Method of locomotion impacts spatial learning tasks in VR HMD environments

Aaditya Vardhan Narain
Software Engineering Research Center
IIIT-Hyderabad
Hyderabad,India
aaditya.narain@research.iiit.ac.in

Ashutosh Rudrabhatla
Cognitive Science Lab
IIIT-Hyderabad
Hyderabad,India
ashutosh.rudrabhatla@research.iiit.ac.in

***Abstract*—Virtual reality (VR) enables users to experience "alternate realities" without real-world risks, offering transformative potential in industries such as military training, therapeutic interventions, and gaming. A critical challenge in optimizing VR design lies in enhancing the user experience. This study investigates how locomotion methods impact user experience in VR environments, with a specific focus on spatial learning tasks using head-mounted displays (HMDs). Building on prior research exploring display and interaction fidelity, we examine how walking-based navigation compares to joystick-based navigation in terms of task performance, sense of presence, and simulator sickness. Our findings indicate that walking-based navigation significantly enhances the overall user experience and performance in spatial learning tasks. In conclusion, we highlight the implications of this result for optimizing VR task design in areas such as training, gaming, and therapeutic applications.**

***Index Terms*—Virtual Reality; Locomotion; Spatial Learning; Immersion; Sense of Presence.**

I. Introduction

Virtual reality (VR) is poised to revolutionize various industries by enabling users to experience "alternate realities" without real-world risks or inconveniences [5]. This makes VR particularly appealing for applications where safety, cost, or practicality is a concern, such as military training simulations, psychological therapies such as exposure therapy, and immersive gaming experiences. The question therefore arises: What is the best way to optimize the user experience in VR? To answer this question, we must first attempt to answer what a 'user experience' of VR entails and how it can be measured.

Sense of Presence is a broad term that refers to the extent to which a virtual environment becomes a user's subjective reality [1], [4], [11]. This sense of "being there" is central to VR applications, as it ensures deeper engagement and better transfer of skills or knowledge to real-world scenarios.

Arguably, achieving a higher sense of presence has been the goal of media long before the advent of VR. Looking back through history, media has evolved with an emphasis on increasing the user's immersion in the experience they are being subjected to, be it fantastical scenarios (like fictional worlds) or emulations of the real world. Media such as books and newspapers (static text and images), radio stations (audio), movies (dynamic images and audio), AAA game titles (dynamic images and audio combined with a sense of agency), to eventually the advent of dynamic XR systems [3], [5], gives a good representation of this idea.

Fidelity is a measure of the degree to which a VR system replicates real world sensory and motor experiences [2], [8]. While the sense of presence can be considered a psychological measure of user experience, fidelity can be considered its technological counterpart. It comprises two main domains:

- **Interaction Fidelity**: The degree to which sensory-motor feedback in VR mimics real-world interactions. Examples include method of navigation in the virtual environment (e.g. walking vs. joystick locomotion) or haptic feedback [1], [4].
- **Display Fidelity**: The extent to which visual features in VR resemble real-world characteristics, such as high-resolution graphics or high frame rates [8].

Although improving fidelity generally enhances the sense of presence, some past studies suggest that not all forms of fidelity yield proportional benefits [12], [13], [14]. In this study, we choose to focus on the **navigation aspect of interaction fidelity**, since this is a relatively unexplored domain.

Spatial learning is the cognitive process through which individuals acquire and store information on spatial relationships between objects and locations [3], [10], [13]. In VR, examples of spatial learning tasks include navigating a virtual maze, memorizing object placements, or reconstructing environments from memory. Spatial learning tasks involve navigation and exploration of a virtual environment. Hence, in this study we choose a spatial learning task to explore the effect of the method of locomotion on user experience and performance in a VR environment.

Despite the progress in understanding aspects that influence user experience and performance in VR, gaps still remain in how specific factors, such as locomotion methods, affect spatial learning tasks [4]. This study investigates the role of locomotion, walking versus joystick movement, in improving spatial learning, presence, and user comfort. The following section gives a brief overview of the previous work that has been done in this domain.

II. Literature Review

This section reviews relevant literature on the influence of interaction fidelity, particularly locomotion methods, in virtual reality (VR) environments. To ensure a comprehensive exploration of the topic, a systematic search was conducted on two academic databases, IEEE Xplore and ACM Digital Library. The search employed the string: ("interaction" OR "locomotion") AND ("fidelity") AND ("Virtual Reality" OR "VR"). The resulting studies provided insights into key aspects of interaction fidelity, including locomotion techniques, user experience, and task performance in VR environments. 289 papers were given out, from which only a handful were carefully picked based on the relevance to our hypothesis.

Research in virtual reality (VR) has emphasized the role of interaction fidelity in shaping user experiences and task performance. High-fidelity interactions, such as whole-body movements, enhance user engagement and presence [1]. Similarly, naturally-mapped controllers outperform gamepads in terms of immersion and ease of use [2]. Studies indicate that high-fidelity AR and VR systems improve the learning and retention of 3D object-related tasks [3]. These findings underscore the importance of optimizing interaction fidelity and locomotion techniques in VR applications.

Research on active control and motion cueing demonstrates that user-driven motion significantly enhances the perception of self-motion (vection) [4]. High-fidelity systems, such as those that enable natural movements and active control, create immersive experiences and reduce motion sickness [5]. Robust avatar control systems have been found to improve communication behaviors in VR [6]. Furthermore, prototyping tools and semi-natural interfaces facilitate the design of high-fidelity VR experiences [7]. Studies also indicate that display fidelity influences physiological responses, with higher fidelity environments leading to more realistic interactions [8]. Haptic feedback systems, like the Flowing-Haptic Sleeve, simulate tactile sensations effectively, further improving the realism of VR interactions [9]. Finally, frameworks like SIVARG underline the importance of spatial interaction in gaming and training applications, demonstrating how fidelity enhances user satisfaction [10]

III. Hypothesis and Experiment Design

Hypothesis

The main research question for this study is: *How does the method of locomotion affect performance in spatial learning tasks in a VR HMD environment?* To address this, we define the following hypotheses:

- **Alternative Hypothesis (H_A):** There is an effect of the method of locomotion on performance in spatial learning tasks in VR HMD environments.
- **Null Hypothesis (H_0):** There is no effect of the method of locomotion on performance in spatial learning tasks in VR HMD environments.

Variables and Operationalization

The following are the variables that were chosen:

- **Independent Variable (IV):** Method of locomotion. The two levels of this independent variable are:
  - **Joystick locomotion:** Participants use a joystick to navigate the virtual environment.
  - **Walking locomotion:** Participants physically walk in the real-world space to navigate the virtual environment.
- **Dependent Variables (DV):**
  1) **Performance in the task:** Operationalized using the below two measures:
     a) **Score in the task:** Number of objects correctly placed in the virtual environment (ordinal scale, from 0 to 4).
     b) **Time taken:** Total time participants take to place the objects during the recall phase (continuous, measured in seconds).
  2) **Sense of presence:** Evaluated using a presence questionnaire, scored on an integer scale.
  3) **Simulator sickness:** Evaluated using the Simulator Sickness Questionnaire (SSQ), scored on a continuous scale.
- **Control Variables:** Factors that were kept constant to minimize possible confounds:
  1) **Display fidelity:** To ensure that all participants experienced the same visual quality in the VR environment, only 1 HMD device was used throughout, which is the Meta Quest 3.
  2) **Task complexity:** The same task was used for all participants, with identical object arrangements and room configurations.
  3) **External environmental conditions:** The study was conducted in a controlled laboratory setting to ensure consistent external factors.
  4) **Performance Effect:** This was mitigated by adopting a between-subjects design, with each participant undergoing only 1 trial.
  5) **Prior Familiarity with VR**: This was controlled by having everyone complete a tutorial phase, which did not have a time limit. We only went forward with the actual experiment when they were comfortable with moving around, picking up and placing objects.

Experiment Flow

The experiment was designed as a **true experiment** with a between-subjects design, where participants were randomly assigned to one of the two locomotion conditions (referred to henceforth as "Joystick" or "Walking"). The steps of the experiment are as follows:

IV. Procedure

The study consisted of five main phases: Consent and Demographic Data, Familiarization, Memory, Recall, and Post-

Task Questionnaire. These phases are outlined in more detail below.

1) **Consent and Demographic Data:** Participants were first briefed on the study's purpose, procedures, and any potential risks involved. They were informed that participation was voluntary and they could withdraw at any time without penalty. Following this, participants provided informed consent by signing a consent form. In addition to the consent, participants completed a demographic questionnaire, which included **age**, **gender**, **prior VR experience** and **motion sickness susceptibility**. Participants were also asked verbally if they were prone to motion sickness. If they were hesitant to participate due to the potential risk of motion sickness, we advised them not to participate.

Fig. 1: Participant Exploring VR using Joysticks

2) **Familiarization Phase:** After completing the consent and demographic data collection, participants were introduced to the virtual reality environment. The VR setup included the use of a head-mounted display (HMD) (**Meta Quest 3**) and controllers. Participants were given a brief demonstration of how to navigate within and interact with the virtual environment.
Participants were given a short tutorial session to allow them to become comfortable with the VR interface and locomotion system. This familiarization phase was intended to reduce any initial discomfort or confusion, ensuring that participants were ready for the main task. The participants were free to take any amount of time until they were confident operating in the VR environment.

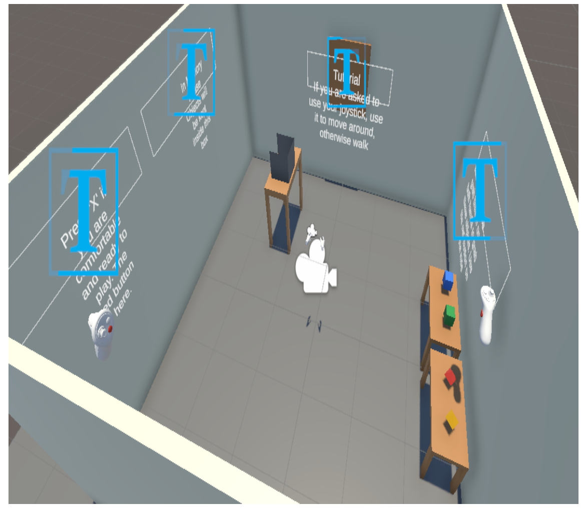

Fig. 2: Top View of Virtual Room in Tutorial Phase

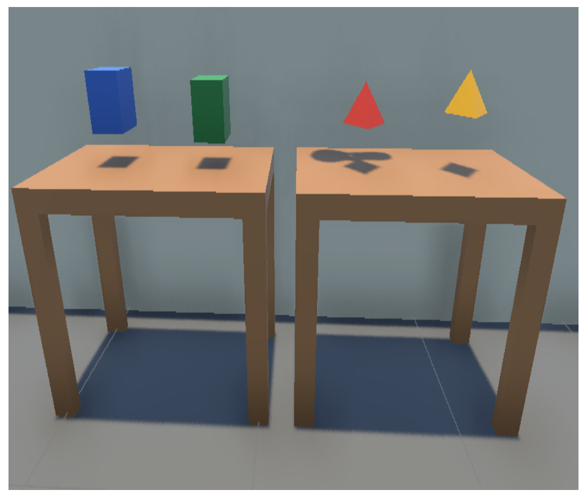

Fig. 3: Different Objects: There were a total of 8 objects (2 shapes and 4 colors for each shape)

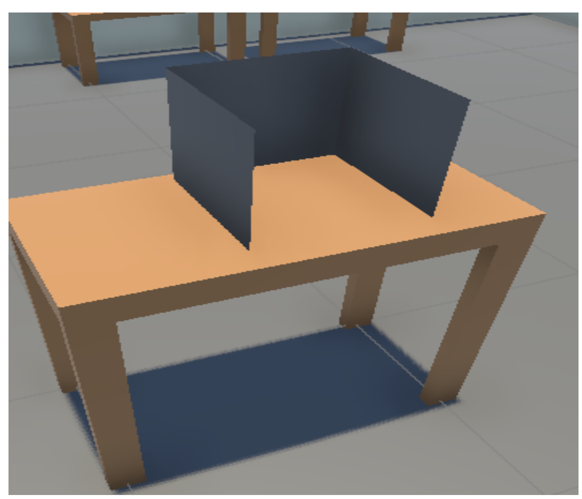

Fig. 4: The Table and the Visual Barrier

3) **Memory Phase:** After participants were comfortable, the main task began. In the memory phase, participants were placed in the center of a virtual room containing four tables with a visual barrier (see Fig. 4), with one object placed on each table (see fig. 3). They were instructed to explore the environment for a fixed duration of 60 seconds and memorize the spatial location of the four objects within the room. We told them not to focus on the orientation of the objects themselves, only on which table they were kept.

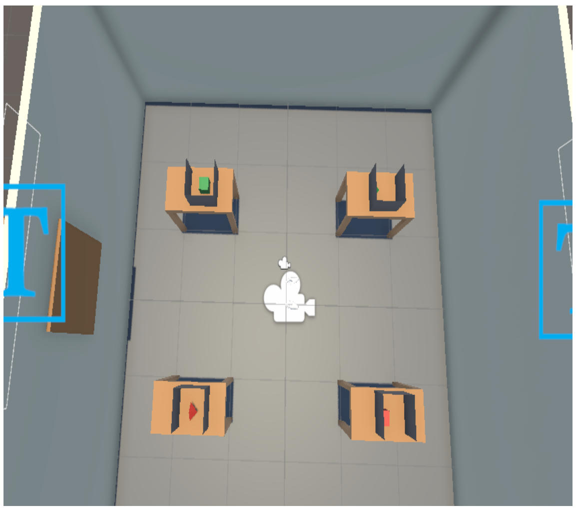

Fig. 5: Top View of Virtual Room with Objects in Memory Phase

4) **Recall Phase:** After completing the memory phase, participants entered the recall phase. It consisted of 8 objects kept around the room and 4 tables with the visual barriers removed (see Fig. 6). Starting from the center of the room, the participants were asked to place the original 4 objects back onto their respective tables. They were not given a time limit to do this. Instead, they were told to finish the task and end the phase when they felt confident with their object placement.
5) **Post-Task Questionnaires:** Once the recall phase was completed, participants were asked to fill out two post-task questionnaires.
   - **Presence Questionnaire:** This questionnaire assessed the participants' sense of presence in the virtual environment. A few questions from the **Witmer-Singer Presence Questionnaire** [15] were used. Participants rated their experience on aspects such as immersion, realism, and involvement in the task.
   - **Simulator Sickness Questionnaire (SSQ):** To measure any discomfort or motion sickness experienced during the VR task, participants completed the **SSQ** [16], [17], which provided a score based on symptoms such as nausea, dizziness, and general discomfort.

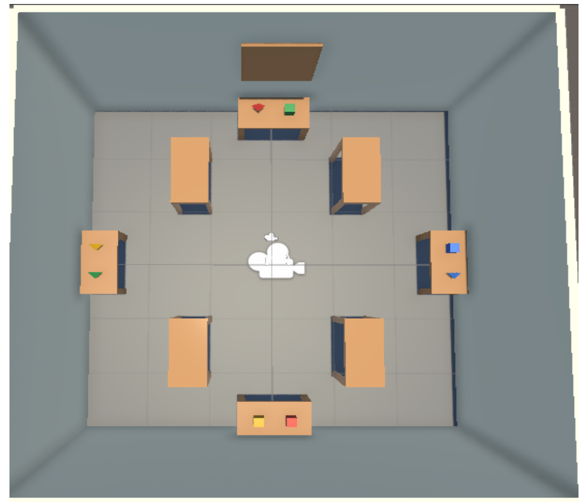

Fig. 6: Top View of Virtual Room with Objects in Recall Phase

V. Data Collection and Analysis

Participants and Data Collection

This study recruited a total of **40 participants (10 Women, 30 Men) of ages 18 to 22 (Mean: 19.43 yrs, SD: 0.931 yrs)** using a combination of **convenience and snowball sampling techniques**. The participants were undergraduate students from **IIIT Hyderabad**, selected for their accessibility and relevance to the study's target demographic. The study was a between group study. **20 participants were randomly allocated to each condition** based on an initial participation form they had filled out.

Almost all participants had **little to no prior experience with VR**. Most participants had no visual impairments. Some participants reported Myopia (which does not affect their performance in the task), while none reported **colorblindness** which we had identified as a possible issue given our experiment design. As a result, we did not have to exclude any participant from the study on these grounds. One participant was excluded due to their susceptibility to motion sickness.

Data collection took place over the course of **5 days spread across 3 weeks**. Each participant took around **13.05 minutes to complete the entire experiment on average (SD:2.37 min)**. We initially rolled out a participation form to gather participants. Later, we urged those who had participants to bring more people to participate. A small monetary benefit was offered to the participants. The data collection took place in the Dance Room (Nilgiri room 314), during the evening time (when most participants were free).

Data Analysis

Task Performance:

1) **Time Taken (measured in seconds):**
   - **Walking condition:** Mean: **44.07 s** (SD: **11.594 s**), Median: **44.40 s**. No outliers were observed.
   - **Joystick condition:** Mean: **92.90 s** (SD: **48.88 s**), Median: **82.15 s**. One outlier (**246 seconds**)

was identified and excluded from the joystick data during significance testing.

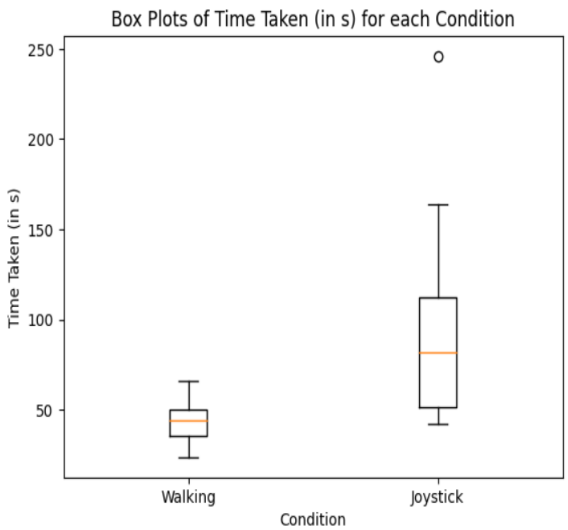

Fig. 7: Boxplot of Time Taken ($p < 0.001$)

2) **Objects Correctly Placed:**
   - **Walking condition:** The median and mode were both **4**.
   - **Joystick condition:** The median and mode were both **2**,.
   - One outlier (**2 objects**) was identified in the walking condition but was not excluded during the statistical analysis.

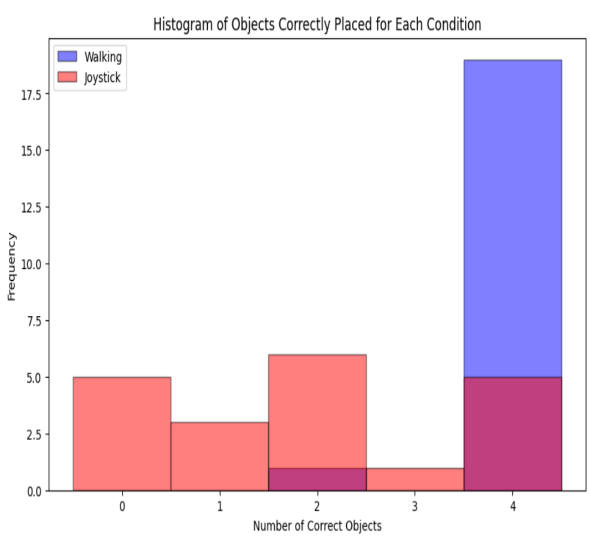

Fig. 8: Histogram of objects correctly placed ($p < 0.001$)

***User Experience:*:**

1) **Sense of Presence:** Presence was measured on a scale from 0 to 7 using a validated presence questionnaire. Higher scores indicate a stronger sense of immersion in the virtual environment.
   - **Walking condition:** The mean score was **6.10**, with a median of **6.09**, indicating a strong sense of presence in this condition.
   - **Joystick condition:** The mean score was **5.15**, with a median of **5.22**, reflecting a slightly weaker sense of presence compared to walking.
   - One outlier (**5.09**) was identified in the walking data but was retained for analysis.

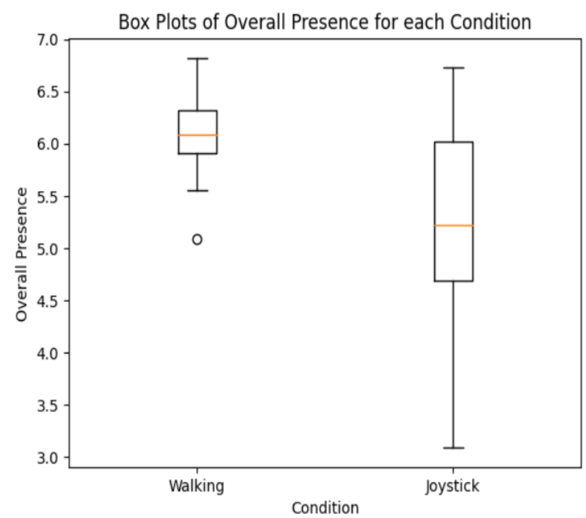

Fig. 9: Box plots of self-reported overall presence (out of 7) ($p < 0.001$)

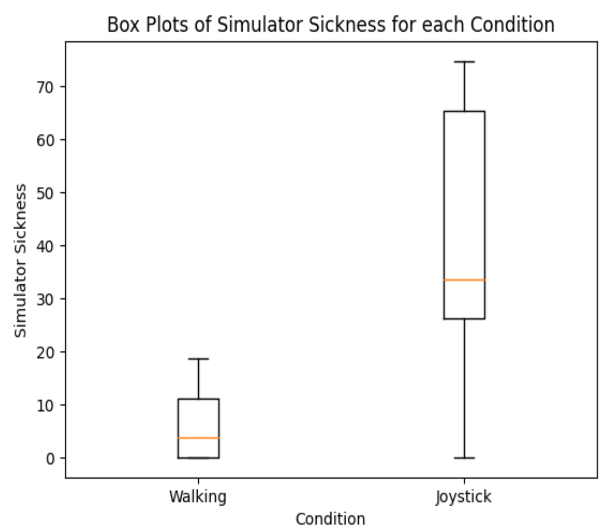

Fig. 10: Box plots of self-reported Simulator Sickness scores (out of 300) ($p < 0.001$)

2) **Simulator Sickness:** This was measured using the Simulator Sickness Questionnaire (SSQ), with higher scores indicating greater levels of discomfort. The maximum possible SSQ score is approximately 300.

- **Walking condition:** The mean score was **5.98**, with a median of **3.74** and a mode of **0**, suggesting minimal simulator sickness in this condition.
- **Joystick condition:** The mean score was substantially higher at **40.14**, with a median of **33.66** and a mode of **33.66**, indicating higher levels of discomfort.

VI. Results and Discussion

Significance Testing:

- **Time Taken:** After removing outliers and confirming acceptable normality (Shapiro-Wilk test), an independent t-test was conducted, yielding a significant result ($p < 0.001$).
- **Objects Correctly Placed:** Since normality was not observed, a Mann-Whitney U test was used, with a significant result ($p < 0.001$).
- **Simulator Sickness:** Normality was not observed, so a Mann-Whitney U test was performed, yielding $p < 0.001$.
- **Sense of Presence:** Normality was observed, so an independent t-test was applied, yielding $p < 0.001$.

Findings:

- **Task performance:** The Walking condition consistently outperformed the Joystick condition in terms of both time taken and spatial memory accuracy. Participants using the walking method completed the task faster and placed more objects correctly. This is consistent with previous findings and indicates that more naturalistic methods of locomotion can lead to improvement in task performance.
- **Sense of Presence:** Participants in the Walking condition reported a higher sense of presence compared to those in the Joystick condition. This indicates that walking creates a more immersive experience, likely due to its natural alignment with real-world locomotion, when compared to locomotion using joysticks.
- **Simulator Sickness:** Participants in the Walking condition reported significantly lower simulator sickness scores compared to those in the Joystick condition. This is also consistent with previous findings Higher sickness scores for joystick-based navigation could be attributed to a disconnect between physical and virtual movements, causing discomfort or motion sickness.
- **Participant Feedback:**
  - **Clarity of Instructions:** Most participants felt the instructions were well-explained for both conditions.
  - **Task Difficulty:** Participants in the walking condition found the task easier, while joystick users rated it as moderately challenging.
  - **Ease of Navigation:** Walking was rated as significantly more intuitive and comfortable than joystick navigation, which received mixed feedback due to unintuitive controls.

VII. Limitations

Despite the promising results, several limitations of the study must be acknowledged:

- **Sample Size and Diversity:** The sample size of 40 participants was relatively small and restricted to undergraduate students from a single institution. This limits the generalizability of the findings to broader populations.
- **Convenience Sampling:** The use of convenience and snowball sampling methods reduces external validity, as participants may not be representative of typical VR users.
- **Single Task Design:** The study focused solely on a spatial memory task. The findings may not generalize to other types of VR tasks, such as navigation, problem-solving, or collaborative tasks.
- **Ceiling Effect in Walking Condition:** Many participants in the walking condition achieved near-perfect scores, potentially masking more subtle differences in performance.
- **Simulator Sickness' effect on performance:** While simulator sickness was measured, its direct impact on task performance was not explicitly analyzed. Future studies should explore this relationship in greater detail.
- **Control Over External Variables:** Although efforts were made to control environmental conditions, factors such as individual familiarity with VR could still have influenced results.

VIII. Future Work

Building upon this study, future research can explore the following directions:

- **Broader Population Studies:** Conduct experiments with a more diverse participant pool, including individuals from various age groups, professions, and levels of VR experience.
- **Expanded Locomotion Methods:** Investigate additional locomotion techniques, such as teleportation, treadmills, or hand-tracked navigation, to understand their impact on task performance and user experience.
- **Different Task Types:** Evaluate the effects of locomotion on other VR tasks, such as path-finding, problem-solving, or collaborative activities, to generalize findings across different domains.
- **Longitudinal Studies:** Conduct studies over extended periods to assess whether proficiency with joystick locomotion improves performance and reduces simulator sickness over time.
- **Real-World Applications:** Validate findings in applied settings, such as military training simulations, educational environments, or therapeutic contexts, to ensure practical relevance.

IX. Conclusion

We see that a more naturalistic method of locomotion to navigate virtual environments increases the user's performance in a spatial learning task. We also observe that participants tend to be more immersed and experience less simulator sickness when physically walking to move in the virtual environment, rather than when they move with joysticks. Overall, this gives impetus to VR environment developers to add more naturalistic methods of locomotion to increase the user experience and efficiency. What countermeasures can be taken to increase the user experience and efficiency if such methods of locomotion are infeasible (such as when there is not enough space to physically walk) is still an open question and worth looking into in future studies.

X. Acknowledgment

We would like to thank SERC for providing us Meta Quest 3 headsets and IIIT-Hyderabad for allocating us a space whenever required to conduct the experiment. We would also like to extend our thanks to Dr. Vinoo Alluri for her guidance and feedback throughout the process.

References

[1] Exploring Interaction Fidelity in Virtual Reality: Object Manipulation and Whole-Body Movements. (2020).
[2] Comparing Gamepad and Naturally-Mapped Controller Effects on Perceived Virtual Reality Experiences. (2019).
[3] When High Fidelity Matters: AR and VR Improve the Learning of a 3D Object. (2022).
[4] To Move or Not to Move: Can Active Control and User-Driven Motion Cueing Enhance Self-Motion Perception (”Vection”) in Virtual Reality? (2019).
[5] Real Virtuality: A Step Change from Virtual Reality. (2018).
[6] Exploring the Use of a Robust Depth-Sensor-Based Avatar Control System and Its Effects on Communication Behaviors. (2020).
[7] Designers, the Stage Is Yours! Medium-Fidelity Prototyping of Augmented & Virtual Reality Interfaces with 360Theater. (2021).
[8] Impact of Graphical Fidelity on Physiological Responses in Virtual Environments. (2019).
[9] Flowing-Haptic Sleeve: Research on Apparent Tactile Motion Applied to Simulating the Feeling of Flow on the Arm. (2020).
[10] SIVARG: Spatial Interaction in Virtual/Augmented Reality and Games. (2021).
[11] A Separate Reality - An Update on Place Illusion and Plausiability in VR. (2022).
[12] Comparing the Performance of Natural, Semi-Natural, and Non-Natural Locomotion Techniques in Virtual Reality. (2015).
[13] Effect of environmental Features, self-avatar, and immersion on Object location. (2016).
[14] Desktop VR Is Better Than Non-ambulatory HMD VR for Spatial Learning. (2019).
[15] Measuring Presence in Virtual Environments: A Presence Questionnaire. (1998).
[16] Simulator Sickness Questionnaire: An Enhanced Method for Quantifying Simulator Sickness. (1993).
[17] On the Usage of the Simulator Sickness Questionnaire for Virtual Reality Research. (2020).