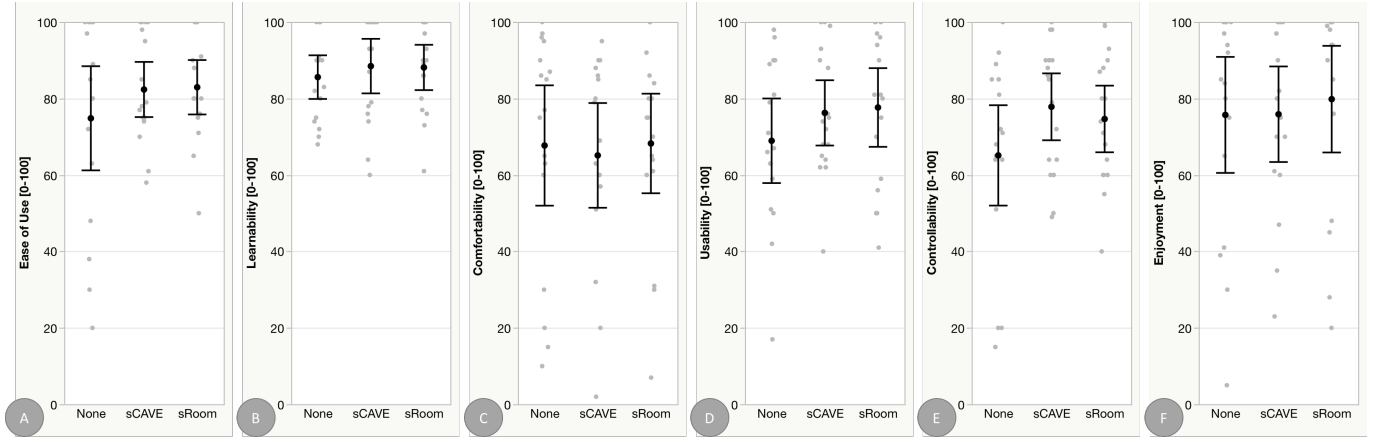
Fig. 7. Mean data of different dependent measures for user evaluation. Error bars indicate confidence intervals ($CI = 0.95$)
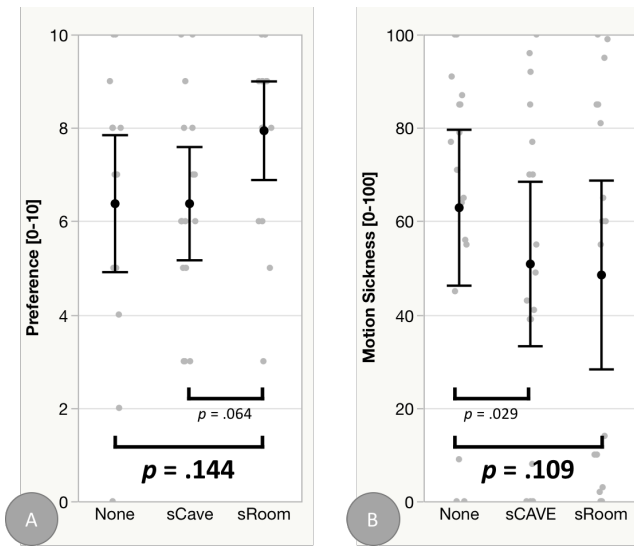

Fig. 8. Mean data of user preference and self-reported motion sickness. Error bars indicate confidence intervals ($CI = 0.95$)

ing process than the simulated room. Moreover, the simulated CAVEs movement might also be a distracting factor, although further research would be needed to investigate this explicitly. Another potential explanation for this observation is that the effect was not visible due to the limited number of participants and trials per condition.

Though frame size could be a factor contributing to the difference, with a rectangular wireframe, there is no additional visible detail except a change in edge length as long as the frame is still visible. More importantly, for a frame that moves with participants, the difference between 3x4m and 5x6.6m might not be that obvious.

Do participants need to become familiar with a simulated CAVE before they can take advantage of it? In several measures, such as travel distance, revisit, ease of use, and motion sickness, the simulated CAVE yielded results that lie between the two other conditions. In addition, previous research has also shown the equal contribution of the two kinds of frames, egocentric and allocentric, in spatial updating tasks [17]. In some situations, the egocentric frame was even dominant [23]. In this experiment, participants even rated simulated CAVE to be the least motion sick condition. For these reasons, we believe that if participants could get more familiar with this reference frame, they might be able to use it more efficiently. In the current study, we merely asked participants to do a single trial per condition because we wanted to reduce the potential for motion sickness. But

this also poses a limitation for this study. Due to this design decision, we have not only a limited number of participants, but also only a small number of trials per condition, which reduced our power to detect potential effects. Some participants whose first condition was the simulated CAVE reported that they did not notice the frame because they did not feel they needed it. Based on the exit interviews, participants might have taken advantage of the reference frame more efficiently after experiencing the no reference frame condition, as they reported to be much more aware of the difficulties in maintaining spatial orientation without any reference frame.

5 CONCLUSION & FUTURE WORK

The ultimate goal of this work is to empower spatial orientation in virtual environments that is as effective as in the real world. One of the explanations for disorientation in VR is the lack of automatic and obligatory spatial updating. Previous research has suggested that physical motion cues are necessary to address this problem. Yet, previous work found that physical motions might not be enough to prevent disorientation [35]. Also, reference frames have been identified to support the spatial updating process [17, 10]. Based on these insights, our work thus investigated a reference frame within a spatial cognition study and visualized such frames as overlaid rectangular boxes in the virtual environment. This study extends previous results by testing the effect of the simulated reference frames on spatial orientation in VR.

While previous studies showed clear benefits of reference frames in a spatial updating task, the current study provides first evidence that simply adding very basic visually simulated reference frames to the virtual scenes can significantly enhance user performance. That is, adding visually simulated reference frames consisting of only a simple wireframe rectangular box was enough to help VR users complete a navigational task in shorter times, with less revisits, and with shorter trajectories. Moreover, the presence of these frames did not yield any significant negative effect on the usability, user comfort, simulator sickness, or enjoyment during the VR experience. Our results provide fundamental knowledge for VR spatial researchers and VR-content designers on how to assist users in maintaining spatial orientation by adding visually simulated reference frames to their virtual scenes.

As previous research has suggested that locomotion modes can substantially affect navigational performance [6], it would have been useful to compare different locomotion interfaces. In the pilot study, we tried to investigate this cross effect by comparing the joystick to a leaning-based interface, but had to abort that experiment design due to excessive motion sickness, which was most likely due to participants' fast movements and accelerations.

For the next steps, we would investigate if different locomotion interfaces might modulate the benefit of simulated reference frames, e.g., with an actual walking condition. The potential to compare with such a condition motivated our design with a circular area of 5 me-

ter diameter for the navigational search task. However, limitations through cables and rapid participant movements make this challenging. Here, we focused on the nature of reference frames, i.e., egocentric versus allocentric frames. It would be interesting to consider different aspect of a simulated reference frame, such as shape (rectangular, spherical, cylindrical) and size. Though the sizes of simulated frames in this study were slightly different, we believe any difference was fairly inconspicuous. In future studies, we plan to investigate these aspects more carefully. Investigating the conditions under which spatial orientation is improved will not only deepen our understanding of human spatial cognition, but can also guide the design of more effective VR simulations. Applying a simulated reference frame to other locomotion interfaces and/or other locomotion modes, such as flying or teleporting, is another planned step toward that goal.

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