Method of Locomotion Impacts Spatial Learning Tasks in VR HMD Environments

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Abstract

Virtual reality (VR) provides immersive simulations, allowing users to experience "alternate realities" without real-world risks, and is a potent tool for studying spatial cognition. Active spatial learning benefits from podokinetic and idiothetic information, which is influenced by the method of locomotion within a virtual environment. Full gait techniques (FGTs) preserve this information, while gait negation techniques (GNTs) can lead to its loss. The present study investigates the effect of locomotion method (physical walking vs. joystick) on performance in a simple, primarily egocentric spatial learning task, in a VR head-mounted display (HMD) environment. Participants were tasked with remembering the spatial locations of objects within a virtual room. They were then asked to recall and correctly place the objects back in their original locations. Our findings indicate that walking-based navigation (FGT) significantly enhanced the participant's performance in spatial learning tasks compared to joystick-based navigation (GNT). This research aims to contribute to the design of effective VR-based training and learning applications, considering cost and space limitations, and inform future directions in VR spatial cognition research.

Keywords Virtual Reality; Locomotion; Spatial Learning; Spatial Cognition; Immersion; Sense of Presence; Simulator Sickness.

Introduction

Virtual reality (VR) is poised to revolutionize various industries by enabling users to experience "alternate realities" without real-world risks or inconveniences (Chalmers, Howard, & Moir, 2009). This makes VR particularly appealing for applications where safety, cost, or practicality is a concern, such as military training simulations (Steven, Hauw, Keane, & Gunawan, 2023), psychological therapy techniques (Wiebe et al., 2022), and immersive gaming experiences (Tao, Garrett, Taverner, Cordingley, & Sun, 2021). VR is also poses as a useful tool to enhance the experience of education in various disciplines (Rojas-Sánchez, Palos-Sánchez, & Folgado-Fernández, 2023). It has immense potential in the field of Cognitive Training, especially for those at risk of cognitive decline (Coyle, Traynor, & Solowij, 2015). In particular, Virtual Reality has proven to be an effective tool in spatial memory training (Diersch, 2019; Plechatá, Nekovářová, & Fajnerová, 2021). This is because VR is successfully able to simulate the feeling of navigating through a physical space, with a level of immersion or realism that no other media has been able to achieve. Considering the effectiveness of VR in applications involving spatial tasks, it is interesting to look at other aspects of spatial memory and whether VR can prove to be useful in those domains.

Before delving into the aspects of spatial memory, we must look at how the brain processes and stores spatial information. The collection, organization, use, and revision of information about one's environment is called *Spatial Cognition* (American Psychological Association, n.d.). Spatial information is processed using two main frameworks: the *egocentric perspective*, which depends on our point of view and our orientation in space, and the *allocentric perspective*, which depends on our memory of objects and stimuli in the environment around us. Studies suggest that different parts of the mammalian brain are associated with storing and processing spatial information in either perspective (Rinaldi et al., 2020). In addition, spatial learning might be either an active or passive endeavor. This can be thought of as being seated in the driver's seat when exploring a new town versus being seated in the passenger seat and being given a guided tour of the town. While passive spatial learning can be thought of as mostly allocentric, factors such as *podokinetic information* and *idiothetic information* contribute to active spatial learning (Weber, Fletcher, Gordon, Jones, & Block, 1998; Mittelstaedt & Mittelstaedt, 2001; Chrastil & Warren, 2013).

When navigating virtual environments in VR, whether or not the user is able to accumulate podokinetic and idiothetic information is majorly dependent on the method of locomotion used. The prevalent methods of locomotion in VR can be classified into 3 major categories (Al Zayer, MacNeilage, & Folmer, 2020): Full Gait Techniques (FGTs), such as real walking to move in the virtual environment, Partial Gait Techniques (PGTs), such as Walking In Place using a virtual treadmill (Slater, Steed, & Usoh, 1995), and Gait Negation Techniques (GNTs), such as navigation using joysticks. Full Gait techniques preserve podokinetic and idiothetic information, while the use of Gait Negation Techniques leads to loss of this information.

What sets VR apart from other forms of media is the level of immersion that it provides. Sense of Presence is a valuable metric used to measure a user's level of immersion. It can be broadly defined as the extent to which a virtual environment becomes a user's subjective reality (Slater et al., 2022). Considering this, it might be tempting to assume that a more 'naturalistic' method of interacting with the virtual environment is always beneficial in tasks involving spatial cognition. However, this is not the case. For instance, previous studies comparing different modes of visual interaction (or *display fidelity*) with virtual environments have yielded mixed results (Feng, Duives, & Hoogendoorn, 2022; Murcia-López & Steed, 2016; Sousa Santos et al., 2009; Srivastava, Rimzhim, Vijay, Singh, & Chandra, 2019). Furthermore, even with the display fidelity constant, more naturalistic interactions with the virtual environment (or higher *interaction fidelity*) do not always lead to better performance in spatial cognition tasks (Mania, Wooldridge, Coxon, & Robinson, 2006). In reality, enhanced visual immersion can often cause a cognitive mismatch, leading to a set of symptoms that are a type of Simulator Sickness collectively called Virtual Reality-Induced Symptoms and Effects (VRISE) (Cobb, Nichols, Ramsey, & Wilson, 1999). Since such symptoms are known to hinder cognitive performance related to navigation (Metzulat, Metz, Landau, Neukum, & Kunde, 2025), the trade-off between higher immersion that VR provides and the VRISE that is induced is not always straightforward in this respect. Furthermore, for situations in which monetary resources and physical space is limited, the difference between usage of FGTs (which are either more expensive or require a large amount of physical space) and usage of GNTs (which might be more feasible in certain scenarios, but might lead to VRISE) becomes important to consider when designing spatial learning tasks in VR.

In the present study, we explore how the method of locomotion affects performance in a primarily egocentric spatial learning task in a VR HMD environment. We choose to compare physical walking to movement via joysticks, since they are two prominent examples of FGTs and GNTs respectively. It is worth noting that there are some existing studies that look into similar domains (León, Tascón, Ortells-Pareja, & Cimadevilla, 2018; Langbehn, Lubos, & Steinicke, 2018). However, they are aimed at either an allocentric perspective or a combination of allocentric and egocentric perspectives. The literature on tasks that focus on an egocentric perspective remains limited. We hypothesize that the locomotion method of physically walking leads to an increase in task performance, when compared to moving using joysticks. We also explore how the sense of presence and simulator sickness levels differ in each condition, and whether they could act as possible confounds. Finally, we talk about some future directions that could be explored in the realm of spatial cognition in VR.

Methods

Data Collection

41 participants (30 male, 11 female, 0 others) were recruited using convenience sampling. Self-reported colorblindness and self-reported history of severe motion sickness were identified as exclusion criteria for the study. One participant was excluded on these grounds. A total of 40 participants with a mean age of 19.43 years ($SD = 0.931$ yrs) completed the experiment. All of the participants were undergraduate college students. Participants were divided into 2 groups in a randomized manner. 20 participants were assigned the *Walking* condition and 20 were assigned to the *Joystick* condition. All participants provided their informed consent to participate in the experiment. Almost all participants were found to have little to no prior experience with VR HMDs. Most of the participants had no visual impairments, while some participants reported myopia (which would not affect their performance in the task).

Data collection was carried out over the course of five days spread over three weeks. Each participant took around 13.05 minutes on average (SD:2.37 min) to complete the entire experiment. The participants spent 4 to 6 minutes wearing the HMD, while the rest was spent filling in short surveys before and after the task was completed. A small monetary benefit was offered to the participants. Data collection was carried out in a well-lit, sufficiently large, closed room in the evening.

Equipment Used

The scenes were presented to the participants through a Meta Quest 3 head-mounted display (horizontal FOV of 110 degrees, 2064x2208 pixels per eye, 120Hz refresh rate). Locomotion was facilitated by physically walking in the room for the *Walking* condition, and using the Meta Quest 3's hand-held joysticks for the *Joystick* condition. The surveys were implemented and presented online using the PsyToolkit platform (Stoet, 2010, 2017).

Figure 1: Participant exploring a virtual environment using joysticks

Design

Our experiment was a between-groups design, with two levels of locomotion (*Walking*, *Joystick*). After filling up the consent form and initial demographic questions, the participant moved onto the spatial learning task, which consisted of the following three phases:

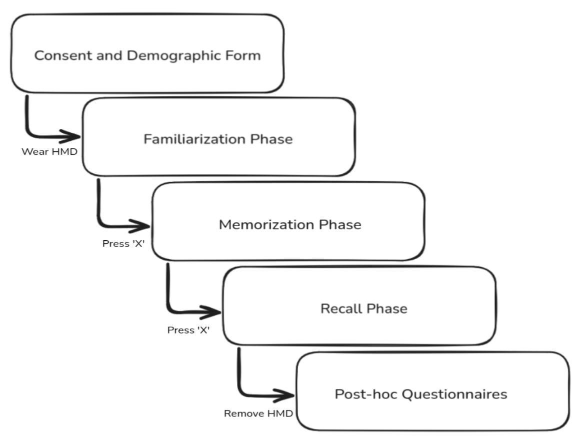

Figure 2: Flow of the experiment.

Familiarization Phase This phase took place in the tutorial room (see Fig. 5). Participants given a detailed explanation of the task (memorization and recall phases) during this phase. They were asked to get comfortable with moving around in the virtual environment, avoiding obstacles (like tables, see Fig. 3), and picking up and placing objects (see Fig. 4). It was ensured that the visual barrier kept on the table was high enough that participants could not bend over it to look at the other side. Also, there were a total of eight objects: four colored cubes and four colored rectangular pyramids. Each type of object was either blue, red, yellow or green. Real-world objects were avoided since a participant's familiarity with an object could influence how well they can remember and recall it. The participants could take as much time as they wanted, and were asked to move on only when they felt comfortable with the controls and had clarity of the task they were going to perform. This phase was meant to help those with little to no prior experience with VR get comfortable and ready for the actual task. It was also meant to let participants familiarize themselves with the actions (picking up and placing objects, moving around, observing their environment) they would have to perform during the task.

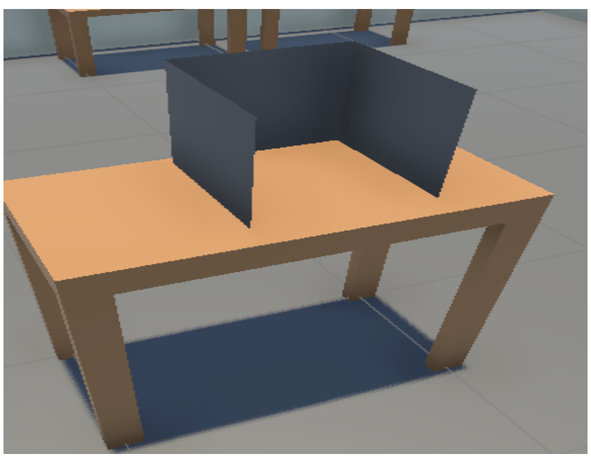

Figure 3: A table with a visual barrier on top.

Memorization Phase Participants were prompted to press 'X' to start this phase. When they did, they were transported to the room for this phase (see Fig. 6). A timer that started counting down from 60 seconds was displayed on all four walls. Starting at the middle of the room, participants were tasked to move behind each table and remember which object had been placed on them. The tables were identical and unlabeled, ensuring that participants would have to remember the spatial configuration of the objects in the room with respect to their starting orientation. Once the 60 seconds were over, participants were transported into an empty room and were instructed to press 'X' when they were ready to proceed.

Recall Phase Participants were transported into the room for this phase (see Fig. 7). They were told to place the right objects on their corresponding tables and press 'X' when they were confident with their placements. There was no time limit for this phase. Instead, the time taken (in seconds) to complete this phase was recorded, as well as how many objects were correctly placed (out of a maximum of 4). These two metrics were used as indicators of *task performance*, as they indicated how well participants could recall the correct configuration of objects, as well as how quickly they felt confident of their placements (both together indicating their overall quality of spatial memory and recall). After completion of this phase, the participants were asked to remove the HMD. They were given some time to recover and moved on when they were ready.

Finally, participants were given a short survey that included a presence questionnaire (adopted from (Witmer & Singer, 1998)), a simulator sickness questionnaire (adopted from (Kennedy, Lane, Berbaum, & Lilienthal, 1993)), and questions regarding general feedback and difficulty of the task.

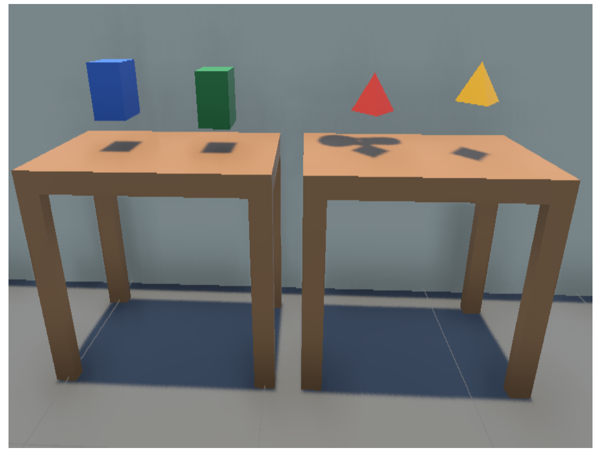

Figure 4: 4 objects placed on stools.

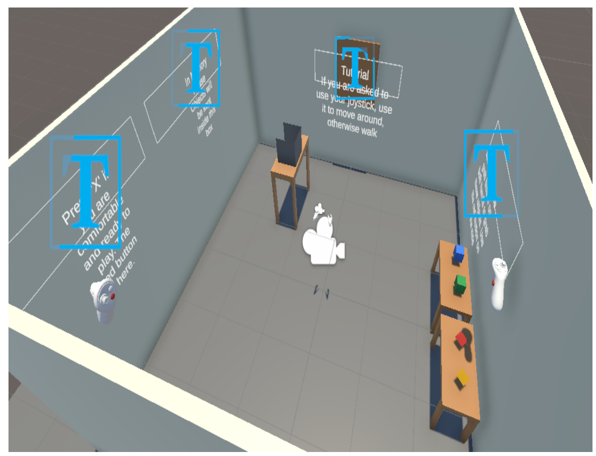

Figure 5: Top view of the virtual room used in the tutorial phase.

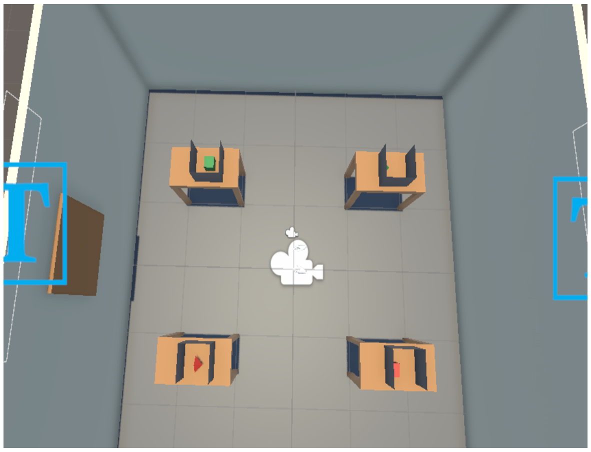

Figure 6: Top View of Virtual Room in the Memory Phase: 4 out of the 8 total objects were randomly selected and placed onto the 4 tables, one on each table. They were not visible from the center of the room due to the barrier. The participant started at the center of the room, facing the square on one of the walls.

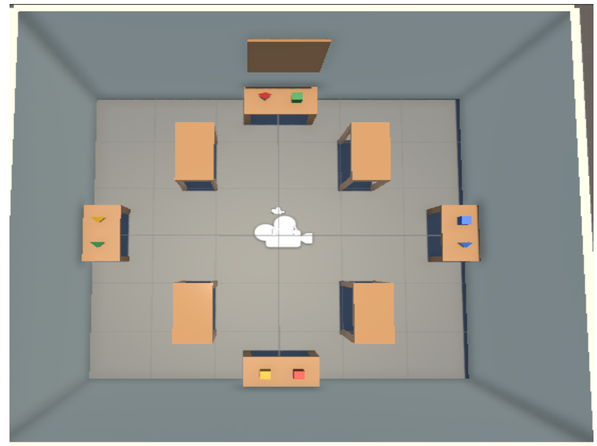

Figure 7: Top View of Virtual Room with the in Recall Phase: 8 objects were randomly placed on tables (with no correlation to how they were placed in the memory phase), 2 each near each wall of the room. The participant started in the same place and orientation as the previous phase.

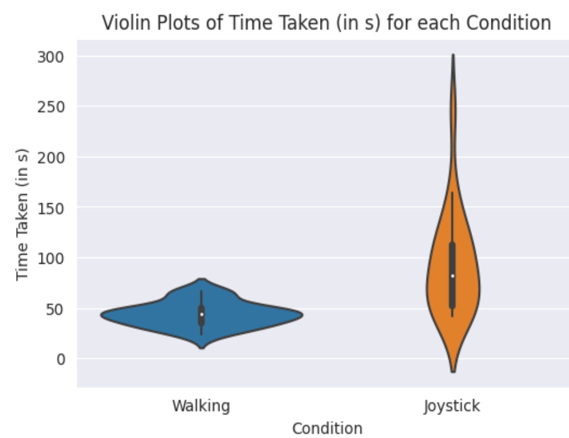

Figure 8: Violin Plot of Time Taken (in seconds).

Results

All outlier calculations were done using the Inter-Quartile Range (IQR) method. They were not excluded during the significance testing (except for in the *time taken* metric, where it was done to preserve normality). Independent t-tests were used for *time taken* and *sense of presence* metrics (Cohen's d reported for effect size), while the Mann-Whitney U test was used for *objects correctly placed* and *simulator sickness* scores (Common Language Effect Size reported for effect size), due to their non-normality (calculated using the Shapiro-Wilk test). SciPy was used for the inferential statistics calculations. The findings are summarized below.

Task Performance

Time taken The *Walking* condition had a mean of 44.07 seconds and a standard deviation of 11.594 seconds, with no outliers being detected. The *Joystick* condition had a mean of 92.90 seconds with a standard deviation of 48.88 seconds. One outlier was detected (246 sec). The time taken to complete the task was significantly lower ($t = 4.81, p < 0.0001$, 95% CI $[0.0000, 0.0011]$) in the *Walking* condition as compared to the *Joystick* condition with a high effect size ($d = -1.526$, 95% CI $[-2.154, -0.899]$) (see Fig. 8).

Objects Correctly Placed The *Walking* condition had a mean and mode of 4. One outlier (2 objects) was observed using the IQR method. It was not excluded during the significance testing. The *Joystick* condition had a mean and mode of 2, with no outliers observed. Participants in the *Walking* condition placed significantly more objects correctly ($U = 343.5, p < 0.0001$, 95% CI $[0.0000, 0.0007]$) compared to those in the *Joystick* condition with a high effect size ($CLES = 0.859$, 95%, CI $[0.825, 0.893]$) (see Fig. 9).

Sense of Presence

Sense of Presence was measured using a set of questions scored on a 7-point lickert scale adopted from the Witmer-Singer Presence Questionnaire (Witmer & Singer, 1998). Average of responses to each question was taken to get a final score out of 7. The *Walking* condition had a mean score was 6.10, with a median of 6.09, with one outlier (5.09). *Joystick* condition had a mean score was 5.15, with a median of 5.22, with no outliers. Participants in the walking condition reported a significantly higher sense of presence ($t = 3.67, p = 0.0004$, 95% CI $[0.0000, 0.0063]$) compared to the joystick condition with a high effect size ($d = 1.162$, 95% CI $[0.542, 1.781]$) (see Fig. 10).

Simulator Sickness

Simulator Sickness was measured using the Simulator Sickness Questionnaire (SSQ) (Kennedy et al., 1993). A mod-

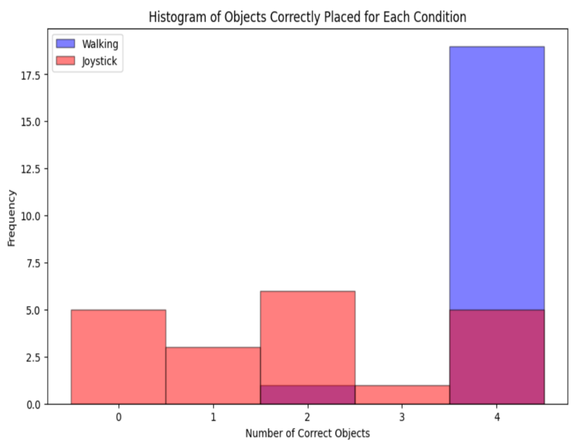

Figure 9: Histogram of number of objects correctly placed.

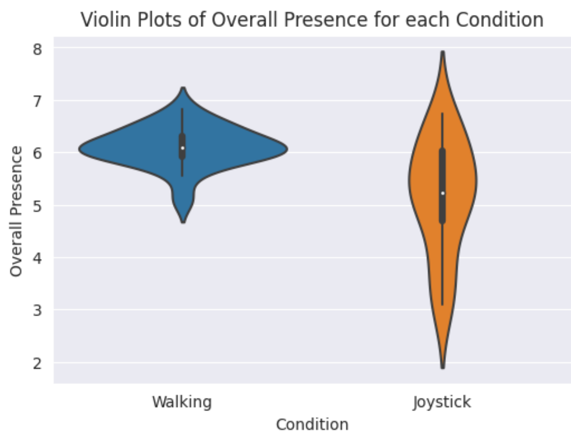

Figure 10: Violin Plot of self-reported Sense of Presence scores.

ified scoring system was adopted (Bimberg, Weissker, & Kulik, 2020) which is more suitable for VR applications. The maximum possible SSQ score under this regime would be 235.62. The *Walking* condition had a mean score was 5.98, with a median and mode of 0. There were 4 outliers (37.40, 18.70, 14.96 and 33.66). The *Joystick* condition had a mean score of 42.64, with a median of 33.66 and a mode of 3.74. The *Joystick* condition resulted in significantly higher simulator sickness scores ($U = 347.0, p < 0.0001$, 95% CI $[0.0000, 0.0016]$) when compared to the *Walking* condition with a high effect size ($CLES = 0.867$, 95%, CI $[0.834, 0.901]$) (see Fig. 11).

Discussion

The method of locomotion matters

The *Walking* condition consistently outperformed the *Joystick* condition in both metrics designed to test performance in the spatial learning task. Furthermore, participants in the *Walking* condition reported significantly higher levels of presence and much lower levels of simulator sickness than participants in the *Joystick* condition. Both of these results are consistent with previous findings. Also, it is worth noting that no significant correlation was found between scores of presence or simulator sickness and the two performance metrics, across both conditions (see Fig. 12). This indicates that presence and simulator sickness were not major factors in influencing task performance.

These findings help strengthen the argument of a more ‘naturalistic’ way of interacting with a virtual environment being better for cognitive tasks such as spatial learning. However, they also indicate that while the method of locomotion plays a very important role, other factors such as sense of presence and VRISE are not significant factors. A possible explanation for this observation could be the strong connection podokinetic and idiothetic cues have with spatial processing. When this information is lost, it becomes much harder for the participant to reorient themselves, especially due to the lack of reference points in the virtual room.

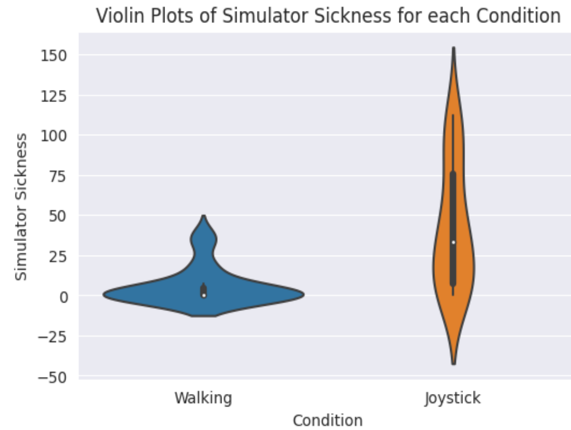

Figure 11: Violin Plot of self-reported Simulator Sickness scores.

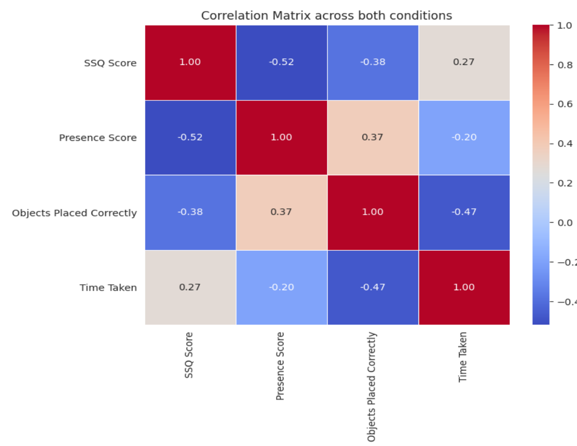

Figure 12: Correlation matrix across conditions.

Future directions

There are many avenues that can be explored to expand upon this study. Even though the results of the study indicate that the method of locomotion affects task performance, it could be argued that the effect is due to the fact that more 'naturalistic' controls are easier to adopt since they are closer to real-world experiences. For this reason, future studies could aim to be longitudinal in nature, with more complex tasks, aiming to see whether the effect of locomotion diminishes as the user becomes more comfortable with the controls. To improve the generalizability of the findings, future studies should use a more diverse participant pool, including individuals from various age groups, professions, and levels of VR experience. Also, Partial Gait Techniques such as hand-tracked navigation and walking in place could be included in future studies, to look at whether they are truly an intermediate between FGTs and GNTs in this respect. Finally, validating these findings in real-world applications, such as military training simulations where users are tasked with navigating unknown terrains, is essential to ensure practical relevance and applicability. This is especially important given the effectiveness of VR in such areas.

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