Locomotion Techniques for Dynamic Environments: Effects on Spatial Knowledge and User Experiences

Hyunjeong Kim, Sang-Bin Jeon, and In-Kwon Lee

Fig. 1: Left: scene of the dynamic environment used for the experiment. The virtual character is idle in the static environment and walks naturally in the dynamic environment; Middle: a scene of the *spatial memory task* to measure spatial knowledge. Participants have to remember the content and location of seven words in pictures in a virtual art gallery; Right: a flag object and target scene used in the *target navigation task* to measure task performances. Participants must grasp the flag object and place it on the seven pink targets in order.

Abstract—Various locomotion techniques are used to navigate and find way through space in virtual environments (VE), and each technique provides different experiences and performances to users. Previous studies have primarily focused on static environments, whereas there is a need for research from a different perspective of dynamic environments because there are many moving objects in VE, such as other users. In this study, we compare the effects of different locomotion techniques on the user's spatial knowledge and experience, depending on whether the virtual objects are moving or not. The investigated locomotion techniques include joystick, teleportation, and redirected walking (RDW), all commonly used for VR navigation. The results showed that the differences in spatial knowledge and user experience provided by different locomotion techniques can vary depending on whether the environment is static or dynamic. Our results also showed that for a given VE, there are different locomotion techniques that induce fewer collisions between the user and other objects, or reduce the time it takes the user to perform a given task. This study suggests that when designing a locomotion interface for a specific VR application, it is possible to improve the user's spatial knowledge and experience by recommending different locomotion techniques depending on the degree of environment dynamism and and type of task.

Index Terms—Locomotion technique, Dynamic environment, Spatial knowledge, user experience, Redirected walking, teleportation, joystick

1 Introduction

Navigation is a fundamental element in virtual reality (VR) applications, and a lot of studies have been conducted on the design of efficient locomotion techniques for immersive virtual environments (VE) [1, 42, 46, 50, 51]. Previous studies have mainly focused on the characteristics of locomotion techniques in static environments with no changes in the VE, comparing the user experience across different locomotion techniques. However, in VR applications, there are many moving dynamic objects, such as other user characters, non-player characters (NPCs), and vehicles. These dynamic objects can interfere with the user's path or interact with the user as obstacles, and users have typically tried to navigate while avoiding collisions with them. Different locomotion techniques can lead to variations in how users control their movements in response to dynamic obstacles, potentially affecting users' task performance and experience [5, 20, 25, 47, 57]. In particular, users often use different strategies when avoiding static and dynamic obstacles [5]. Therefore, in a fresh perspective compared to previous research, it is meaningful to investigate how different locomotion techniques affect user performances and preferences depending on the degree of dynamism of the VE.

Navigation is important for exploring space and finding one's way, and users need to acquire essential spatial knowledge within the VE for effective navigation [36, 64]. An important question that is whether the choice of locomotion technique can affect the user's acquisition of spatial knowledge. From this perspective, our study is concerned with how the degree of dynamism in a given VE and the chosen locomotion technique can affect the different types of spatial knowledge acquired by users. Some studies [18, 24, 38, 48] have compared the extent of spatial knowledge acquisition by locomotion methods, but these studies used the same environmental conditions without considering the difference in whether the virtual objects are moving or not. Therefore, more research is needed to directly compare differences in spatial knowledge acquisition due to differences in the degree of dynamism of VE and movement techniques.

VR locomotion techniques are one of the most essential interaction components for navigation. Locomotion techniques are interaction techniques between the user and the VE that allow the user to move around a large virtual space within a relatively small physical space [60]. Various locomotion techniques have been proposed, usually using controllers or special algorithms developed for locomotion. The most commonly used locomotion techniques are joystick, teleportation, and redirected

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walking (RDW). When using a joystick, the user presses a stick, directional button, or pad in place to continuously move the viewpoint in a selected direction. Teleportation allows users to instantaneously travel long-range distances by jumping to a desired destination using the controller [38]. RDW is most similar to actual walking, and it allows users to navigate in VE that is considerably larger than the limited physical space [53]. The multimodal feedback provided by different locomotion techniques can increase or decrease the user's sense of usability of the locomotion technique, presence, and motion sickness, and which can also affect the user's performance or effectiveness of tasks in VR.

In this paper, we conduct a comparative study of the effects of environmental dynamics (static and dynamic) and three locomotion techniques (joystick, teleportation, and RDW) on spatial knowledge, task performances, and user experiences. Based on our findings, we can propose guidelines for VR application developers to apply different locomotion techniques in different environments to enhance users' spatial knowledge and improve task performances and user experiences. In summary, our main contributions are as follows:

- We compare the user's spatial knowledge, task performances, and user experiences according to the degree of dynamism (static and dynamic) of the virtual environment and three locomotion techniques (joystick, teleport, and RDW).
- Based on the results of the user study, we propose a locomotion interface guideline that recommends appropriate locomotion techniques depending on the type of environment.

2 RELATED WORK

2.1 Locomotion Techniques in VR

Navigation is a fundamental task consisting of the cognitive component (wayfinding) and the motor component (movement) to search for a target and explore the virtual environment [12]. Among the locomotion techniques, the most natural way to move is bipedal walking [62]. However, the method of locomotion with simultaneous walking in virtual and physical space (except walking in place) is difficult to use in VR due to the constraints of small physical environment and limited tracking sensors. Therefore, many VR applications typically use controller-based locomotion techniques such as joysticks and teleportation. Joysticks use controller inputs (wand, directional buttons, or pads) to continuously move the user's viewpoint in a designated direction. However, joystick movement can create a conflict between the user's vestibular and visual senses, which is a leading cause of virtual motion sickness according to the sensory conflict theory [54]. Teleportation is a technique that allows users to instantly travel long distances by pointing the controller at a destination and pressing a button to instantly move the point of view there. While teleportation has the advantage of reducing motion sickness [55], it has a negative effect on navigation by causing users to lose their sense of direction when moving long distances instantaneously [4, 9].

The locomotion technique that most closely resembles actual walking is RDW. Basically, RDW uses subtle techniques to manipulate the mapping between physical and virtual space so that the walking user is not aware of it. However, even when using RDW, the user inevitably exceeds the boundary of the given physical space. In this case, RDW uses overt techniques (e.g., reset technique) that explicitly notify the user of the boundary and indicate a new direction to the user [45]. T-APF (with Reset-to-Gradient) [61], which has been consistently mentioned as a subject of comparative analysis in recent RDW studies [28, 34, 39], redirects the user away from physical obstacles by applying the artificial potential field of physical space. VIS [65] is one of the RDW algorithms using the visibility polygon, which is widely used in robotics and motion planning, and redirects the user by considering moving virtual objects.

2.2 Static and Dynamic Environments

In recent years, numerous studies have investigated the interaction between users and virtual characters or objects [20, 43, 57]. When a virtual obstacle exists, the user moves discontinuously to avoid collision, and task performance or user experience may change while being aware of the obstacles. Sanz et al. [57] conducted a study to investigate the effect of static obstacle (human/box) characteristics on locomotion trajectories and found that users implement different locomotion strategies for collision avoidance depending on the type of virtual object. Mousas et al. [43] conducted a study to compare the trajectories and user experience measured when a user walks to avoid a character in the center of a virtual room using a joystick and RDW, and found the differences in results depending on the locomotion techniques. Collision avoidance can improve the realism of the VE and enhance the sense of presence [37].

In particular, humans use different strategies to avoid obstacles depending on whether the obstacle is moving or not [5]. For example, static obstacle avoidance relies on fixations and changes in parallax displacements, while dynamic obstacle avoidance relies on visual tracking of obstacle displacements and invariants or changes in the gaze angle [25]. There are many studies using virtual dynamic obstacles to investigate these human behavioral patterns [20, 33, 47, 58]. Huang et al. [33] investigated the impact of non-verbal behaviors of virtual humans (static/dynamic) on collision avoidance, and found that male and female show different behavior patterns and user experiences. Chihak et al. [20] investigated how to avoid moving obstacles in a VR cycling task, while Scavarelli and Teather [58] conducted a pilot study using dynamic characters to prevent collisions between VR avatars. Previous study in which users avoid collision with dynamic virtual humans using joysticks showed that users' collision avoidance trajectories in VE and real life share common characteristics [47]. However, these studies were conducted in the same environment (static or dynamic) or using a single locomotion technique. Since there may be different types of objects within the same application, it is necessary to investigate the differences between different locomotion techniques depending on the dynamism of the environment. Since there can be many types of objects in the same application, it is necessary to study the differences between different locomotion techniques according to the degree of dynamism in VE.

2.3 Spatial Memory for Navigation

Navigation is a fundamental task for *travel* and *wayfinding* in VR, whether it is remembering a target object, remembering what is around an object, or navigating through space. While physically walking through a VE is known to provide the best spatial awareness [26], it is difficult to use because the amount of space that can be explored using tracking sensors is limited. For this reason, much research has been conducted on how best to navigate VEs that are larger than real-world spaces while maintaining spatial awareness [32]. Given the importance of navigation in VEs, there are a number of studies that compare the effects of locomotion techniques on spatial knowledge [4, 18, 19, 38]. These studies typically compare teleportation and steering and do not directly compare the effects of moving objects in VEs.

Existing studies have included the following as indicators of spatial knowledge: i) object recall accuracy (e.g., the precision of recalling objects presented in the VE) [18], ii) object-to-object spatial relations (e.g., identifying which object is adjacent to another) [2, 18], and iii) object location accuracy (e.g., marking the location of objects on a map) [18, 38]. The main research results showed variability depending on the type of spatial knowledge and research methodology, and some studies showed that the characteristics of VEs (indoor/outdoor) can influence the research results [18]. These types of spatial knowledge are strongly related to each other because humans often use one type of spatial knowledge to infer another type of spatial knowledge. On the other hand, each type of spatial knowledge can also be used independently; for example, even if people cannot remember the exact location of a particular object, they can easily remember the relationship between that object and another object. The influence of locomotion techniques on the acquisition of spatial knowledge will be discussed in more detail in Section 2.4.

2.4 Comparison of Locomotion Techniques in VR

There have been several studies in the past comparing different VR locomotion techniques [14, 17, 18, 24, 30, 38, 43, 48]. A considerable number of these studies focused on the empirical comparison of performance aspects by comparing several VR locomotion techniques [8], or on the experiential comparison of locomotion techniques with a specific thematic focus [13]. The measures compared in each study are diverse, categorized as spatial knowledge [18, 38, 48], task performance [14, 17, 24, 38], user experience [14, 18, 30, 38, 43, 48], etc. In particular, this study focuses on joystick, teleport, and RDW locomotion techniques using HMD, so we focus on previous studies that compared two or more locomotion techniques using HMD. Studies that do not use HMDs (such as CAVE, Monitor, etc.) are not considered because hardware differences may affect the results. The supplementary document contains a summary of the details of the main studies related to our research, showing the compared locomotion techniques, tasks performed, dependent variables, and main findings related to our topic.

The tasks that participants were required to perform varied according to the goals of the research. Studies focusing on spatial knowledge typically required participants to remember the location of targets or draw a map of the navigated virtual space [18, 24, 38, 48]. Langbehn et al. [38] conducted a study to evaluate users' cognitive mapping as a function of different locomotion technologies (joystick, teleportation, and RDW) in a static indoor VE. The results of the study indicated that RDW showed superior performance in terms of spatial knowledge compared to joystick or teleportation, and no difference was observed between joystick and teleportation. Peck et al. [48] confirmed that users placed objects more accurately on the map when using RDW than a joystick. Buttussi and Chittaro [18] conducted a study evaluating object-to-object spatial relationships by having participants remember 8 virtual objects while exploring the VE using a joystick or teleportation. The results showed that using a joystick resulted in fewer spatial memory errors than using a teleportation. In particular, several studies reported that the instantaneous movement of the teleportation induced a loss of spatial orientation [11, 52].

Studies evaluating locomotion performance typically compare the travel time, travel distance, and collision frequency [13, 14, 17, 48]. Travel time was generally faster with a joystick than with teleportation [13, 14, 17] or RDW [14], and teleportation was faster than RDW [14]. Travel time showed different results depending on the presence of obstacles in the VE; teleportation moved faster than RDW in VE without virtual obstacles, and slower than joystick in VE with virtual obstacles [13, 14]. Travel distance was generally shorter with joystick than with RDW [48]. Some study results comparing collision frequency confirmed that teleportation causes fewer collisions than joystick [13] or RDW [14]. In addition, several studies have also compared the locomotion techniques in terms of task load and usability. In the existing study results, the joystick generally induced less task load than RDW because it is commonly used in video games [14, 43]. Also Buttussi and Chittaro [17] confirmed that teleportation provides superior usability compared to joystick. According to the study results of Bozgeyikli et al. [13], both joystick and teleportation require less task load than RDW. Several studies have compared presence and sickness according to locomotion techniques [13, 30, 38]. Previous study results showed that teleportation increased presence compared to joystick [38], and no significant difference was observed between the two locomotion techniques compared to RDW. Several study results comparing sickness reported that teleportation induced less dizziness than joystick [13, 30].

In general, humans update their spatial knowledge or spatial perception by perceiving changes in the surrounding objects as the VE changes, similar to the real world [64]. Therefore, providing appropriate locomotion techniques depending on whether the environment is static or dynamic can lead to an improvement in the user's navigation performance. However, while studies comparing locomotion techniques have been extensively researched, there is no study comparing the effects of locomotion techniques according to the degree of dynamism of the VE in terms of spatial knowledge. Our study focuses on comparing the effects on spatial knowledge, task performances, and user experiences when using different locomotion techniques (joystick, teleportation, and RDW) in different environments (static and dynamic).

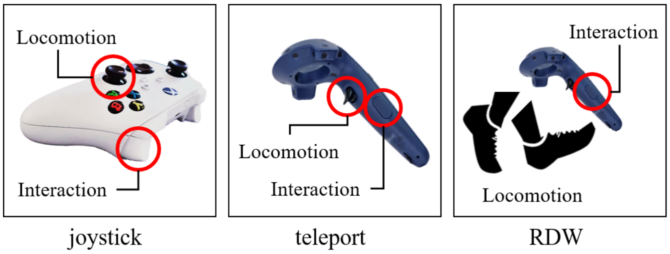

Fig. 2: The controllers used in our experiments: for joystick, teleportation, and RDW.

3 USER STUDY

3.1 Hardware Setup and Virtual Environment

We used the HTC Vive Cosmos Elite HMD (2448×2448 pixels per eye) for the VR setup and established wireless communication using four base stations between the HMD and a PC with an Intel Core i7 2.90GHz CPU, NVIDIA GeForce RTX 3070 GPU, and 32GB RAM. The Xbox wireless controller and Vive controller were wirelessly connected to a PC for the locomotion interface. A square physical space of $7 \times 7m^2$ with no obstacles was provided where the participants actually walked. Two VEs (static and dynamic) were implemented for the experiment, with a virtual art gallery of $22m \times 34m$ size, containing obstacles of walls and 20 virtual characters Figure 1. In the static environment the characters stand still, while in the dynamic environment the character agents move continuously using the ORCA algorithm [63]. Simultaneously with task initiation, 20 ORCA agents are algorithmically instantiated at random spatial coordinates and orientations within the designated movable area of the virtual art gallery. Each agent changes its destination every 5 to 10 seconds, moving while avoiding virtual obstacles or other agents. The destination was set to a random point within the movable area, and the agents moved with a walking animation at a speed of $1.2m/s$, similar to human walking speed [7]. There are 26 picture frames on the walls of the virtual art gallery, and 7 of them have different words written on them to measure spatial knowledge. To measure task performances, an interactable flag (height 1.5 m) was placed in front of the user. The scene of the virtual space was rendered using the Unity3D engine, and the refresh rate was $90Hz$.

3.2 Locomotion Technique Design

We designed a 2×3 experiment to evaluate according to two environments (static and dynamic) and three locomotion techniques (joystick, teleportation, and RDW). There are six conditions in total: Joystick Static (JS), Teleport Static (TS), RDW Static (RS), Joystick Dynamic (JD), Teleport Dynamic (TD), and RDW Dynamic (RD). To conduct the experiment under the same conditions, participants navigated the VEs while standing, and the camera height was set to 170 cm, close to the average adult height [44].

Joystick We implemented the joystick input controller using the bottom right stick and right rear trigger button of the Xbox wireless controller Figure 2. A Vive tracker was attached to the top of the joystick to track the joystick's position in virtual space. Users can operate the joystick controller while standing, and can turn their body or head to look the other way. By pushing the stick of the joystick, the VE could be explored at a speed of 1.2 m/s, similar to the speed of human movement in the direction of gaze. The default value of the joystick is 0; pushing the stick forward enters a +1 value, and pulling it back enters a -1 value. If a positive value is entered, the user moves forward based on the user's line of sight, and if a negative value is entered, the user moves backward. The user can also slow down the speed by partially pushing or pulling the stick. The right trigger of the joystick worked as an interaction button to grab the flag object.

Teleportation When the user points to the floor while pressing the trigger button on the index finger of the Vive controller, an anchor appears with a curved line pointing to the floor to which the user can teleport. When the trigger is released, the user's position is instantly moved to the (x,z) coordinates of the desired location anywhere on the floor. Users can operate the teleportation controller while standing, and can rotate their body or head for rotation. The grip button on the side of the Vive controller worked as an interaction button to grab the flag, and users were instructed to operate the button with their middle finger.

Redirected Walking (RDW) RDW allows users to move through virtual space as naturally as they walk through physical space without a controller. In RDW condition, a user can explore a VE of $22m \times 34m$ by walking directly in a physical space of $7m \times 7m$ in size. Only one grip button on the Vive controller was used to interact with the flag. To select an RDW algorithm suitable for our virtual static experimental environment, we implemented VIS and T-APF on OpenRDW [40] and performed a simulation test. The simulated user repeatedly walks straight towards a target created within 4-8m of the surrounding area, walking a total of 300m virtual path per trial. We compared the number of resets and traveled distance between resets in the results of the simulation test. As a result of the Mann-Whitney U-test with a normality test (Shapiro-Wilk test) and an equal variance test (Levene's test), we confirmed that T-APF was dominant in our virtual static experimental environment without physical obstacles as follows: (1) the number of resets ($U(98) = 642.5$, $p < .001$, $large(.75)$) of T-APF ($M = 34.49, SD = 5.239$) vs. VIS ($M = 44.84, SD = 4.668$)). (2) mean virtual distance traveled between resets ($U(98) = 9371$, $p < .001$, $large(.76)$) of T-APF ($M = 8.542$, $SD = 1.469$) vs. VIS ($M = 6.523$, $SD = 0.725$)). From the simulation result, we decided to use T-APF as the RDW algorithm.

3.3 Procedure

The protocol was approved by the university's Institutional Review Board (IRB) before beginning the recruitment (No. 7001988-202311-HR-2109-02). Upon arrival at the research lab, participants listen to an explanation of the purpose of the research and sign an IRB-approved informed consent form. Participants complete a survey about their age, gender, VR experience times, 3D gaming hours per week, and answer the pre-SSQ questionnaire [35] to measure their level of sickness before the experiment. The participant then listens to the explanation of the experiment and performs a tutorial task to practice three locomotion techniques while wearing the HMD. Participants performed a total of 6 experiments (JS, TS, RS, JD, TD, and RD) combining two environments (static and dynamic) and three locomotion techniques (joystick, teleportation, and RDW) in the VE. The experiment was conducted in a within-subjects design in counterbalanced order.

Participants performed a *target navigation task* to find out user performance and usability according to the locomotion techniques, and a *spatial memory task* to measure spatial knowledge at the same time. In the *target navigation task*, participants pick up the flag in front of them by pressing the interaction button on the controller, move to the portal-shaped target while pressing the button, and release the interaction button to put down the flag. Only one target can be seen at a time, and when the flag is placed on the target, the next target appears sequentially. After reaching the target, participants must repeat the process of picking up the flag, moving to the next target, and dropping the flag. At the same time, participants were instructed to memorize the locations and contents of 7 words placed in the VE to perform the *spatial memory task*. The words used in the experiment consisted of 42 words with different meanings, and 7 non-overlapping words were assigned to each condition to prevent users from memorizing the words in advance. For the fairness of the experiment, the sum of the lengths and placement of the 7 words and the placement for each condition were all assigned the same, so there was no difference in spatial knowledge depending on the difficulty or location of the words. When the participant reached the 7th target, the task ended 5 seconds later. Participants were cautioned to move as much as possible without colliding with virtual objects, and they had to perform tasks while avoiding moving virtual agents, especially in the dynamic conditions.

After about 3 minutes of the VR experiment, the spatial knowledge test and questionnaires were administered. The spatial knowledge test consists of object recall accuracy, object-to-object spatial relationships, and object location accuracy. After evaluating spatial memory, participants completed five standardized questionnaires to measure the user experience in VR: NASA-TLX (NASA Task Load Index) [31] for task load, System Usability Scale (SUS) [15] for usability, Igroup Presence Questionnaire (IPQ) [59] for presence, Engagement, Enjoyment, and Immersion (E2I) [41] for immersion, and Simulator Sickness Questionnaire (SSQ) [35] for motion sickness. In addition, participants completed three custom questionnaires to quantify *ease of use*, *ease of memory*, and *overall rating*. Participants rested until they were no longer dizzy, then wore the HMD again and repeated the 6 conditions in the same manner as before. After performing all conditions, a simple interview was conducted to ask about the user's feelings during the VR experience, and they received a reward of $15. The experiment was conducted within 70 minutes.

4 Dependent Variables and Hypotheses

During the tasks, we structured the spatial knowledge measurement indicators based on previous studies [18, 38] and measured post-questionnaires. In addition, our system recorded the total travel time, travel distance, and percentage of collisions with virtual objects for each condition to measure the performances of the participants. Detailed explanations and our hypotheses for each dependent variable are as follows.

4.1 Spatial Knowledge

Object recall accuracy To assess recall of the words seen while exploring the VE, we asked participants to write down all the words they saw. One point was awarded for each correct word, and the score for each condition could range from 0 to 7.

Object-to-object spatial relationships To assess spatial knowledge in terms of spatial relationships between objects, we asked participants three questions: 1) Which word was placed closest to the center of the room? 2) Which word was placed closest to the door? 3) Which word was placed on top of the banana picture? If the participant answered correctly, the participant received 1 point, so the score for each condition could range from 0 to 3.

Object location accuracy To assess memory for target location, participants were presented with a top-view 2D map of the experimental VE and the 7 words, and were asked to mark the locations of the words on the map. The map drawing task is often used as a metric of spatial knowledge because the map is a familiar navigation metaphor [26]. If the participant places the correct word in the correct location on the map, the participant receives 1 point, so if the participant places all 7 words correctly, the participant receives 7 points. The hypotheses we propose regarding spatial knowledge are as follows:

- H1: The locomotion technique that enhances spatial knowledge will differ in static and dynamic environments, respectively. This is because humans use different locomotion strategies when avoiding dynamic obstacles compared to static ones [5].
- H2: Different types of spatial knowledge will show different tendencies. In particular, in dynamic environments, the location-based type of spatial knowledge (object location accuracy) will show the best spatial knowledge acquisition with RDW, which is similar to actual human movement [48], while teleportation is probably the worst because it makes map construction difficult [11, 52].
- H3: Participants' spatial knowledge will be superior in static environments compared to dynamic environments, because users' concentration is dispersed to avoid moving characters.

4.2 Logging Data

We measured travel time, travel distance, and collision frequency for each condition to compare user performances. The travel time is collected from the beginning to the end of the task for comparison for each condition. Since the task ends after the user has reached all 7 targets, the total travel time varies for each condition. Travel distance

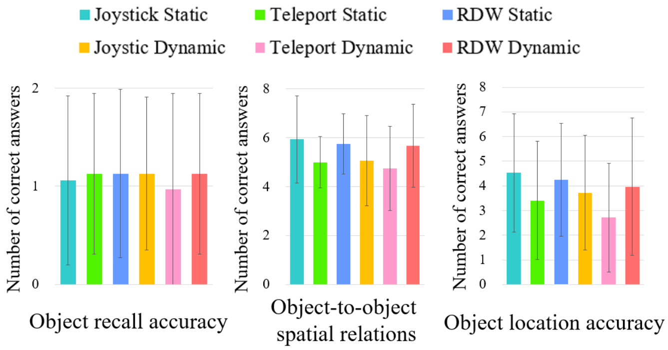

Fig. 3: Mean results of spatial knowledge acquired in six different conditions. The error bars indicate 95% confidence intervals.

is calculated by collecting the user's coordinates in the VE in real time during the task, and calculating the distance between the coordinates. For the joystick and RDW conditions, we summed the values calculated as the distance in position from the current frame to the next frame, and for the teleportation condition, we summed the values calculated as the linear distance from the current position to the teleported position. Collision frequency represents the rate at which the user collided with virtual objects. To measure collision frequency, we first recorded the number of collisions the invisible user object in the VE collided with virtual obstacles (e.g., walls, characters). When participants teleported in a direct line through objects, the number of collisions increased by the number of objects on the line. The collision frequency was calculated as the number of collisions divided by the total travel time, since the travel time varied for each task. All data were collected at 60 FPS. Our hypotheses regarding the logging data are as follows:

- H4: It will take a lot of time using RDW, joystick, and teleportation in that order based on existing research [14]. Also, travel time will increase in dynamic environments compared to static environments.
- H5: Travel distance will increase in a dynamic environment compared to a static environment to avoid moving obstacles.
- H6: Collision frequency between the user and other objects will be the lowest using teleportation, similar to existing research [13, 14].

4.3 Standardized Questionnaires

The following questionnaires are used to investigate the effect of locomotion techniques on the user's experience. IPQ consists of 15 items (7-point Likert scale) used to measure spatial presence. E2I is a questionnaire used to measure immersion and consists of 9 items on a 7-point Likert scale. SSQ is a widely used questionnaire to measure motion sickness and consists of 16 items on a 4-point Likert scale. NASA-TLX is a representative questionnaire that can evaluate the task difficulty perceived by the user and is mainly used to evaluate task performance and efficiency while using the system without cognitive load. This questionnaire has six subscales, including *Mental Demand*, *Physical Demand*, *Temporal Demand*, *Own Performance*, *Effort*, and *Frustration Level*. Users can rate the items in the questionnaire from 0 to 100 in 5-point increments, and the lower the score, the lower the task load. SUS consists of 10 items on a 5-point Likert scale and is often used to measure overall system preference. Based on the results of these surveys, we developed the following hypotheses:

- H7: Locomotion techniques that demonstrate high presence and immersion will differ in each environment, and will be higher in dynamic environments than in static environments. In particular, teleportation will have the lowest scores because it is very different from actual movement experiences, and RDW will have the highest scores because it is most similar to actual walking.
- H8: The joystick technique will cause more motion sickness than RDW and teleportation due to the sensory conflict between the visual and vestibular systems [54].
- H9: There will be differences in task load and usability depending on the locomotion techniques. In particular, users will find joystick and teleportation more convenient than RDW because they are more familiar with video game controllers [17, 43].

4.4 Custom Questionnaires

We created three customized questions to measure user preferences: *ease of use*, *ease of memory*, and *overall rating*. *Ease of use* asked users to rank the locomotion techniques in order of how easy they were to use. *Ease of memory* asked users to rank the locomotion techniques in order of how well they helped them remember the virtual space. *Overall rating* asked users to rate their overall preference for each locomotion technique on a 7-point Likert scale.

- H10: The preferred locomotion technique for navigating or remembering space will be different.

5 Participants

For this study, we performed a preliminary power analysis using G*Power software to determine the appropriate sample size [23]. According to the significance level (= 0.05), large effect size (= 0.5), and statistical power (= 0.95) from Cohen's guidelines, the recommended sample size was 30. Participants were recruited through advertisements placed on the university campus. Our study included 32 participants (16 male, 16 female) aged 20-38 years ($M = 25.94$, $SD = 2.88$). 26 participants reported having experienced VR on average 8.81 times ($SD = 19.56$), while the rest reported never having experienced VR. The average number of games played by the participants per week was 1.37 times ($SD = 2.09$). There were no differences in results based on the user information.

6 Results

Based on our hypotheses, we analyzed the data using IBM SPSS Statistics. We performed the Shapiro-Wilk test for normality and used nonparametric tests because all the data sets did not have a normal distribution. We performed Friedman's test to analyze the results according to the differences in the six conditions, and we performed the Wilcoxon signed-rank test for post-hoc testing. To ensure robust statistical accuracy, all statistical significant measures were corrected using the Bonferroni correction. A detailed description of the statistical tests for all results are provided in the supplementary material.

6.1 Spatial Knowledge between VEs

Regarding research hypotheses 1, 2, and 3 (H1, H2, and H3), we performed Friedman's test to verify statistical differences. Figure 3 shows the results of different types of spatial knowledge obtained in six conditions.

There was no significant differences for object recall accuracy ($p > .893$). Among them, TD had the lowest score. Object-to-object spatial relationships ($\chi^2 = 11.441$, $p < .05$) showed statistically significant differences for each condition. The post-hoc tests revealed significantly higher scores in the RS condition as compared to the TS condition ($p < .05$). We also found significantly higher scores in the RD condition than the TD condition ($p < .05$).

Object location accuracy results showed statistically significant differences for each condition ($\chi^2 = 11.556$, $p < .05$). The performed post-hoc tests revealed significantly higher accuracy for the JS compared to the TS condition ($p < .05$), and the RD condition compared to the TD condition ($p < .05$). There was no significant differences in other conditions ($p > .673$). There were no significant differences between each locomotion technique in static and dynamic environments ($p > .627$).

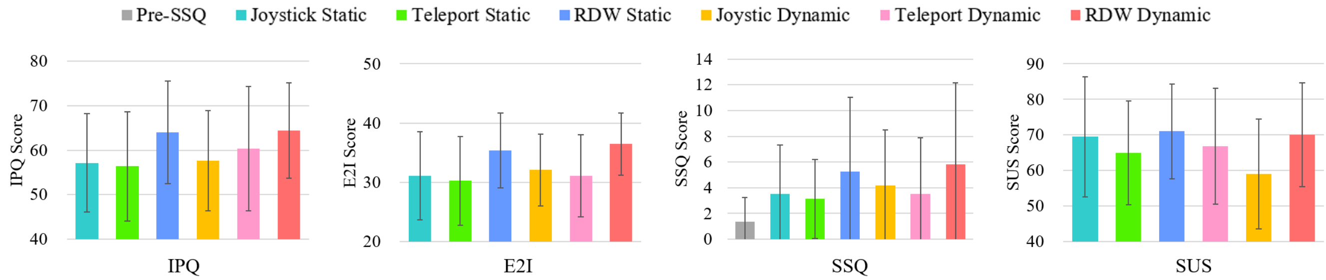

Fig. 4: Mean results of standardized questionnaires for pre-SSQ questionnaire and each of the six conditions; IPQ: Igroup Presence Questionnaire, E2I: Engagement, Enjoyment, and Immersion, SSQ: Simulator Sickness Questionnaire, and SUS: System Usability Scale. The error bars indicate 95% confidence intervals.

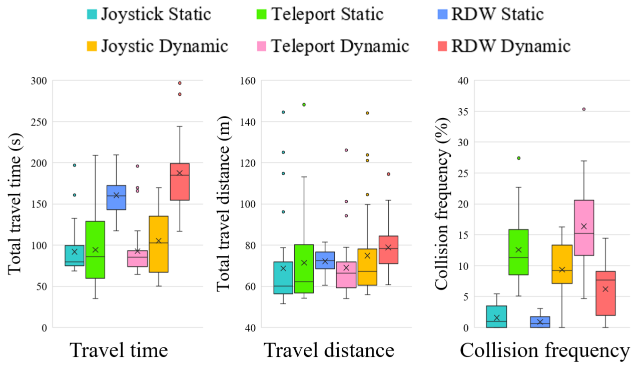

Fig. 5: Mean and standard deviation (SD) results of travel time, travel distance, and collision frequency acquired in six different conditions. The error bars indicate 95% confidence intervals.

6.2 Logging Data

Figure 5 shows the results of the logging data. To analyze the performance ability according to the conditions performed in the *target navigation task*. Significant results were observed in all logging data measures based on Friedman's test: travel time ($\chi^2 = 88.164$, $p < .001$), travel distance ($\chi^2 = 23.016$, $p < .001$), and collision frequency ($\chi^2 = 117.879$, $p < .001$). Concerning research hypothesis 4 (H4), the results of post-hoc analyses for travel time showed that higher in the RS condition than the JS ($p < .001$) and the TS condition ($p < .001$), also higher in the RD condition than the JD ($p < .001$) and the TD condition ($p < .001$). Travel time was significantly lower for the RS than RD condition ($p < .001$). The remaining results did not showed statistically significant differences ($p > .681$).

In the post hoc analysis results of travel distance (H5), participants moved a significantly shorter distance in the JD than RD condition ($p < .005$), and in the RS than RD condition ($p < .001$). The differences between the remaining conditions were not statistically significant ($p > .640$). In the post hoc analysis results of the collision frequency data (H6), all conditions showed statistically significant differences except that between the JS and the RS condition ($p > .104$). The results of collision frequency were significantly higher in the TS compared to the RS ($p < .001$) and the JS condition ($p < .001$). Post hoc tests revealed significantly higher collision frequency for the TD condition compared to the RD ($p < .001$) and the JD condition ($p < .001$), and the JD compared to the RD condition ($p < .05$). We created a heat-map (Figure 7) and a path graph (Figure 8) to visualize the data, with a detailed description of the graphs in the supplementary materials.

6.3 Standardized Questionnaires

The followings are the results for research hypothesis 7 (H7). As shown in the Figure 4, the IPQ results showed statistically significant differences in Friedman's test ($\chi^2 = 33.383$, $p < .001$). According to the post-hoc analysis, participants reported higher levels of presence, as measured by the IPQ, in the RS condition as compared to the JS condition ($p < .001$) and TS condition ($p < .001$). Reported levels of IPQ presence were higher in the RD condition than they were in the JD condition ($p < .05$) and the TD condition ($p < .001$). There were significant differences between TD condition and the JD condition ($p < .05$), with the TD condition showed a higher presence score than the JD condition. However, there was no significant difference between the TS and JS condition ($p > .423$). In the joystick condition, IPQ scores were higher for dynamic environments than static environments ($p < .05$).

However, no environmental differences were observed in the teleport and RDW conditions ($p > .985$). The E2I results were analyzed with Friedman's test and showed statistically significant differences ($\chi^2 = 54.561$, $p < .001$). Post hoc tests revealed significantly higher levels of immersion for the RS condition compared to the JS ($p < .001$) and TS condition ($p < .001$). Reported E2I scores were higher in the RD condition than they were in the JD ($p < .001$) and TD condition ($p < .001$). There were no significant differences between the TS and the JS condition, the TD and the JD condition ($p > .433$). There were no differences between the environmental conditions ($p > .266$).

Regarding research hypothesis 8 (H8), SSQ results revealed significant differences between conditions in Friedman's test ($\chi^2 = 30.952$, $p < .001$). Post hoc pairwise comparisons revealed that participants in the RS condition had a significantly higher SSQ score than the TS condition ($p < .005$). Reported levels of motion sickness were higher in the RD condition than they were in the TD condition ($p < .05$). The SSQ scores of all conditions were significantly higher compared to the pre-SSQ scores measured before the experiment ($p < .01$).

The results for research hypothesis 9 (H9) are as follows. The mean scores of NASA-TLX for measuring task load showed statistically significant differences in Friedman's test ($\chi^2 = 14.540$, $p < .05$). According to the post hoc analysis, the users in the TD condition had a higher mean score than the JD condition ($p < .05$), and RD condition ($p < .05$). We found no significant differences between all static environment conditions and in the JD and RD conditions ($p > .945$). Only the *Temporal Demand* ($p < .05$) and *Effort* ($p < .001$) sub-scales were showed statistically significant differences in Friedman's test. There were no statistically significant differences for remaining sub-scales in Friedman's test ($p > .680$). For *Temporal Demand*, participants in the TD condition had a higher mean score than the RD ($p < .05$), and JD condition ($p < .05$). For *Effort*, participants in the TS condition had a higher mean score than the RS ($p < .05$), and the JS condition ($p < .05$), and in the TD condition had higher than RD ($p < .001$) and JD condition ($p < .001$). For the SUS results, significant differences were found in Friedman's test ($\chi^2 = 16.808$, $p < .005$). Reported levels of SUS usability were higher in the RD condition as compared to

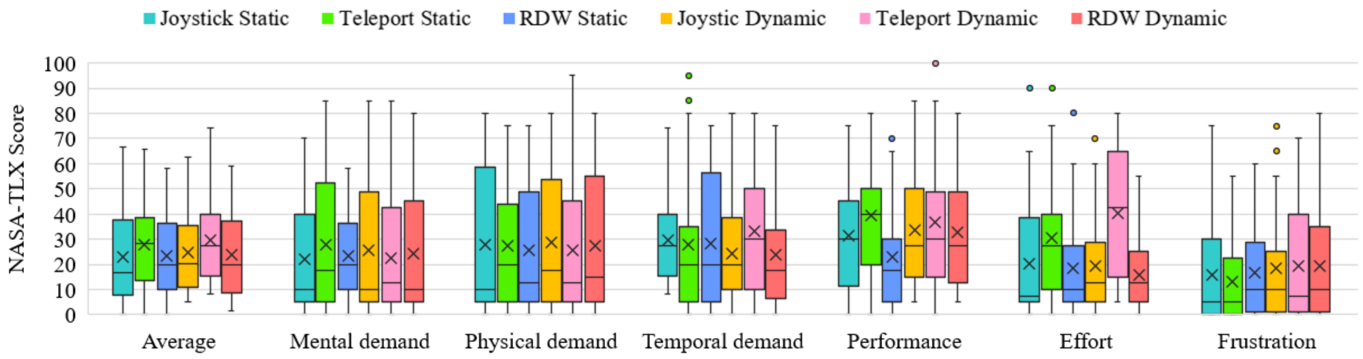

Fig. 6: Mean and standard deviation (SD) results of NASA Task Load Index (NASA-TLX) scores for each sub-scale and condition. The error bars indicate 95% confidence intervals.

the TD condition, and in the JD condition compared to TD condition ($p < .01$).

6.4 Custom Questionnaires

The followings are the results for research hypothesis 10 (H10). For *ease of memory*, 18 (56%) preferred the RDW, 10 (31%) preferred the joystick, and 4 (13%) preferred the teleportation. For *ease of use*, 13 (40%) preferred joystick, 12 (38%) preferred the RDW, and 8 (22%) preferred teleportation. The results of the *overall rating* were analyzed using Friedman's test and showed a statistically significant difference ($\chi^2 = 6.118$, $p < .05$). Post hoc analysis showed that RDW was the most preferred method, followed by joystick and teleportation. RDW and teleportation showed significant differences ($p < .05$), while the others were not significant ($p > .391$).

7 DISCUSSION

Our study compared six conditions (JS, TS, RS, JD, TD, and RD) based on the dynamism of the two VEs (static and dynamic) and three locomotion techniques (joystick, teleportation, and RDW). The results confirmed our hypothesis, and there were some interesting findings. Each variable is discussed in more detail below.

7.1 Spatial Knowledge

We found interesting results for each condition and each type of spatial knowledge. Differences in memory occurred when using different locomotion techniques depending on the environment (static and dynamic) in the results of object location accuracy (H1). Joystick in a static environment and RDW in a dynamic environment can be confirmed to be more effective for memory. RDW is the most ecologically valid of the three locomotion techniques because it resembles real-world movement [3]. Physical activity through walking is associated with increased hippocampal volume and improved memory, which causes activation of the brain leading to better memory [27]. Previous studies asking participants to find hidden objects in VE also found that spatial memory performance improved significantly when physical walking was used instead of a button-pressing interface [56]. In contrast, when the VE was stationary, the joystick that was more familiar to the participants induced higher spatial knowledge. The teleportation condition produced the lowest memory across all environments, extending previous findings that teleportation is more difficult for spatial memory than joysticks [11, 52]. Participants reported in interviews that when using the other locomotion techniques, they had time to review as they walked to the next target, but in the teleportation condition, they moved so quickly that they had less time to review, making it more difficult to memorize. In interviews, participants reported that they had time to walk to the next target and recall it when using a joystick or RDW, but found it more difficult to memorize in the teleportation condition because they jumped so quickly that recall time was shortened. These results suggest that users lose their sense of direction, which may impair users' spatial memory because it takes time for users to understand the new environment after teleportation [4, 9].

Differences in cognitive function may also vary depending on the context [18]. We conducted three tests of spatial knowledge, but no significant results were found in the object-to-object spatial relationship test (H2). This result shows that not all types of spatial knowledge are affected in the same way, and in particular that tasks directly related to location can be affected by locomotion techniques [18]. In the dynamic environment, participants reported that virtual characters moved around the virtual space, obscuring words, or that users were distracted from memorizing words because they were focused on avoiding the characters. Although no difference in spatial knowledge was found between environments (H3), it can be seen that a static environment may be more suitable for performing memory tasks in terms of user preference. There were also participants who found it difficult to remember words in the RDW condition because they had to rotate when a reset occurred. These results support existing research findings that RDW imposes cognitive demands on users that affect spatial knowledge [16].

7.2 Time, Distance, and Collision

Users took longer to complete tasks with the RDW than with the joystick or teleport in all conditions extending previous research (H4) [17]. However, contrary to our hypothesis that teleportation would be the fastest, no difference was observed between teleportation and joystick. This result can be attributed to the presence or absence of obstacles. Previous research has shown that in environments without obstacles, teleportation performs tasks faster than joystick [13, 14], and in environments with obstacles, teleportation could be faster or slower [13, 17]. In particular, participants showed an interesting behavior pattern when using the teleportation; while the time taken to reach the target was very fast, after reaching the target, they continuously looked around in order to remember the words. As shown in the results in Figure 7, this is probably because it takes time for the participants to figure out their position or orientation as a result of the sudden spatial transition [4, 9]. In addition, we confirmed that RD took longer than RS. On the other hand, no significant differences were found between JS and JD, and TS and TD. In this context, we observed that participants paid less attention to collisions with dynamic virtual obstacles when using joystick or teleportation. In contrast, with RDW, which is based on the user's natural gait, participants exhibited real-life-like behaviors such as short pauses or quick detours to avoid dynamic virtual obstacles. In doing so, users often took very short sidesteps or backsteps [21]. However, such behaviors caused users to frequently use the reset technique around the physical boundary, and these frequent resets increased task time.

We observed that JD traveled a shorter distance than RD in the dynamic environment. This result can be attributed to the fact that users behave similarly to reality when avoiding the approach of virtual characters. Previous studies have shown that people's proprioceptive and vestibular signals are triggered during the process of avoiding

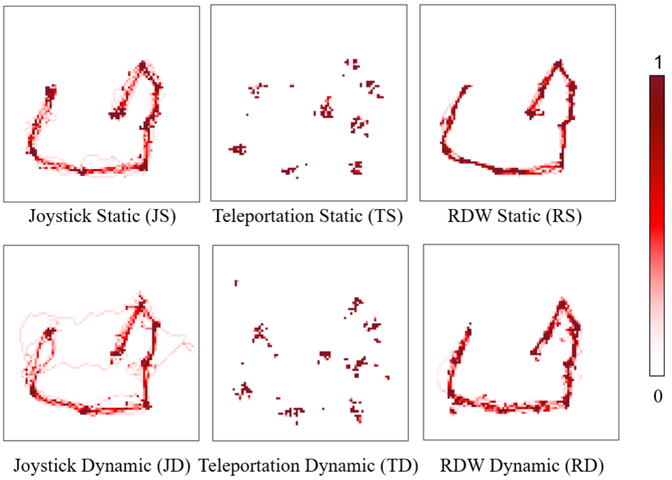

Fig. 7: Heat-map showing how long users stayed at any location for six different conditions. Duration is normalized to [0,1].

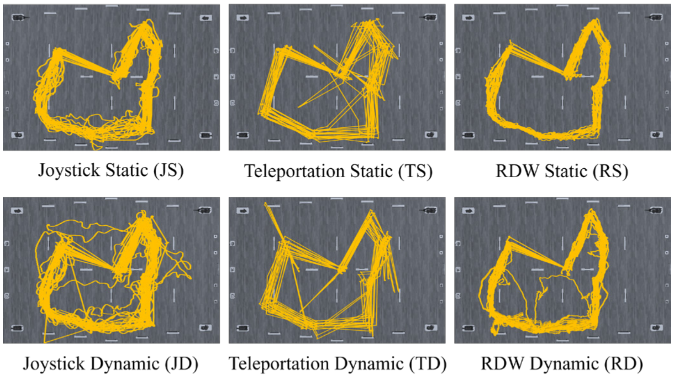

Fig. 8: Path data for each of the 6 conditions. In the graph, the straight line connecting the start point (center) and final destination (top left) is not the path the user actually traveled.

virtual characters in VEs [19,29], which increases the level of realism of walking in VEs and makes users more aware of their bodies [52]. These activities enhance spatial awareness of the environment [66], leading users to maintain a greater distance when avoiding virtual characters in RD compared to JD. Indeed, participants exhibited behavioral patterns similar to actual walking when experiencing RD, showing fear of approaching virtual characters and efforts to avoid them at greater distances compared to other conditions. On the other hand, a study comparing the differences between RDW and joystick in a static maze environment found that the joystick traveled a shorter distance than the RDW. This may be due to the nature of the maze environment, which required movement through narrow passageways, and the nature of the obstacles (human/object) may have influenced the results of the study [57]. In addition, the significantly increased distance traveled by RD compared to RS may be the result of the greatest effort to avoid the moving virtual character when using RDW, which is also supported by the results in Figure 7, which show that the movement distribution of RD is more spread out than that of RS (H5).

Teleportation condition verified to induce the most collisions, which differs from previous studies that have shown teleportation to cause fewer collisions than joystick or RDW (H6) [13, 14]. Although participants were aware that they should avoid obstacles during the task, they did not make an active effort to avoid them in the teleportation condition. This behavior may be due to the fact that participants performed the task with a focus on spatial memory rather than collision avoidance. In particular, participants avoided the moving virtual character by changing paths because the joystick and RDW provide intuitive movement, whereas users sometimes stood in place and waited for the virtual character to pass by instead of using the teleportation to avoid it. This behavior is consistent with previous research where Buttussi and Chittaro [17] explained that when users use teleportation, they let the teleportation beam pass over obstacles in VEs with scattered obstacles or multiple types of obstacles. This pattern extends the findings of previous research, which found that when users use teleportation, they pass over obstacles in VEs with scattered obstacles or multiple types of obstacles [17].

7.3 Presence, Immersion, and sickness

The hypothesis regarding presence and immersion (H7) showed partially consistent results. RS showed higher levels of presence compared to both JS and TS, and this result was also consistent with immersion. RDW provides a realistic locomotion interface that most closely resembles walking in the real world, while disorientation through teleportation reduces presence and immersion [9]. An interesting finding was that joystick produced higher scores than teleportation in all other conditions, while TD produced significantly higher presence than JD.

This result can be considered in conjunction with the collision frequency results. When frequent collisions occur in teleportation, users report that synchronous visuo-proprioceptive correlations increase their sense of self-location [49]. In the well-known rubber hand illusion experiment, users feel a sense of control and body ownership over the avatar through the virtual hand, which can also be experienced through contact with virtual objects [10]. Such correlated vestibular signals may enhance spatial perception, possibly explaining why collisions in TD induced higher presence [6]. Another interpretation is that, especially in TD, participants moved quickly to the target to avoid the virtual characters and then looked around to memorize the words, which may have increased the time spent looking around and made them feel more presence in the VE. In addition, participants reported in interviews that the VE was more realistic when the virtual characters were moving, as evidenced by the higher presence of JD than JS.

Sickness results are similar to previous studies [17, 22, 38], confirming that RDW induced more sickness than teleportation in both environments (H8). In addition, the longer travel time of RDW compared to other locomotion techniques may have led to more sickness due to the longer duration of the VR experience. In our interviews, many participants reported that the joystick induced more motion sickness, especially when the direction of movement and the visual field were mismatched. This is likely due to the sensory mismatch between the visual and vestibular systems, as well as the proprioceptive cues that occur when a user is physically stationary while navigating with a joystick [54]. Although the results of this study did not show significant differences, previous studies have reported that joysticks induce higher levels of motion sickness compared to teleportation [17, 18, 24, 30, 38].

7.4 Task load, Usability and Preference

The results for task load showed that it was highest for TD, followed by JD, and lowest for RD. The usability ratings also ranked RD, JD, and TD in descending order of *ease of use* (H9). These results tend to differ from the hypothesis based on previous research [43], which may be due to task effects. Participants often missed the flag and moved on, especially in the teleportation condition, and responded that they confused two buttons (trigger and grip). Many participants did not realize they had dropped the flag while moving to another location without it, and then had to return to the previous location to retrieve it, which is also related to the increased travel distance in the teleportation conditions. The path graph results Figure 8 also show that users move irregularly to non-target points, especially in TD. On the other hand, in the RDW conditions, users only used the controller to grab the flag, which made it easier for them to perform the *target navigation task*. Since the two input systems were different, the joystick was easier to use than the teleportation, which was related to task load and usability. Participants preferred different locomotion techniques depending on the task, preferring RDW for spatial memory and joystick for movement (H10). The *target navigation task* had a strong influence on the preferences, and the *overall rating* showed that the majority of participants preferred the RDW method the most (19 with a score of 6 or higher, 59 percent). Interestingly, despite the joystick and teleportation conditions, many participants attempted to walk in physical space, suggesting that they may have subconsciously assumed that RDW was the most comfortable way to move.

7.5 Locomotion Interface Guidelines in VEs

In VE, it is advisable to recommend appropriate locomotion techniques for different environments and contexts. Specifically, in terms of spatial knowledge, using a joystick in a static environment and RDW in a dynamic environment is more effective for remembering the locations of virtual objects. However, these patterns can vary depending on the type of spatial memory and show distinct differences in tasks directly related to location. On the other hand, the use of teleportation, while not good for spatial knowledge, is effective in reducing travel time and motion sickness. teleportation may not be the most usable, especially when performing multiple types of tasks simultaneously within the VE. Users can get confused about which button to press, especially if they need to use multiple buttons within a single controller. When a task requires using a controller for both movement and operation, avoiding using the same type of input interface as much as possible can reduce the user's task load and increase usability. For example, it is good practice to design so that movement is accomplished by pushing or pulling a stick, and grasp interaction is accomplished by pressing a button. If it is unavoidable to use two buttons simultaneously on a single controller, it is better to consider using RDW.

RDW scored well against other locomotion techniques in several aspects. VR applications that aim for high levels of presence and immersion may prefer to use RDW. RDW is superior for presence regardless of the dynamism of the environment, but shows differences depending on whether the environment is moving or not. Providing a teleportation in a dynamic environment and a joystick in a static environment can help improve user presence. If the VR application only requires the use of a joystick, then providing a dynamic environment can lead to high user presence. However, some criteria (e.g., sickness) may be different, so it is important to consider the prioritization of different criteria in the application domain to design and choose the most appropriate locomotion technique for the situation. Based on the results presented in this paper, a joystick is appropriate when spatial knowledge is required in a static environment. Joystick or teleportation may also be appropriate in situations where the user needs to move quickly. In particular, it may be best to use teleportation when targeting users who are prone to motion sickness or for content that is prone to motion sickness. Providing RDW is appropriate in environments that require a sense of presence or immersion, but RDW may be best used when traveling short distances to minimize resets due to sickness. The travel time of RDW is also longer than other locomotion techniques, making RDW a good choice for applications that need to slowly explore the VE and create a sense of presence or immersion.

In summary, RDW is most effective for remembering locations in dynamic environments, as physically walking through the actual actions can increase presence and immersion. This movement was most effective when performing the *target navigation task*, as using the controller only when grabbing the flag reduced task load and increased usability. Therefore, using RDW is most effective when performing a specific task using a controller along with movement in a dynamic VE. On the other hand, travel time and distance were measured high in RDW, and sickness was also induced high. In order to reduce the time needed to perform tasks, a joystick or teleportation should be used, especially the use of a joystick has the advantage of reducing the travel distance. Therefore, using a joystick may be suitable for applications where urgent movement is needed a lot. On the other hand, teleportation increases the task load and decreases the usability, because the method of moving and grabbing the target both use button presses. However, teleportation can induce a higher presence than a joystick and can greatly reduce motion sickness in dynamic environments. Based on the results of this study, VR application designers will be able to select the most appropriate locomotion technique for the VR characteristics or context.

8 Conclusion

In this paper, we investigated the effects of different locomotion techniques on different types of spatial knowledge acquisition, task performances, and user experiences when navigating two types of VEs (static and dynamic), depending on whether the virtual objects are moving or not. The main findings presented can provide guidelines for locomotion interface design for practitioners who need to design VR applications, which can be summarized as follows. First, different locomotion techniques have different positive effects on spatial knowledge acquisition in static and dynamic environments, with joysticks performing better in static environments and RDWs performing better in dynamic environments. Second, the differences between the locomotion methods are mainly in terms of remembering the spatial location of objects, not in terms of remembering the types of objects or the correlations between objects. Third, different locomotion techniques lead to different user performances and experiences. These findings have important implications for practitioners as the environment or context varies in different VR applications.

Limitations of this study include the fact that the experiment was conducted in a within-subject design. Although counterbalancing was performed to prevent the learning effect, it may be desirable to perform the experiment in a between-subjects design by dividing the subjects into groups. It is also worth noting that only two types of environments were compared in this paper. As a future work, it is necessary to compare the conditions considering more diverse dynamic environments. In the dynamic environment of this study, the virtual characters all moved at the same speed, but it is possible to compare the results regarding variations in speed. In addition, differences in spatial knowledge may be influenced by the type of dynamic objects (e.g., human or inanimate) or the complexity of the environment (e.g., open world or maze). These findings can be extended to further research, even within a single VR application, by recommending optimal locomotion techniques as the degree of dynamism or context of the environment changes.

Acknowledgments

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