International Conference on Artificial Reality and Telexistence
Eurographics Symposium on Virtual Environments (2024)
S. Hasegawa, N. Sakata and V. Sundstedt (Editors)

Influence of Virtual Reality Setup on Locomotion Technique Usage during Navigation with Walking, Steering and Teleportation

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Abstract

The evaluations of Locomotion Techniques (LTs) provide information regarding the advantages and shortcomings of LTs for navigating in Virtual Reality (VR). While the primary approach is to assess the LTs separately (e.g., comparing walking versus steering versus teleportation), little is known about how LTs can be used simultaneously (i.e., how users navigate when several options are offered), especially in different VR setups. This paper aimed to investigate the influence of real and virtual environment size on LT usage during VR navigation for the first time. We conducted a user study (n=24), where participants had to explore a virtual garden and pick up mushrooms. Participants could choose to walk, steer, or teleport. We varied the size of the virtual environment as well as the size of the user's physical workspace. We found that users' LT usage depends on the VR setup. For instance, they tend to do more displacements with teleportation (which was users' favorite technique overall) but would rather walk or steer when the size of the virtual environment is the same as the workspace. This work contributes to understanding user behavior in VR, particularly regarding LT usage, which tends to be an overlooked topic.

CCS Concepts

• ***Human-centered computing*** → ***Virtual reality; User studies;***

Figure 1: *Left - Participants could freely choose between three locomotion techniques (walking, steering, teleportation) during the navigation task. Right - User's view when using the 2:1 Turn technique: top - the user is requested to perform a half-turn rotation to gaze at a sphere; bottom - once the gaze is aligned with the sphere, we ask the user to walk towards to reset the view of the VE.*

1. Introduction

Navigation is an essential interaction task in Virtual Environments (VEs) that consists of controlling the virtual position of the user [LKMP17], involving two main subtasks: traveling, user's control of movement through the VE [CGBL98], and wayfinding, the ability to update the self-position and orientation relative to the known places in the environments and defining a path through it [DS96]. This paper only focuses on the traveling part and how the Locomotion Techniques (LTs) can influence the subcomponents of traveling such as exploration, search, and maneuvering [BJH99]. We excluded wayfinding, which relies more on a cognitive process. The evaluations of Virtual Reality (VR) interfaces can be complicated because they involve additional factors than traditional human-computer interfaces, such as the physical environment (e.g., size of the workspace, users sitting or standing), multi-modal input generating a lot of activity logs, or users-related issues (e.g., VR can cause sickness or fatigue, the user experience with VR can impact the usability and comfort in VR). Besides, the design space of LT evaluations is very vast, which means that it is unrealistic to have exhaustive evaluations assessing every factor. This means that the current and past evaluations of LTs can lead to an overgeneralization (i.e., where claims regarding the properties of LTs are not further discussed) and lack reproducibility (i.e., making sure that the observation remains with similar conditions) of results that compare one or several techniques in a user study [ZW23].

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DOI: 10.2312/egve.20241377

Bowman et al. proposed one of the most used VR evaluation methodologies in several publications [BKH97,BKH98,BDHB99], where they describe the central methodology and required components to assess LTs. Many studies focused on comparing the benefits and shortcomings of LTs, particularly regarding walking, steering, and teleportation [ZMF18]. Those studies showed, in general, that walking is the most ecological approach for exploring VEs but is limited to the physical user's workspace; steering enables continuous trajectories but can lead to some cybersickness; teleportation enables one to travel faster in larger VE but can lead to some disorientation. Most of those evaluations compared each LT separately using within-subject design (e.g., testing walking, then steering, then teleportation) and considered only one size of VE and one size of workspace, which may influence how the user navigates with the different LTs. Thus, little is known regarding what the users would do if (1) we allow them to use every technique during a task (i.e., having the choice to switch between walking, steering, and teleportation) and (2) if we ask them to perform a similar task with different VR setups.

This paper reports to our knowledge the first VR study comparing simultaneous LTs with different real environments (REs) and virtual environment sizes. We conducted a user study to investigate how the size of VEs and REs could influence 'LT usage during pickup tasks. We introduce the concept of *user's navigation state*, which represents which technique is used; we present a first exploratory analysis for modeling the user navigation state while performing the task using discrete Markov chains and n-grams. Our results contribute to understanding user locomotion behavior and preferences during navigation in VR, and we discuss the design of LTs, which could improve users' experience.

2. Related Work

2.1. LTs for Navigating in VR

Walking is accepted to be the most ecological approach to navigate in a VE, as it better matches real locomotion tasks. However, the limited size of the physical workspace often prevents us from using it in most VR setups. Several ways exist to manipulate users' rotations and translations to increase walking in the restricted workspace. The main approach consists of increasing the user's translation, but they are not the focus of our study; for further detail, please refer to [NSSN18]. Another approach is to reset the user position (i.e., to replace the user at the center of the workspace) while trying not to break user immersion. For example, [WNR*07a] designed three overt techniques to fulfill this requirement: freeze-backup, the freeze-turn, and the 2:1 turn. These three techniques allow the users to infinitely walk in the VE while being recentered at the center of the workspace when they reach boundaries while minimizing the number of resets.

In contrast, steering techniques [BJH01] are by far the most employed in most VR applications and only require a small workspace. They are mainly characterized by how the user provides the navigation direction and speed [LKMP17]. The navigation direction is typically provided by a user's body segment, such as the head, the hand, or the torso, and is defined by pointing or looking toward the desired direction [BOMA20]. Then, the navigation speed is determined by a control law that defines the navigation speed depending on the user's inputs (discrete, e.g., a button press, or continuous, e.g., a joystick). However, steering and automatic techniques do not provide proprioceptive or vestibular information about walking and, therefore, can decrease spatial awareness [CBCWS18] and the potential increase of motion sickness [SCMW08].

To enable to reach longer distances in the VE faster than walking and steering, teleportation can be used. The user's viewpoint can be updated instantly, with a fixed speed to provide optical cues [BMF18], or with reorientation mechanisms so that the user would remain at the center of the workspace [FRK14, LPAZF18], or even with jumping metaphor [BSB11]. While most teleportation techniques use a hand-held controller to select the future direction, other inputs can be considered (e.g., the feet [vWSM*20]). Teleportation is one of the most common LTs for navigating VEs and has been extensively studied. For further information about teleportation in VR for single users, please refer to [PAF21].

2.2. Evaluations of Walking, Steering, and Teleportation

In the VR community, walking is considered the most ecological approach for navigating in VEs since the users' motion in the real and the virtual environments are the same, thus providing an intuitive interface for users. However, research work has been done to show the benefits of walking versus the use of virtual locomotion techniques. First evaluations showed that walking increases the presence compared to steering [UAW*99] thanks to the proprioceptive and vestibular feedback provided by walking [SUS95]. Besides, walking induces fewer cybersickness symptoms than virtual steering techniques during straight navigation tasks in VEs [JM01], which was confirmed in a more recent study comparing walking and teleportation in see-through augmented reality [SSH20]. However, the type of task can influence these results. [SFR*09] showed that during short exposure (five minutes) in a virtual complex 3D maze, walking increased cybersickness scores more than head steering. Another work indicated that virtual LTs increase spatial working memory demands compared to walking and that locomotion with a lower FOV increases general attentional demands [MKDO13]. Regarding performance in achieving different tasks in a VE, Ruddle et al. conducted several experiments regarding the benefits of walking compared to other techniques. First, walking with complete body-based information provided better search results than the other techniques [RL06]. They confirmed these results in another experiment where walking yielded less imperfect search than the head steering or joystick control with monitor [RL09]. Last, they revealed potential limitations of their original findings where steering techniques could provide similar performance results than walking during a search navigation task [RBM*10]. Regarding spatial awareness, walking generates less turning error than other LTs and provides lower distance estimation [WKMW16].

Steering and teleportation are often compared. In one experiment, participants had to go from one point to another (information was given through a map) and collect tokens in a VE [CA17]. They reported that task completion was faster with teleportation than steering and lower cybersickness scores. Similar results were found in another study in a point to origin task [WKFK18]. In terms of presence, they both seem to provide similar immersion, but teleportation seems more usable than steering in goal-directed tasks [BC19]. [LLS18] also demonstrated in their experiment that users prefer teleportation over steering, which also provided higher cybersickness. A recent study investigated the influence of heading selection and control laws with steering techniques [GMTD21]. Participants had to perform a straight motion, and the results demonstrated that linear control allow them to travel faster but with less trajectory precision. On the contrary, the non-linear control law provided a slower travel timer but better trajectory precision. Concerning the virtual trajectories achieved with steering techniques, [COMP13] showed that in the case of navigation with different LTs (steering, leaning, keyboard), the control of the trajectory was similar, even though continuous interfaces were more conform with the kinematics of accurate walking trajectories than virtual interfaces. LT navigation performance can also increase over time. Nasisir et al. investigated how novice users navigate VR with steering or teleportation over time [NPKR23]. Their results showed that performance improved faster with steering than with teleportation, but spatial performances improved faster with teleportation than steering.

Since a vast number of factors, including the design of the LTs, the type of task to perform, the metrics to assess the study, and the human factors can impact users' behavior while using LTs, some work focused on taxonomies for describing the relationships between LTs [PMW22]. While several taxonomies and classifications have been done to understand better the shared characteristics of similar techniques, some meta-analysis of LTs showed that some LTs could be identical and clustered to understand better the similarity and the extensions of results conducted in some studies [DLSEGF21]. Walking, steering, and teleportation are three distinct techniques that achieve different purposes and provide different user behaviors regarding performance and spatial awareness that can be considered to maximize one factor or another based on the navigation task. However, a recent survey of LTs in commercial VR applications showed that teleportation is still the most used technique; steering is being more and more adopted by practitioners, and while walking is investigated a lot in academia, practitioners are not using them due to workspace limitations [ACST24].

3. User Study

Most of the evaluation studies of LTs focus on a between or within-subject design where each LT is assessed separately. To the best of our knowledge, no studies allow participants to use every LT simultaneously to understand why participants would instead use one technique or another based on the VR setup (i.e., VE and WS sizes). We know the benefits and drawbacks of each LT (walking, steering, teleportation), but we do not know whether participants would take advantage of each technique to perform a given task.

3.1. Locomotion Techniques and Navigation States

Participants could perform the task with three LTs: Walking (including a resetting technique), Head-Steering, and Teleportation. Walking was an isometric mapping between the motion in the RE and the VE (i.e., walking 1 meter in the RE resulted in walking 1 meter in the VE). To allow participants to perform the task only with walking if they wanted to, we implemented an overt reset technique (*2:1 Turn*) based on [WNR*07b]. Whenever the user faces the borders of the tracked area, the environment freezes, and the user is requested to do a half-turn (Figure 1). The turn is completed if the player is gazing at a sphere, which is situated in the center of the room, thus urging the player to make a turn. When the user is looking at the sphere, the virtual environment unfreezes. It is worth highlighting that the virtual world did not change in this scenario. Hence, the user can continue to walk as usual. The player will stop their natural walking path when colliding against the borders of the tracked area to perform the necessary turning motion and can proceed afterward.

Regarding steering, the virtual movement was initiated using the Meta Quest controller's joystick, but the head orientation defined the heading. Even though it has some limitations for searching tasks, we chose the head as the heading direction to navigate in the VE as it does not require additional hardware compared to torso steering and is primarily implemented in VR setups. In addition, we considered the joystick as a binary input as it is easier for users to navigate with constant control law than linear [BOMA20]. When the joystick is pressed, movement is initiated with an acceleration of $10m/s^2$ until a maximum tangential speed of $2m/s$ is reached; at this point, the speed remains constant. If the joystick is released, a deceleration of $-10m/s^2$ is applied to reach a speed of $0m/s$ in approximately 0.30 seconds.

Teleportation allowed the user to change their position from one point to another in the VE. By pressing the left controller trigger, a virtual white ray appears to select the future destination. We added a visual indication by ray casts that update the valid destinations for the users to prevent collisions with the VE or going beyond the virtual fences and leaving the VE when selecting the future virtual position. The users were instantly moved to the selected VE destination by releasing the trigger. Users could cancel the teleportation by pressing a button on the left controller. To have a fair comparison between the different LTs while keeping the advantages of each technique, we set a maximum distance where users could teleport to 4m (that corresponds to the width of the workspace in our experiment; see subsection 3.2). This still enabled users to, in practice, travel faster with teleportation than with walking or steering, but would require to use the teleportation several times to reach the boundaries of the VEs as in steering or walking.

Since participants could choose which LTs to select during the task, we also designed an algorithm that detects in which Navigation State (NS) the user is across time. We defined four different states: None (*NS-None*), Walking (*NS-Walk*), Steering (*NS-Steer*), and Teleportation (*NS-Teleport*). The navigation state was updated and recorded in every frame. *NS-Steer* corresponded to whether or not the controller joystick is pressed. *NS-Teleport* was set whether the controller's trigger was pressed or not, encoding the duration to choose the next destination. *NS-Walking* navigation state was defined as a displacement of at least 10cm of the user's headset over the window time of 0.1 seconds. *NS-None* navigation state was set should any of the above states were not set, resulting in an unmoving user not using any of the LTs.

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3.2. Experimental Design and Hypotheses

The navigation task was to search and gather mushrooms in a garden-like environment while not colliding with the obstacles present in the VE (Figure 2). We chose this pickup task as it requires exploration of the entire VE to collect the mushrooms, and such protocols have already been used in similar work [DHLA20]. Two types of mushrooms with different colors and shapes (cylindrical brown and spherical red) were present in the VE, and participants should only pick up the red one to ensure that they were paying attention to the task. To investigate the influence of physical and virtual environments on user navigation behavior, our experiment had a two Workspace Size (**WS-Size**: WS-Small, WS-Medium) x 3 Virtual Environment Size (**VE-Size**: VE-Small, VE-Medium, VE-Large) within-subject design. **WS-Size** referred to the size of the physical workspace. The Small **WS-Size** (referred after as *WS-Small*) was 2 by 2 meters, as it is the minimal room-scale workspace size required for running SteamVR applications. The Medium **WS-Size** (*WS-Medium*) was 4 by 4 meters, which represents a recommended **WS-Size** by Meta and Steam. **VE-Size** referred to the size of the VE. We defined the Small **VE-Size** (*VE-Small*) as a room-scale VE (4 by 4 meters), the Medium (*VE-Medium*) as 10 by 10 meters (more extensive than WS-Medium), and the Large (*VE-Large*) as 20 by 20 meters. The experiment comprised 6 blocks corresponding to a combination of **WS-Size** and **VE-Size**. Each block was counterbalanced using a Latin square design. A trial consisted of navigating the VE for three minutes and collecting as many brown mushrooms as possible.

Users could navigate in the VE by using any of the techniques presented in subsection 3.1, which means they could alternate between those three techniques depending on their own will. Based on our analysis, we hypothesized that the workspace and virtual environment size could affect participants' navigation behavior and, more precisely: **[H1]** - The **VE-Size** will affect the distribution of usage and distance achieved per LTs. In particular: **[H1.1]** - the bigger the **VE-Size**, the more inactive users will be (i.e., higher NS-None detection); **[H1.2]** - the higher the **VE-Size**, the more users will teleport; and **[H1.3]** the smaller the **VE-Size**, the more users walk. **[H2]** - The **WS-Size** will affect the distribution of usage and distance achieved per LTs. In particular: **[H2.1]** users will be less active in WS-Small than WS-Medium (i.e., higher NS-None detection); **[H2.2]** - users will less teleport in WS-Medium than WS-Small; and **[H2.3]** users will walk more in WS-Medium than WS-Small. **[H3]** - Users will subjectively prefer Teleportation over Steering over Walking for navigating.

While most of the related work showed the benefits of using each LT individually between Walking, Steering, and Teleportation, our motivations are to investigate whether users would use more or less some LTs if we offered them the freedom of choosing a technique. Our hypotheses are similar to results already found in previous studies (section 2), where we would say that users maximize the advantages and shortcomings of each technique to perform the task (i.e., traveling faster with teleportation in bigger VE, walking more if the workspace is bigger...)

3.3. Participants and Apparatus

A total of 24 participants (14 males, 10 females) aged from 22 to 38 years old ($M = 29.5$; $SD = 4.15$) participated in the experiment. 16 participants had only one or no prior experience with VR, whereas 8 participants had regular experience with VR. They signed an informed consent form and were naive to the purpose of the experiment. No ethical approval was required by our institution to conduct the study, which conformed with the standards of the Declaration of Helsinki. The headset used for the experiment was a Meta Quest 1 with its controllers (Figure 1). The experimental platform was guaranteed to run at the minimum of the headset's frame rate (72Hz). The VE was developed with Unity3D (version 2021.3.31f) and was a square garden with fences to define the boundaries of the VE (Figure 2). We used a grass texture for the floor and different obstacle elements such as trees, rocks, bushes, and flowers to prevent linear trajectories. A procedural generation of the VE was used to prevent learning effects. The mushrooms were put on a one-meter-high tree stump so users would not have to crouch to collect them from the ground. To avoid bias regarding the performance task (i.e., collect as many mushrooms as possible), the density of mushrooms depended on the **VE-Size**. We also procedurally placed the mushrooms at different locations, and we guaranteed that the distribution of mushrooms would be equal between VEs, which corresponded respectively to 4, 24, and 48 mushrooms for the *VE-Small*, *VE-Medium* and *VE-Large*. The proportion of red and brown mushrooms was equal (i.e., half red, half brown). When a participant collected all red or brown mushrooms, we respawned a new set at different randomized locations with the same density property. The limits of the user's workspace were represented by a transparent black plane (see Figure 2). We turned off the Meta Quest guardian system to prevent breaks in the user's presence and used our resetting technique instead (see subsection 3.1).

3.4. Procedure

Before starting the experiment, participants were briefed on the study (i.e., instructions and explanations about the task, including information about rotational gain), provided written consent, and completed a demographics questionnaire (covering age, gender, and experience of VR). Subsequently, participants were equipped with the necessary hardware and engaged in a training session to become familiar with the three different LTs and the picking mushroom task. The experiment consisted of 6 trials, where one was a combination of a **WS-size** and **VE-Size**. At the start of the trial, the users had to calibrate by placing themselves at the center of the workspace, represented by a small yellow plane on the ground. Then, they pressed a button on their controller to start the trial, and the calibration plane disappeared. The users performed the navigation task by collecting as many mushrooms as possible while minimizing collisions with the VE. After three minutes, the trial ended, and the user took off the headset and filled out a subjective questionnaire for this condition, including the following questions: (1) "Which technique did you prefer the most to navigate in the virtual environment? Sort the techniques from the most preferred to the least preferred." "(2) Did you have a particular strategy to navigate during the tasks? (e.g., using a particular technique for a given situation, such as the path to collect mushrooms)". After filling out

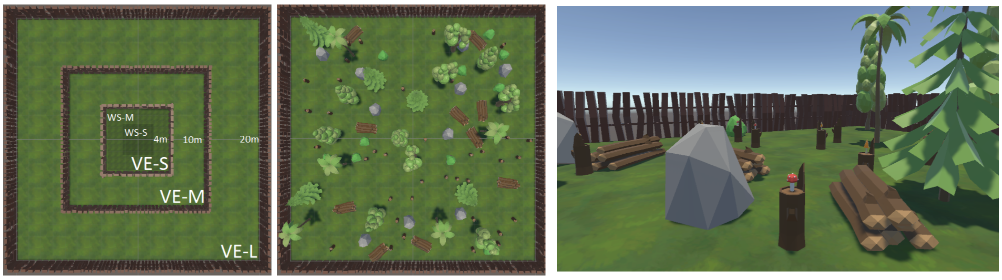

Figure 2: *Left - Empty Top view of the VEs (overlaid). We can notice at the center the two transparent black workspace sizes (only one was displayed depending on the condition). Middle - Example of a random generation of the VE-Large environment. Right- User's point of view in the VE.*

the subjective questionnaire, a new **WS-Size** and **VE-Size** conditions were set for the subsequent trial. Users were allowed and encouraged to take breaks during the experiment between trials. The experiment lasted approximately 45 minutes, including pauses, explanations, questionnaires, and the experimental protocol.

3.5. Data Processing and Analysis

We recorded data for each trial. Objective data were recorded for each frame and included the time of the trial, the users' head position and orientation in both RE and VE, the users' navigation state, the users' traveled distance in VE and RE, the number of mushrooms (red and brown) collected and the number of collisions with the VE. Subjective data were collected after each condition and included the questions to assess cybersickness, the ranking of the techniques in terms of preferences, and open questions regarding the strategy to navigate during the condition. We collected 144 trials, (24 users x 3 **WS-Size** x 2 **VE-Size**). As every trial lasted three minutes and was recorded at 72Hz (resulting in 12 960 frames recorded), we did not have to resample the data to compare them. We computed the traveled distance over a trial as the sum of the user's headset displacement in both VE and RE and the distance achieved per LT (walking, steering, teleportation). We also computed the percentage of NS detection of each LT as the ratio between the number of occurrences of an NS during the trial and the number of frames, then multiplied by 100.

For normally distributed metrics, assessed using the Shapiro-Wilk test, we analyzed variance (ANOVA) with repeated measures factors. Greenhouse-Geisser adjustments were applied to the degrees of freedom when the sphericity assumption was violated. For metrics that deviated from a normal distribution, we used the non-parametric Aligned Rank Transform (ART) test [WFGH11]. The post-hoc analysis involved pairwise t-tests with Bonferroni corrections for customarily distributed dependent variables or the multi-factor contrast test procedure presented in [EKHW21] for the non-normally distributed ones.

4. Results

4.1. Task Performance

Table 1 shows the mean and standard deviations for the objective metrics related to the task (collisions, number of mushrooms collected, distance achieved in RE and VE). A two way ART-ANOVA with **VE Size** and **WS Size** as within subjects factors showed no significant effect of **VE Size** ($F_{2,115} = 1.27$, $p = 0.28$) or **WS Size** ($F_{1,115} = 0.36$, $p = 0.55$) on collisions with the VE. However, we noticed a significant effect of **VE Size** on number of mushrooms collected ($F_{2,115} = 113.42$, $p < 0.001$, $\eta_p^2 = 0.69$), where posthoc tests showed that more mushrooms were collected in the **VE-S** than the others. Regarding distance achieved in RE, we noticed a significant effect of **VE Size** ($F_{2,115} = 138.47$, $p < 0.001$, $\eta_p^2 = 0.71$) on distance achieved in RE, where posthoc tests showed that more physical motion was completed in the **VE-S** than in the **VE-M** and **VE-S**. Regarding distanced achieved in the VE, we noticed a significant effect of **VE Size** ($F_{2,115} = 143.59$, $p < 0.001$, $\eta_p^2 = 0.70$), where posthoc tests showed that more virtual motion was achieved in the **VE-L** and **VE-M** than **VE-S**.

Table 1: *Mean and Standard deviation of objective metrics related to the task grouped by **VE Size** and **WS Size**. Main effects are reported with * for **VE-Size** (no effect was found for **WS-Size**). Posthoc tests are reported using superscripts. Two levels sharing the same superscript are not significantly different.*

	Collisions	Mushrooms*	Dist RE (m)*	Dist VE (m)*
VE-S	3.35±2.06	48.71±8.49^1	17.81±4.21^1	75.39±10.22^1
VE-M	2.73±2.10	27.02±6.66^2	10.47±3.47^2	144.79±24.97^2
VE-L	3.23±2.07	25.12±5.54^3	9.16±2.17^2	139.81±28.35^2
WS-S	3.04±1.82	32.8±13.35	12.21±2.47	118.18±39.10
WS-M	3.16±2.23	34.40±12.25	12.10±6.90	121.81±38.8

4.2. Usage of techniques

Regarding the percentage of detection of navigation state (Figure 3), a three-way ART-ANOVA with **NS**, **VE Size** and **WS Size** as within-subjects factors showed a significant effect of **NS** ($F_{3,529} = 862.43$, $p < 0.001$, $\eta_p^2 = 0.83$), where post-hoc showed that the navigation state distributions followed that following patterns: %NS-None (48.23±7.72) > %NS-Walk (22.71±8.42) > %NS-Steer (17.46±5.87) > %NS-Teleport (11.58±4.27). When we considered the **NS** individually, we conducted two-way ART-ANOVA with **VE Size** and **WS Size** as within-subjects factors for the detection of NS. Table 2 summarizes the main effects found and pairwise comparison: **% NS-None -** We observed an effect of **WS-Size** and

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VE-Size, where post-hoc showed that NS-None was more detected in the WS-Small than WS-Medium, and more in VE-Medium and VE-Large than VE-Small. **% NS-Walk -** We observed an effect of **WS-Size** and **VE-Size**, where post-hoc showed that NS-Walk was more detected in the WS-Medium than WS-Small, and more in VE-Small than VE-Medium and VE-Large. **% NS-Steer -** We observed an effect of **WS-Size** and **VE-Size**, where post-hoc showed that NS-Steer was more detected in the WS-Medium than WS-Small, and more in VE-Large than VE-Medium than VE-Small. **% NS-Teleport -** We observed an effect of **WS-Size** and **VE-Size**, where post-hoc showed that NS-Teleport was more detected in the WS-Small than WS-Medium, but no differences were observed between **VE-Small**, **VE-Medium** and **VE-Large**.

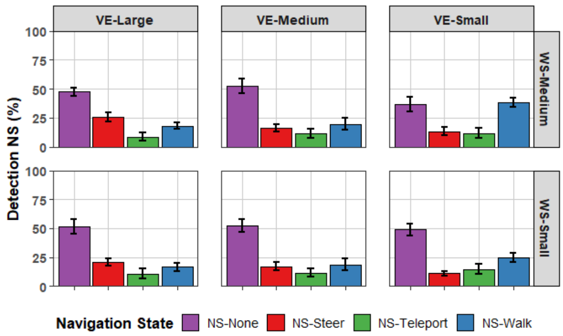

Figure 3: *Bar plots showing the mean and standard deviation of Detection (in percentage) of NS per NS, WS-Size, and VE-Size.*

Regarding the distance achieved per navigation state (Figure 4), a three-way ART-ANOVA with **NS**, **VE Size** and **WS Size** as within-subjects factors showed a significant effect of **NS** ($F_{2,391} = 1645.03$, $p < 0.001$, $\eta_p^2 = 0.89$), where post-hoc showed that users achieved more distance with Teleportation (141.41±54.25) than Steering (31.31±9.1) than Walking (12.15±5.24). We also considered the **NS** individually and conducted two-way ART-ANOVA with **VE Size** and **WS Size** as within-subjects factors for the distance achieved per LTs. Table 2 summarizes the main effects found with pairwise comparison: **Dist NS-Walk -** We did not observe an effect of **WS-Size**, but we observed an effect of **VE-Size**, where post-hoc showed that the distance achieved in walking was higher in VE-Small than VE-Medium and VE-Large. In addition, we observed an interaction effect of **VE-Size** and **WS-Size** on distanced achieved in RE ($F_{2,115} = 166.41$, $p < 0.001$, $\eta_p^2 = 0.75$), where posthoc tests showed that the highest physical motion was achieved in the **WS-M, VE-S** condition ($M = 21.54$; $SD = 2.01$). **Dist NS-Steer -** We observed an effect of **WS-Size** and **VE-Size**, where post-hoc showed that the distance achieved in steering was higher in the WS-Small than WS-Medium, and higher in VE-Small and VE-Large than VE-Medium. **Dist NS-Teleport -** We did not observe an effect of **WS-Size**, but we observed an effect of **VE-Size**, where post-hoc showed that the distance achieved in teleportation was higher in VE-Large than VE-Medium than VE-Small.

4.3. Subjective Questionnaires

Regarding ranking the preferences between the techniques after each block, Figure 5 shows the ranking distribution for each LT (either ranked first, second, or third) per **WS Size** and **VE Size**. We can observe that for both **WS Size**, the distribution of ranking is similar participants ranked teleportation as the most preferred technique (46 for both) followed by steering (45 for **WS-Small**, 53 for **WS-Medium**) and then walking (48 for **WS-Small** and 50 for **WS-Medium**). Similar observations were found for the **VE-Large** (40 first-rank teleportation, 39 second-rank steering, 45 third-rank walking) and **VE-Medium** (36 first-rank teleportation, 36 second-rank steering, 37 third-rank walking). However, for the **VE-Small** environment, the distribution was different, where we observed a similar count for the ranked technique (17 steering, 16 teleportation, and 15 walking).

5. Discussion

5.1. Influence of VE-Size on Locomotion Technique Usage

In this experiment, we wanted to see whether the same task within different VE sizes would influence how users navigate. We chose the pickup mushroom task as it involved exploration, recognition, and collection of objects which are similar to what users would do in some VR games (e.g., gathering, gardening, mining). As observed on Figure 3, the most detected navigation state was NS-None, followed by NS-Walk, NS-Steer, and NS-Teleport. Users usually spent half of the trial not using the LTs. It does not mean they were not doing anything. For instance, they could have gathered information in the VE to find the mushrooms and decide the next destination and LT to choose, or they could have taken some time to update their spatial awareness. In particular, we noticed that users were more in NS-None when the VE was bigger (Figure 3). This makes sense as participants may need to pay more attention to a larger area where the mushrooms were located before initiating their next movement. We then confirm our hypothesis **[H1.1]**.

However, while teleporting was the least NS detected (since it requires less time to achieve distance compared to walking or steering), we noticed that users were traveling more with teleportation than the other techniques (Figure 4) and that they were even more traveling with teleportation with bigger **VE-Size** (Table 2). We can perform the task entirely with only one LT if the user wants to. Still, it seems pragmatically more efficient to use teleportation as the size of the VE starts to be bigger than the workspace. This confirms **[H1.2]**, where teleportation has already shown its benefits over steering and walking when achieving quick travel. Nevertheless, it is worth noticing that being fast does not necessarily mean being more efficient since the number of mushrooms collected was smaller in VE-Large (Table 1). We suggest that this difference is due to the spatial disorientation that teleportation may produce, as already observed in previous work [BC23].

Similarly, we observed that users tended to walk the most in the VE-Small, where the distance was almost twice as much compared to VE-Medium and VE-Large (Table 2). We suggest that the room-scale size of the VE invites users to perform the task as they would do in real life by naturally moving. This behavior has already been observed between walking and teleportation [SSH20], which confirms **[H1.3]**. Overall, our work showed that users may navigate differently depending on the **VE-Size**, where walking was more used in VE-Small, steering in VE-Medium, and teleportation in VE-Large, which confirms **[H1]**.

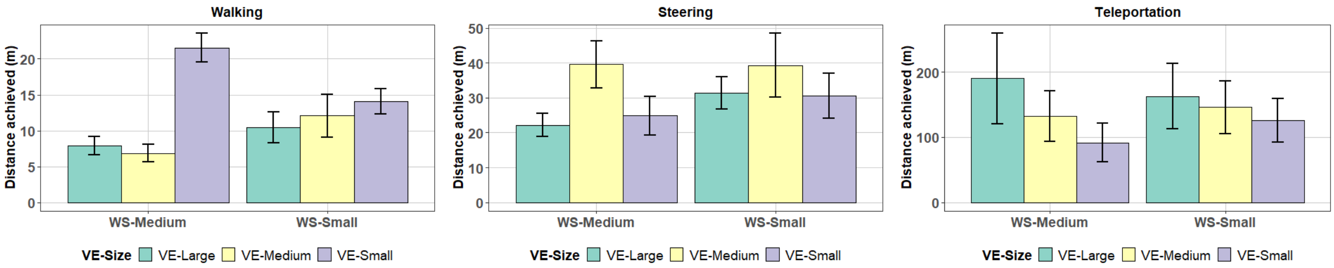

Figure 4: *Bar plots showing the mean and standard deviation of Distance achieved per LTs, WS-Size, and VE-Size.*

Table 2: *Mean and standard deviation, reported as M±SD, for usage of LTs metrics (% of NS detected and distance achieved by LTs), grouped by **WS-Size** and **VE-Size**. The two effect columns report whether there was a significant effect of **WS-Size** and **VE-Size**. Post-hoc tests for main effects are reported using superscripts. Two levels sharing the same superscript are not significantly different.*

	WS-Small	WS-Medium	Effect	VE-Small	VE-Medium	VE-Large	Effect
% NS-None	50.90 ± 5.59^1	45.55 ± 8.62^2	$F_{1,115} = 43.53$, $p < .001$, $\eta_p^2 = .27$	42.87 ± 8.38^1	52.29 ± 5.83^2	49.52 ± 5.39^2	$F_{2,115} = 44.80$, $p < .001$, $\eta_p^2 = .46$
% NS-Walk	20.11 ± 5.51^1	25.89 ± 9.94^2	$F_{1,115} = 59.48$, $p < .001$, $\eta_p^2 = .34$	31.53 ± 7.67^1	19.33 ± 4.93^2	17.27 ± 3.36^2	$F_{2,115} = 132.40$, $p < .001$, $\eta_p^2 = .69$
% NS-Steer	16.50 ± 5.01^1	18.42 ± 6.51^2	$F_{1,115} = 11.01$, $p < .01$, $\eta_p^2 = .01$	12.30 ± 2.93^1	16.68 ± 3.54^2	23.41 ± 4.46^3	$F_{2,115} = 140.82$, $p < .001$, $\eta_p^2 = .71$
% NS-Teleport	12.47 ± 4.40^1	10.70 ± 3.97^1	$F_{1,115} = 9.64$, $p < .01$, $\eta_p^2 = .08$	12.29 ± 4.56^1	11.69 ± 3.61^1	10.78 ± 3.90^1	$F_{2,115} = 12.18$, $p < .001$, $\eta_p^2 = .17$
Dist NS-Walk	12.21 ± 2.76	12.10 ± 6.90	$F_{1,115} = 0.07$, $p = 0.78$	17.81 ± 4.20^1	9.48 ± 3.47^2	9.16 ± 2.17^2	$F_{1,115} = 138.4$, $p < .001$, $\eta_p^2 = .70$
Dist NS-Steer	33.77 ± 7.95^1	28.86 ± 9.38^2	$F_{1,115} = 22.43$, $p < .001$, $\eta_p^2 = .16$	27.68 ± 6.61^1	39.44 ± 7.98^2	26.83 ± 6.15^1	$F_{2,115} = 60.27$, $p < .001$, $\eta_p^2 = .51$
Dist NS-Teleport	144.77 ± 44.06	138.04 ± 62.96	$F_{1,115} = 1.97$, $p = 0.17$	108.88 ± 35.66^1	139.06 ± 39.97^2	176.29 ± 61.30^3	$F_{2,115} = 25.21$, $p < .001$, $\eta_p^2 = .30$

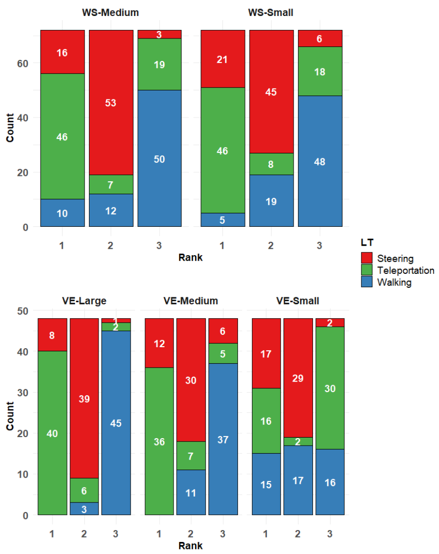

Figure 5: *User subjective ranking of LTs per **WS-Size** (top row) and **VE-Size** (bottom row).*

5.2. Influence of WS-Size on Locomotion Technique Usage

Another factor that we were interested in our study was the workspace size, which is a major limitation of navigation in VR setups, as users cannot physically explore larger VEs. We wondered whether the users would navigate differently depending on whether they have more physical workspace. As observed on Table 2, participants had less NS-None detection in WS-Medium, particularly with VE-Small. We suggest that providing a higher workspace would motivate the users to move more or be less careful about reaching the limits of the workspace and thus reduce the moment when they are idle. We thus validate **[H2.1]**, but future work is required to explore how workspace size and shapes can influence user engagement in VR. Indeed, those results might not be generalized, as our workspace and VE had the same shapes, which is unlikely in most VR applications. As such work has already been done for redirected walking [MHB19], we could imagine similar studies to understand how we could influence users to use one technique over another based on the VR setup.

Regarding teleportation usage, we did not observe the difference in NS-Detection and distance achieved between WS-Small and WS-Medium (Table 2). Contrary to the results for the **VE-Size**, we expected less teleportation by providing a bigger workspace that would increase walking (which we also did not observe). Still, we saw higher steering usage in the WS-Small as an alternative to teleportation. We rejected both **[H2.2]** and **[H2.3]**, where teleportation and walking behavior were similar across **WS-Size**. Future analyses should deepen the interaction influence between **WS-Size** and **VE-Size** as we observed that users walked the most when the workspace size was more significant and the VE the smallest. One suggestion would be that a bigger workspace would require fewer resets for physically exploring the VEs. This may have encouraged users to move more, explaining a higher NS-Walk detection for WS-Medium than WS-Small.

5.3. Users Preferences and Navigation Behavior

Figure 5 showed that users preferred overall Teleportation, Steering, and Walking. This result aligns with the literature, where people generally prefer virtual techniques as they do not require physical movement in the workspace [LLS18]. We suggest that participants are more familiar with Teleportation and Steering as they are still the main techniques used in VR commercial applications [ACST24]. However, we noticed that the ranking differed for the VE-Small condition, where each technique had the same number of votes for the first ranking. This means that walking could remain a viable option when the size of the VE matches the size of the workspace. Yet, most studies comparing LTs often have bigger VE to demonstrate the benefits of virtual techniques and not be limited to room-scale applications. We then partially confirm **[H3]** and we sum up hereafter the takeaway messages we noticed from our user study for navigating with each LT:

Walking seems the most appropriate technique when the workspace and VE match. Our results showed that walking had the highest 1st ranking and distance achieved with an LT during the WS-Medium$\times$VE-Small condition (Figure 4). While we hypothesized that might happen, we must say that this result still surprises us as we expected users to be *lazy* and always prefer steering over walking in case teleportation is irrelevant. In addition, from our observations, walking seems to be the most appropriate as users get closer to a mushroom after teleporting or steering, as it seems more accessible for users, to be more precise. However, further analyses would be required to demonstrate which technique was most used depending on the closest mushroom distance. Last, users reported that they never intended to navigate by repeating the reset technique while walking and reset only got triggered when people were not aware of the limits of the VE anymore.

Steering was mainly used as an intermediate between Walking and Teleportation, especially when the workspace is smaller. For instance, when teleportation was not *suitable* (i.e., cannot find a mushroom or too many obstacles), users would steer to explore the VE without physical movement. This was reported as a reasonable trade-off between faster movement and walking without disorientation of teleportation. This is mainly observed in our results, where the distance achieved with Steering was higher in the VE-Medium (Figure 4). One reason why steering was less used in VE-Small might be because of the implementation (head-steering) that was preventing participants from looking around to find mushrooms while navigating. Users' strategy was reported as using this technique more after teleportation to have finer control of the trajectory to reach a mushroom. Further analysis would be required to understand how steering could be more beneficial than walking in the larger workspace.

Teleportation was, as expected, the technique that enabled faster travel in larger environments. Even though we limited the maximal distance of travel per teleportation to 4 meters, users still found this LT the most suitable for exploring. Users mostly reported that their strategy was to always consider teleportation as a potential first option after getting a mushroom if no other mushrooms were within walking range. This explains why teleportation was less used as the VE-Size decreased, as users would rather walk or steer (Figure 3). We suggest that participants felt it was harder to perform the task in smaller VEs to move precisely enough without disorientation to get as many mushrooms as possible. Future work could investigate how to improve the use of teleportation for room-scale use, like redirected teleportation [LPAZF18].

Regarding the users' navigation patterns, we often noticed the following sequence: (1) teleportation to travel further than what the workspace offers; (2) steering to the closest mushroom; (3) walking to grab the mushroom. While we believe those sequences and patterns could exist when users interact in VR, additional analysis in future work would be required to use different LTs simultaneously patterns using a similar protocol from our study.

6. Limitations and Future Work

First, we are aware that the choice and usage of LTs are likely task-dependent, preventing our results from being generalized. Future works must consider expanding the range of tasks and environments beyond the searching and selecting tasks we assessed. For instance, a higher cognitive load might influence how users choose the LTs, and additional experiments could investigate it by considering tasks involving remembering the environment's layout (e.g., escaping a maze) or using n-back tasks. Second, the insights regarding the long-term effects of using LTs should be investigated, too. In our experiment, participants only performed three minutes per condition, which minimizes cybersickness and prevents users from getting used to the task. The usage of techniques might change over time based on experience or user comfort, and further studies considering the user adaption to LTs would help to understand how users prefer to navigate over time as well as how they become familiar with each LT. Last, the range of the navigation state could be extended. In our experiment, we considered that a user was doing nothing as long as they were not using an LT. Future work could focus on improving the navigation states to model user navigation states better, including user rotation. While there exists a lot of work trying to predict the user's trajectory while navigating in VR to improve redirection-based techniques [SBL22, MCFH24, ARB22, BBM*21], there are very few works tried to understand how and why users would prefer a LT for different locomotion task (e.g., involving different size of environments) to perform in VR [NK12]. Such user behavior modeling could help VR practitioners understand when such LT is appropriate for users.

7. Conclusion

Understanding user locomotion behavior and preferences has significant practical implications for improving LTs in VR. Yet, the analysis of simultaneous uses of LTs in the literature is limited, particularly in understanding why and how VR users tend to use or prefer LTs. Overall, our study showed that users basically use all techniques that are available to them (as long as they make sense) and integrate them into their workflow to navigate. This supports earlier design suggestions to provide users with multiple different interaction techniques and they will use what fits best depending on the VR setup. However, this is only a tiny step toward the precise understanding of navigation patterns between teleportation, steering, and walking, with limitations such as generalization to more prolonged VR exposure, consideration of different models to understand the user's navigation state and potential human factors such as learning. This work opens new perspectives on evaluating LTs and could help propose adapted LTs for the user's workspace, VE size, and tasks to perform to improve the user experience.

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