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Master Media Technology

Cognitive Voyages:
Navigating the Impact of Locomotion on Memory within Virtual Reality Memory Palaces

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Contents

Abstract

Virtual reality (VR) offers immersive spaces that challenge how we learn, move, and remember. As this technology becomes increasingly embedded in education and training, an open question remains: how do the ways we move through virtual spaces influence what we remember? Teleportation, while widely used, interrupts spatial continuity and may fragment memory, whereas embodied methods like Walking-in-place (WIP) engage sensorimotor cues that could strengthen recall. Yet little is known about whether such differences in locomotion meaningfully affect memory in VR.

This thesis investigates how teleportation and WIP influence spatial memory within a virtual memory palace, an adaptation of the ancient Method of Loci (MoL). The WIP condition was implemented through head-bobbing detection, providing a lightweight but embodied alternative to physical locomotion. Using a between-subjects experimental design, participants encoded and later recalled object–location pairs under one of the two locomotion conditions.

Results show that locomotion influenced both recall accuracy and the strategies participants employed. WIP participants achieved higher recall accuracy and more often developed path-based spatial narratives, whereas teleportation users relied on fragmented or visually anchored approaches. These findings underscore how embodied navigation fosters richer spatial encoding than abstract movement, emphasizing the role of sensorimotor cues in shaping memory strategies and outcomes. Together, they contribute to research on embodied cognition, highlight the need for further study of embodied interaction in VR memory systems, and offer practical guidance for designing VR environments and mnemonic tools that leverage active spatial engagement.

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1 Introduction

As digital technologies continue to advance, virtual reality (VR) and augmented reality (AR) are becoming increasingly embedded in domains such as gaming, education, training, and healthcare. Among these, VR has emerged as a particularly promising tool for cognitive training, offering immersive environments that support novel forms of learning and memory engagement [Hamad and Jia, 2022].

VR technology has progressed rapidly, moving from its early foundations in computer graphics to widespread use across multiple fields. Despite initial limitations, today's systems offer immersive experiences that overcome past technical barriers and hold the potential to transform human interaction across a range of domains [Cipresso et al., 2018]. As research continues to expand, VR presents unique opportunities for innovation and cognitive enhancement in education, healthcare, and beyond.

One of the most intriguing intersections of VR and cognitive science can be found in spatial cognition, which refers to the ability to acquire, organize, and use spatial knowledge to navigate environments [Kljajevic, 2021]. Spatial navigation is a fundamental cognitive skill that supports orientation, memory formation, and interaction within both physical and virtual worlds [Epstein et al., 2017].

In VR environments, the method of navigation significantly affects users' spatial awareness, memory, and overall engagement [Jeung et al., 2023]. The ability to interact with and move through virtual space shapes how users comprehend and recall spatial relationships around them, a key factor in many learning and training contexts.

VR's immersive qualities also make it well-suited for enhancing memory through embodied experiences. Applications range from surgical simulation and aviation training to therapeutic interventions, with empirical evidence that immersive VR can enhance recall compared to desktop conditions [Krokos et al., 2019].

However, a critical design factor in VR systems remains underexplored: how different locomotion techniques shape users' spatial experiences. Research has shown that the choice of locomotion interface "has a substantial impact on the kind of spatial experience" users gain [Tan, 2020], suggesting that more embodied approaches like walking-in-place may support richer spatial understanding, compared to teleportation, which lacks continuous sensory feedback. Yet, little is known about whether such embodied locomotion strategies truly enhance memory performance compared to more abstract forms of movement. This gap motivates the present study: to examine whether the type of locomotion employed fundamentally shapes how spatial information is encoded and recalled within a virtual memory palace, an adaptation of the MoL.

This thesis investigates how two locomotion techniques, teleportation and Walking-in-place, impact spatial memory and cognitive engagement in virtual reality. Using a virtual adaptation of the Method of Loci (MoL), an ancient mnemonic strategy that relies on spatial mapping, the study examines how embodied versus abstract movement influences object and location recall within a structured virtual environment.

Integrating principles from cognitive psychology into VR offers a novel way to enhance engagement and memory. Understanding how different locomotion techniques shape these processes could help guide the design of future VR systems for education, training, and therapy.

To address current gaps in the literature, this study compares the cognitive outcomes of teleportation and walking-in-place within a controlled experimental design. Previous research in VR memory has highlighted these gaps [Krokos et al., 2019; Vindenes et al., 2018], motivating a focus on how locomotion influences memory accuracy, task duration, and behavioral patterns, while also accounting for individual differences in virtual reality familiarity.

Participants are introduced to the VR environment and assigned one of two locomotion techniques. They then complete an Association Phase, where they place 12 distinct objects within a virtual apartment and are encouraged to form personal associations between each item and its chosen location. This is followed by a Recall Phase, in which they attempt to return the items to their original locations, guided by the system to retrace the path they created during the Association Phase. Behavioral and subjective data are collected to assess performance, strategies, and perceived immersion.

The findings of this study offer theoretical and practical insights into the role of movement in memory formation, with potential implications for the design of educational and training applications in VR. More broadly, understanding how embodied interaction supports cognitive processing could inform future approaches to immersive learning, cognitive rehabilitation, and digital memory tools.

This thesis is organized as follows: Chapter 2 reviews the development of VR, its cognitive applications, the Method of Loci in virtual settings, and relevant locomotion techniques. Chapter 3 outlines the research aims, guiding question, and hypotheses. Chapter 4 describes the experimental design, including participants, apparatus, procedure, and analysis methods. Chapter 5 presents the results, while Chapter 6 discusses their implications in relation to the research questions and literature. Finally, Chapter 7 concludes with a summary of key findings, limitations, and directions for future research.

By investigating how locomotion in VR influences memory performance within a mnemonic framework, this research contributes to the growing field of embodied cognition and enhances our understanding of how movement and memory interact in immersive environments.

2 Background and Related Work

2.1 Background and Evolution of VR

Originally emerging in the field of computer graphics, the study of VR has significantly expanded its domain. It now spans a diverse range of disciplines, reflecting both its evolution and the growing interest in its potential applications across different fields [Mazuryk and Gervautz, 1996].

2.1.1 Current state of VR

Recent advances in VR technology have transformed the field from its experimental origins into a widely accessible and versatile platform. A significant shift occurred in the 2010s with the release of consumer-grade headsets such as the Oculus Rift and HTC Vive, which introduced high-quality graphics, motion tracking, and interactive capabilities. These developments were further accelerated by major technology companies such as Meta, Sony, and Samsung [Jerald, 2015].

Modern VR is now integrated into diverse domains including simulation-based training, industrial prototyping, exposure therapy, surgical planning, and education [Basu, 2019]. A 2023 meta-analysis of 12 RCTs in nursing education found VR significantly improves theoretical knowledge, practical skills, retention, and satisfaction versus traditional teaching. [Liu et al., 2023]. These applications are not only practical but also enable the study of cognitive processes in ecologically valid environments that preserve experimental control.

For instance, early virtual environments were less effective than real-world navigation for supporting spatial learning, with users acquiring weaker spatial knowledge compared to physical exploration [Richardson et al., 1999]. However, more recent systems have overcome many of these issues, offering sensorimotor-rich interactions that improve spatial orientation and knowledge acquisition [Nürnberger et al., 2021]. These advancements make it possible to investigate how immersive, movement-based experiences shape cognitive functions such as memory. Recent comparisons of VR locomotion methods indicate teleportation can match walking for declarative learning outcomes [Rihs et al., 2024].

2.1.2 Core Components of Immersion in VR

Immersion in VR is not merely a matter of visual realism but a multifaceted experience involving perceptual, cognitive, and interactive dimensions. Two key components often highlighted as drivers of realistic responses in VR are *place illusion* (the sensation of being in a place) and *plausibility* (the credibility of events happening within that place) [Slater, 2009]. These arise from a convergence of several design factors: the presence of a coherent virtual environment, high levels of sensory fidelity (visual, auditory, and sometimes haptic), and meaningful user interaction with the environment. One critical but sometimes overlooked aspect of this interaction is the method of locomotion—how users move within the virtual space—which shapes their sense of embodiment and spatial presence [Caputo et al., 2023].

As VR technologies evolve to provide richer sensory input and more naturalistic interaction, researchers are increasingly investigating their potential to enhance learning and memory. Experience-based learning in VR, where users actively engage with content in contextually meaningful ways, has shown promise in supporting memory retention and conceptual understanding. This has opened new avenues for applying VR in educational and cognitive enhancement settings, particularly in domains requiring spatial or episodic memory.

2.2 Applications of VR Memory Enhancement

The immersive nature of VR has been shown to enhance engagement, which benefits learning and memory tasks. Its capacity to replicate real-world scenarios supports contextual learning and memory retention through immersive spatial engagement [Gamberini, 2000].

Moreover, VR offers controlled and ecologically valid environments that enable precise manipulation of variables and the collection of rich multimodal data, including behavioral and cognitive measures [Creem-Regehr et al., 2023]. This level of control makes VR particularly well-suited for investigating memory processes. Prior work has also highlighted the importance of studying how users interact with VR systems Creem-Regehr et al., 2023, and emphasized the need to design VR environments in alignment with established models of visuospatial memory [Vindenes et al., 2018].

Despite these advances, a critical aspect remains underexplored: the role of the locomotion method in immersive memory tasks. Although previous studies highlight VR's potential to enhance memory through visual and contextual immersion [Krokos et al., 2019; Vindenes et al., 2018], few have examined how different locomotion methods, such as teleportation, natural walking, or walking-in-place, influence spatial mnemonic strategies like the MoL.

The current study addresses that gap by examining how embodied versus non-embodied movement within VR impacts memory performance in a spatially structured memory task.

Research indicates that active navigation in VR environments can significantly improve object recognition compared to passive observation [Hahm et al., 2007; Sauzéon et al., 2015], suggesting that increased interactivity strengthens spatial encoding and enhances memory retention in immersive settings.

Research comparing VR-based cognitive training and medication on memory performance in students with ADHD found greater improvements in the VR group during both post-test and follow-up stages, suggesting VR's potential as an effective therapeutic intervention [Tabrizi et al., 2020].

A study on a spatial wayfinding game (Labyrinth-VR) examined its effects on high-fidelity long-term memory (LTM) in older adults. Participants in the Labyrinth-VR group showed significant memory gains over the control group and performed comparably to younger adults in earlier trials, underscoring VR's potential as a cognitive training tool for enhancing memory in aging populations [Wais et al., 2021].

Additional studies support VR's role in cognitive rehabilitation, though they focus more on general therapeutic outcomes than on spatial memory specifically [Buele and Palacios-Navarro, 2023; Georgiev et al., 2021; Liao et al., 2020; Maggio et al., 2019].

While immersive VR has demonstrated notable effects on memory, understanding why these effects occur requires a closer look at the spatial mechanisms underpinning memory formation. The next section explores the foundational role of spatial cognition and navigation in both physical and virtual environments.

2.3 Spatial Cognition, Navigation and Memory (in the context of VR)

Spatial memory is deeply interconnected with navigation and cognitive mapping. Memories are generally more robust when anchored to specific spatial and temporal contexts, a process central to episodic memory formation [Bond, 2021]. This spatial binding allows individuals to recall not just facts or objects, but also the context in which they were encountered.

2.3.1 Spatial Memory Theory and Navigational cues in VR

Spatial memory theory involves the encoding, storage, and retrieval of spatial information, such as distances, object locations, and spatial layouts. It is primarily associated with the hippocampus and related brain structures [Mehta, 2010]. In VR, this theory is applied to how users mentally represent virtual environments, remember locations, and navigate within them.

Importantly, VR offers controlled settings in which spatial cues can be manipulated with high precision. Researchers distinguish between two key categories: environmental cues (landmarks, geometric structures) and self-motion cues (vestibular and proprioceptive feedback related to one's own movement) [Jeung et al., 2023]. VR enables these inputs to be isolated and studied in detail, showing how they interact to shape spatial memory and navigation.

2.3.2 Cognitive Maps and Spatial Encoding

Cognitive maps are internal spatial representations formed through perception, movement, and memory. They guide wayfinding, orientation, and decision-making in both physical and virtual environments [Kitchin, 1994]. Landmark recognition plays a crucial role, helping individuals construct mental models of environments [Lew, 2011].

These cognitive maps extend beyond physical navigation. They also support navigation in abstract domains, such as social or conceptual spaces, reinforcing the idea that spatial cognition underpins a wide range of memory functions [Epstein et al., 2017].

In virtual environments, the formation of cognitive maps depends heavily on how users move through space. Movement influences what is seen, directs attention, and updates memory. As such, locomotion in VR is not merely a technical choice but a cognitive one, it shapes how spatial knowledge is acquired and retained [De Back et al., 2024].

This section established the conceptual basis for understanding how movement influences memory formation in virtual environments. The following section examines two primary locomotion methods: teleportation and Walking-in-place. It explores how each method interacts with spatial memory processes.

2.4 Locomotion in VR

Locomotion in VR is a central interaction component that enables users to navigate and explore digital environments. For movement to feel natural and immersive, VR systems must simulate key sensory cues involved in real-world locomotion. These include *optic flow* (visual motion), *proprioception* (internal body awareness), and *vestibular input* (balance and head movement) [Keil et al., 2021]. The quality of these simulations affects not only how users move but also how they perceive space, maintain orientation, and encode spatial memories [Bozgeyikli et al., 2016].

Embodied cognition theory emphasizes the inseparability of body and mind in shaping thought and perception, proposing that knowledge emerges through dynamic interactions between the observer, the environment, and the object of focus [Lin et al., 2024]. In VR, this perspective comes to life through immersive simulations that activate users' sensory and motor systems, enabling more natural interaction, deeper spatial learning, and improved memory encoding.

2.4.1 Teleportation in VR

Teleportation is a widely adopted non-continuous locomotion technique in VR that allows users to instantly traverse virtual space. It is especially popular for reducing VR-induced motion sickness, as it avoids the sensory mismatch between visual input and vestibular signals that often accompanies continuous movement [Shahbaz Badr and Amicis, 2023].

Despite its practical benefits, teleportation can disrupt spatial learning and memory. Because it bypasses the physical act of movement, it deprives users of continuous visual, proprioceptive, and vestibular cues that are essential for building an embodied sense of space. This absence of self-motion information can impair the integration of spatial relationships between landmarks, leading to weaker cognitive maps. Users may struggle to maintain a consistent orientation or understand the spatial layout of the environment, resulting in spatial disorientation and fragmented spatial awareness [Prithul et al., 2021].

This study focuses on a partially concordant form of teleportation, in which users physically rotate their bodies to adjust orientation after teleporting. Among the various implementations, ranging from non-concordant to fully concordant, this version offers a compromise between intuitive spatial orientation and motion comfort [Tan, 2020].

2.4.2 From Natural Walking to Walking-in-Place in VR

Natural walking in VR involves physically moving within a tracked space, allowing the user's real-world motion to be mirrored directly in the virtual environment. Considered the gold standard for immersive locomotion, it engages visual, proprioceptive, and vestibular systems simultaneously, enhancing presence and spatial awareness [Keil et al., 2021].

Natural walking has been shown to significantly enhance spatial understanding. When users actively explore a virtual environment through physical actions like walking and turning, they build more robust and detailed cognitive maps. These embodied interactions help encode spatial relationships between landmarks, improving navigation and recall [König et al., 2021].

The cognitive benefits of natural walking are grounded in embodied cognition: the idea that perception, memory, and learning are tightly linked to sensorimotor experience. Moving the body in meaningful ways activates neural pathways that support spatial learning, allowing users to more effectively internalize the structure of the virtual world [Tan, 2020].

However, natural walking requires a large, open tracking area, which is not always feasible in research or real-world settings. As a practical alternative, this study adopts walking-in-place (WIP) to replicate key benefits of physical movement without requiring large spaces.

WIP simulates the act of walking through rhythmic leg or body movements while the user remains physically stationary. Although users do not traverse real space, WIP engages proprioceptive and motor systems, fostering a sense of embodiment and continuity of motion in the virtual environment [Wilson et al., 2016]. By mimicking the physical engagement of walking, it preserves important aspects of embodied cognition. Studies show that WIP can support spatial learning and memory by promoting active movement and maintaining alignment between user intention and virtual feedback [Usoh et al., 1999].

This balance between realism and accessibility makes WIP a compelling locomotion method for spatial cognition research. Accordingly, this study uses WIP as a substitute for natural walking and focuses on comparing its cognitive effects, especially memory encoding, with those of teleportation.

2.4.3 Comparative Analysis

Triangle-completion tasks comparing walking, partially concordant teleportation (translation via teleport, physical rotation), and discordant teleportation (translation + rotation via controller) have shown the lowest spatial updating errors for walking, the highest errors for discordant teleportation, and intermediate errors for the partially concordant version. This highlights the cognitive importance of both translational and rotational self-motion cues [Cherep et al., 2020].

Beyond natural walking, walking-in-place (WIP) has also been shown to replicate some of the embodied benefits of physical walking, making it a viable proxy for studying spatial cognition in constrained VR setups [Usoh et al., 1999]. WIP thus represents a middle ground, offering embodied cues without the spatial constraints of natural walking, making it especially suitable for experimental designs where space is limited.

Although teleportation lacks continuous movement, the partially concordant approach preserves embodied feedback through real-world rotation, which reduces spatial disorientation compared to fully non-concordant designs. This suggests that incorporating physical elements into teleportation can improve spatial cognition while preserving its practical advantages, such as reduced motion sickness [Cherep et al., 2020].

This balance between comfort and spatial effectiveness is a central challenge in VR locomotion design: teleportation offers ease of use and reduced motion sickness, but may hinder spatial encoding, while embodied methods like walking (or walking-in-place) better support spatial learning through sensorimotor engagement [Caputo et al., 2023].

These distinctions become particularly important in contexts where memory strategies depend on spatial structure, such as the MoL. This technique involves mentally navigating through familiar environments to anchor information to specific locations [Yates, 1966]. Its effectiveness depends on the perception of a stable and coherent spatial layout, making the type of locomotion during encoding a potentially critical factor. If movement lacks continuity or disrupts spatial awareness, the mental path used for recall may weaken, reducing accuracy and fluency [Legge et al., 2012]. The following section explores the foundations of the MoL and how its adaptation into VR may enhance or challenge its mnemonic power.

2.5 Mnemonics: The Method of Loci

2.5.1 History and Traditional Use

Mnemonics are cognitive strategies that enhance memory by linking new information to familiar, structured frameworks. As described by Gobet and colleagues, these techniques promote meaningful encoding by forming associations between incoming data and pre-existing knowledge structures [Qureshi et al., 2014].

Among the oldest and most effective of these techniques is the Method of Loci (MoL). Originating in ancient Greece, the MoL leverages the human capacity for spatial navigation and place memory by mentally mapping information onto physical landmarks. This spatial-scaffolded encoding method allows individuals to recall abstract or sequential material by mentally traversing a stable route through an imagined or familiar environment [Yates, 1966].

In its most elementary form, MoL leverages the innate human capacity to remember places and spatial relationships, allowing individuals to mentally or physically navigate through a familiar environment, associating items to be remembered with distinct landmarks. This technique effectively uses spatial memory to aid in recalling non-spatial information, proving highly effective in memory encoding and retrieval [Krokos et al., 2019].

2.5.2 Empirical Evidence of Effectiveness

Numerous studies and meta-analyses have confirmed the efficacy of the MoL across educational, laboratory, and clinical settings. Early research showed that MoL consistently outperformed baseline recall strategies [Roediger, 1980]. More recently, a meta-analysis reported a medium effect size ($g = 0.65$) across 13 controlled trials, affirming MoL's robustness across diverse populations and contexts [Twomey and Kroneisen, 2021].

Additional evidence indicates that MoL training can improve student recall in real-world classroom settings, particularly when participants use familiar environments such as their own campus as the mnemonic scaffold [McCabe, 2015].

Despite its promise, MoL remains underutilized in formal education, often due to the effort required to construct vivid mental scenes or to maintain the necessary spatial layout internally without visual support.

2.5.3 Limitations of MoL: Cognitive Mechanisms and Individual Differences

The effectiveness of the MoL relies on users' spatial cognition and mental imagery skills, which are essential for constructing and navigating coherent memory spaces. Common strategies include *spatial anchoring* (linking items to salient features or landmarks), *semantic elaboration* (forming narratives or personal associations), and *mental walkthroughs* (rehearsing the route and placements mentally). These techniques draw on spatial memory, episodic recall, and mental imagery, cognitive functions closely tied to hippocampal activity [Bower, 1970; Maguire et al., 2003].

The success of these strategies often depends on individuals' imagery abilities and familiarity with spatial layouts. Those with weaker spatial imagery or limited environmental familiarity may struggle to build vivid mental routes or to recall item–location associations reliably [Qureshi et al., 2014]. The abstract nature of mental navigation can also impose high cognitive load, particularly in the absence of concrete sensory cues or a guided spatial structure [van Dijck and Fias, 2011; Wolbers and Hegarty, 2010].

These limitations highlight a potential advantage of adapting the MoL to immersive virtual environments. In VR, the spatial layout is externally provided and visually persistent, reducing the cognitive burden of mentally constructing and maintaining an internal spatial structure. Navigable virtual environments can act as scaffolds that support memory encoding and retrieval, especially for individuals with weaker mental imagery abilities or less-developed spatial strategies [Krokos et al., 2019; Reggente et al., 2020].

The following section discusses how integrating MoL into VR settings may enhance both usability and cognitive effectiveness, with particular attention to the influence of different VR locomotion methods.

2.6 Adaptation to Virtual Method of Loci (VMoL)

2.6.1 Enhancing MoL through Immersive Technology

The adaptation of the MoL to virtual reality (VR), referred to as the Virtual Method of Loci (VMoL), bridges ancient mnemonic techniques with immersive digital environments [Huttner and Robra-Bissantz, 2017]. VR's persistent and spatially structured scenes reduce reliance on internal imagery and prior familiarity with real-world spaces, making the MoL more accessible to individuals with weaker spatial skills [Legge et al., 2012; Peeters and Segundo-Ortin, 2019].

Beyond accessibility, VMoL also enhances the usability of MoL by allowing users to directly interact with and navigate through 3D environments. These environments can be themed, customized, or dynamically generated, creating engaging and memorable contexts for spatial association [Lege and Bonner, 2020]. The immersive quality of VR, combined with its potential for experimental control, offers researchers a powerful platform to study the cognitive underpinnings of spatial memory and mnemonic performance.

2.6.2 Locomotion in VMoL: A Cognitive Variable

The MoL depends on mentally traversing space, making the way users move through virtual environments a critical aspect of design. Locomotion in VR shapes how spatial information is perceived, encoded, and recalled [Cherep et al., 2020; Tan, 2020].

Techniques such as teleportation and walking-in-place offer varying levels of embodied feedback and spatial continuity. These differences may affect users' ability to anchor information within spatial contexts, which is central to the MoL strategy. VMoL tasks, therefore, provide a valuable opportunity to examine how locomotion methods interact with spatial memory processes [Reggente et al., 2020].

Research also shows that individuals with higher spatial abilities benefit more from VMoL-based tasks. At the same time, excessive immersion can increase cognitive load and, in some cases, impair recall. This suggests that the effectiveness of VR as a memory tool depends on the alignment between environmental design, user characteristics, and task complexity [Vindenes et al., 2018].

Together, these insights establish a rationale for investigating the relationship between locomotion and spatial memory in VR. While VR opens new possibilities for immersive memory training, its cognitive impact likely hinges on how movement through virtual space is experienced and enacted.

The following section presents the research aim, guiding question, and hypotheses, outlining how the study explores the cognitive impact of different VR locomotion methods within a virtual memory palace task.

3 Research Statement

This study investigates how locomotion methods in virtual reality influence spatial memory performance and user engagement within a virtual memory palace task. Specifically, it compares Walking-in-Place and Teleportation to evaluate how physically enacted versus abstract movement affects the encoding and recall of object–location associations.

Grounded in the Virtual Method of Loci (VMoL), the research examines whether embodied interaction through Walking-in-Place promotes stronger memory traces and more deliberate spatial navigation compared to point-and-click teleportation. By analyzing recall accuracy, task duration, reset behavior, and subjective strategies, the study aims to clarify how different forms of movement shape cognitive processing in immersive environments.

Beyond theoretical contributions to embodied cognition and spatial memory research, the findings have practical implications for the design of VR applications in education, training, and cognitive rehabilitation. Understanding how movement design supports or hinders memory performance can inform the development of more effective and engaging virtual experiences.

3.1 Research Question & Hypotheses

- **Research Question (RQ):** In the context of a virtual-reality memory palace, how does the type of locomotion—specifically Walking-in-Place versus Teleportation—influence the recall accuracy of object–location associations?

- **Main Hypothesis (H1):** Participants using Walking-in-Place will recall more correct item–location associations than those using Teleportation. This performance difference is expected to reflect the benefits of physically enacted movement, which may support stronger spatial encoding through embodied interaction.

- **Sub-Hypothesis (H1a):** Participants in the Walking-in-Place condition will spend more time in both the Association and Recall phases. This extended interaction may reflect more deliberate spatial exploration or increased cognitive involvement.

- **Sub-Hypothesis (H1b):** Participants in the Walking-in-Place condition may exhibit fewer item resets during the Association phase. Although this hypothesis was formulated post hoc based on observed trends in the data, it aligns with the theoretical assumption that embodied movement encourages more confident or intentional encoding behavior. This exploratory insight may help guide future studies on the behavioral correlates of embodied navigation.

Complementary exploratory measures, such as participants' self-reported strategies collected through qualitative data, were also analyzed to provide additional context. However, these exploratory variables were not part of the formal hypothesis testing.
It is important to account for the fact that each incorrect recall effectively results in two misplaced items: the item placed in the wrong location and the item originally assigned to that location. To align with the logic of the MoL, recall accuracy was therefore analyzed in a binary manner, scoring each placement as either correct or incorrect.

4 Methodology

4.1 Participants

Participants will be primarily recruited from Leiden University through various channels, including university mailing lists, notice boards, and social media groups. Additionally, we will recruit participants from our social circles to ensure a diverse sample. All recruitment materials will include a brief overview of the study's purpose, the nature of the tasks involved, the duration of participation, and any incentives offered for participation.

Participants will be selected based on specific criteria to ensure reliable and valid results. Eligible participants, aged 18 and older, must have normal or corrected vision. Both males and females are welcome. Exclusion criteria include a history of severe motion sickness or migraines that VR might potentially induce. Fluency in English is necessary to understand the instructions and tasks. Prior VR experience is not required, allowing both novices and experienced users to participate. Informed consent will be obtained from all participants before the study begins.

In this study, a sample size of 24 participants is targeted, which will be divided into two groups of 12 each to explore the impact of different locomotion techniques in a VR environment on spatial cognition and memory. This between-subject design allows for a clear comparison between two distinct conditions: Condition A, where participants use a teleportation interface to move instantaneously within the VR space, and Condition B, where participants navigate by Walking-in-place, simulating actual movement.

With 12 participants in each group, the sample size was chosen to balance feasibility and exploratory aims. While it provides an initial basis for comparing locomotion techniques, future studies with larger, power-calculated samples could build on these findings to confirm and extend the results.

4.2 Apparatus and Materials

4.2.1 Hardware

The experiment makes use of a Meta Quest 2 headset and standard controllers, provided by the Research Support team at the Faculty of Social and Behavioural Sciences (FSW), Leiden University. The system operates in standalone mode, without requiring a connected PC. The experimental application is developed in Unity, compiled into an APK file, and directly installed on the headset. Once connected to Wi-Fi, the system logs all participant actions and gameplay data in real time, storing the output in a structured Google Sheet linked to the device.

Participants receive guidance when putting on the headset and controllers, with adjustments made to ensure comfort and optimal visibility. Prior to each session, the headset view is recalibrated to establish correct orientation. In the Walking-in-Place condition, a piece of tape is placed on the floor to mark the participant's starting position. This allows the experimenter to monitor for positional drift and gently assist participants in maintaining alignment as needed, while taking care not to interfere with the immersive experience. These small positional corrections help prevent issues such as camera-controller desynchronization.

All positional and rotational tracking was handled through the Quest 2's built-in sensors. No external tracking devices were used.

4.2.2 Real-World Lab Setup

The study takes place across three physical locations, each providing a consistent and suitable environment for virtual reality interaction.

- VR Lab (Room 2.5.25), Sylvius Building, Leiden
- Study Space Lab, The Hague
- Study Space/Lab, Utrecht

All three spaces share similar characteristics in terms of size, layout, and environmental conditions. Each room provides a quiet, distraction-free setting, allowing participants to concentrate fully on the task. The physical environments are deliberately kept neutral and unfamiliar to prevent associations with prior experiences, thereby reinforcing the novelty of the virtual context.

Each lab is equipped to ensure participant safety, freedom of movement, and immersion. These spaces are selected specifically because they do not impede navigation or introduce confounding factors such as background noise, visual distractions, or space constraints. Collectively, the lab environments support a controlled and consistent experience across sessions while preserving ecological validity and participant comfort.

4.2.3 Software

The experiment is developed using Unity Engine version **2021.3.45f1**, with XR Plug-in Management configured for OpenXR and Meta Quest support. The build is exported as an Android APK and deployed directly onto the Meta Quest 2 headset.

Development relies on the Unity XR Interaction Toolkit alongside supporting packages tailored for immersive VR development, interaction handling, and UI integration. These include Unity's Input System, XR Core Utilities, and other XR-specific plug-ins.

Source control and collaborative versioning are managed through GitHub throughout the development process. Unity's version control integration ensures consistent synchronization of scripts, scenes, and prefab configurations across the project lifecycle.

This software stack enables modular design, real-time data logging, and a seamless VR deployment pipeline optimized for standalone use on the Meta Quest 2.

The full Unity project and analysis code are openly available on GitHub (see Appendix, Supplementary Materials)

4.2.4 In-Game Systems and Logic

Development is conducted using Unity's XR Interaction Toolkit, supplemented by a set of key packages and tools, including:

- XR Interaction Toolkit
- XR Plug-in Management
- Oculus XR Plugin
- OpenXR Plugin
- XR Core Utilities

- XR Hands
- Input System
- TextMeshPro
- Timeline
- Unity UI
- Version Control
- JetBrains Rider Editor (IDE integration)
- Mathematics
- XR Legacy Input Helpers

The virtual environment is constructed using free assets, primarily sourced from the Unity Asset Store. The base scene includes furniture, lighting, and materials, built using the Brick Project Studio asset pack. Object interaction and locomotion are managed through the XR Interaction Toolkit and a custom walking-in-place (WIP) system, both extended with purpose-built logic to meet the requirements of the experiment. The WIP system was implemented using a head-bobbing mechanic, where the vertical oscillations of the headset during stepping in place were translated into forward movement in the virtual environment. Movement stopped automatically once head-bobbing ceased. This approach was chosen for feasibility reasons, ensuring a lightweight and easily deployable solution that minimized additional setup time and cognitive load for participants, while still providing an embodied alternative to abstract locomotion methods.

A total of twelve memorization objects are manually selected from free online sources such as TurboSquid and the Unity Asset Store. These objects are chosen for their recognizability, variety, and cultural neutrality, while avoiding features that might lead to simplified grouping strategies. Each object is tested and optimized to ensure it functions smoothly within the VR environment.

In addition to the base environment, the interactive experience is driven by a custom scripting system. A total of 23 unique scripts are implemented to support all core in-game systems, including:

- Inventory logic and item instantiation
- Item placement and reset functionality
- Placement zone logic and collider/teleportation-based proximity detection
- Scene management and phase-specific behavior (Association vs. Recall)
- Session condition assignment and alternation between walking-in-place and teleportation
- UI interaction and condition-based button states

Each script is designed with modularity in mind and is adapted where necessary to support both the Association and Recall phases. Small logic adjustments between the two phases ensure that the task flow, interaction style, and memory demands remain aligned with the experimental objectives, while maintaining clear functional separation in the codebase.

A custom DataManager script handles the real-time logging of structured in-game data to a secure Google Sheet. Logged variables include object placement choices, timestamps, phase transitions, locomotion condition, and total task duration. This data serves as the primary source for evaluating memory accuracy and behavioral differences across the two locomotion groups.

All collected data are pseudonymized using anonymized participant IDs, with no personally identifiable information recorded. The structured dataset stored in Google Sheets forms the basis for subsequent statistical analysis and visualization.

4.2.5 In-Game Analytics and Logged Variables

To analyze how participants interact with the two-phase Association–Recall task, each zone-level event is recorded in a structured log file. Each entry captures contextual information, including the locomotion condition, along with timestamped in-game actions. This structure allows for a detailed reconstruction of participant behavior and supports the calculation of summary performance metrics.

A custom logging system developed in Unity continuously records each interaction, capturing the following fields: locomotion condition, participant ID, task phase (Association or Recall), timestamp, zone identifier, and item name.

Based on the logs, the following metrics are calculated:

- **Total Placements** – the total number of item–zone placement actions made by each participant across both the Association and Recall phases, including repeated placements due to resets.
- **Resets** – instances in which a participant places a new item in a zone that already contains an item during the Association phase.
- **Association Phase Duration** – the elapsed time between the first and last placement event during the Association phase.
- **Recall Phase Duration** – the elapsed time between the first and last placement event during the Recall phase.
- **Gap Duration** – the fixed five-minute interval between the conclusion of the Association phase and the beginning of the Recall phase.
- **Recall Accuracy** – the proportion of placements during the Recall phase that correctly match the original item–zone pairings from the Association phase.

All extracted metrics are exported to CSV format for subsequent analysis. These gameplay-based measures are examined in conjunction with participants' questionnaire responses to provide a more comprehensive understanding of how each locomotion method influences both memory performance and subjective experience.

4.2.6 Tracking

Movement tracking is managed entirely through the internal sensors of the Meta Quest 2 headset and controllers. Each locomotion condition applies distinct tracking logic tailored to the interaction demands of its respective mode.

4.2.7 Locomotion Techniques

This study compares two distinct locomotion techniques in VR: Teleportation and Walking-in-Place (WIP). These were selected for their contrasting levels of physical engagement and their potential to differentially influence spatial perception and memory encoding. Both techniques were implemented in Unity and operated using the Meta Quest 2 headset and controllers.

Teleportation is a widely adopted VR navigation method that allows users to move instantaneously between locations. Participants in this condition aim a visual arc projected from their controller, select a target location using the trigger button, and are immediately relocated upon release. Rotational adjustments are made via joystick, eliminating the need for physical turning.

This method requires minimal physical effort and reduces the risk of motion sickness. However, it introduces discontinuous movement, lacking continuous visual and proprioceptive feedback, which may constrain spatial awareness and memory encoding. Teleportation serves as the baseline condition in this study, representing low-immersion and cognitively less demanding navigation. Its inclusion supports ecological validity, as teleportation is widely used in commercial VR applications.

Walking-in-Place (WIP) is implemented using a custom locomotion system developed in Unity that relies solely on the headset's built-in inertial measurement unit (IMU), specifically its accelerometer and gyroscope. Forward movement is triggered by detecting rhythmic vertical head motion, commonly referred to as headbobbing. Once a consistent pattern above a calibrated threshold is identified, the system translates this into continuous forward movement in the direction of the user's gaze. Physical body rotation is used to change direction, allowing intuitive and embodied navigation.

This approach offers a dynamic and responsive locomotion experience that replicates the sensorimotor feedback of natural walking, without requiring a large tracking area or additional wearables. Compared to foot trackers or controller-based motion, the headset-only method reduces setup complexity while maintaining high levels of embodiment, responsiveness, and flow. It is well-suited for studying embodied cognition in virtual spatial memory tasks.

Limitations and Controls

To ensure a fair and isolated comparison between conditions, the following controls were implemented:

- Both locomotion methods use the same virtual environment, item set, interface design, and timing structure.
- Interaction mechanics and placement behavior are consistent across conditions, with locomotion as the sole manipulated variable.
- Participants are randomly assigned to one condition to eliminate order effects
- The WIP system is calibrated to ignore minor or unintentional head movements, ensuring that only deliberate, rhythmic motion initiates forward movement.

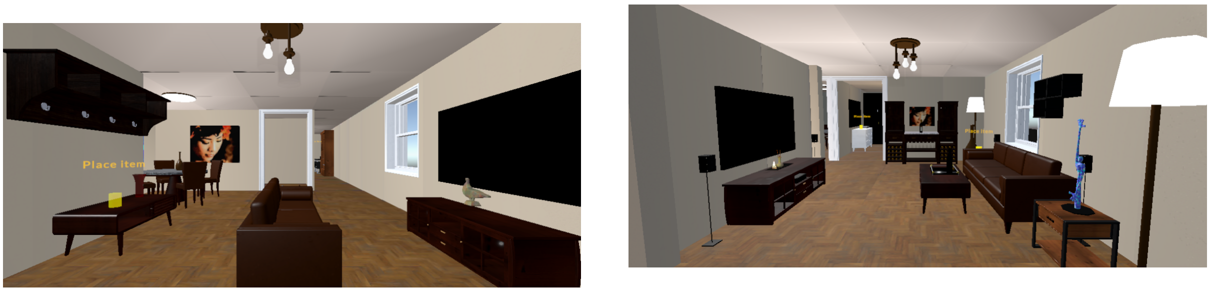
All interactions, including placement zone entries and item selections, are timestamped and systematically logged across both conditions to enable detailed session reconstruction and facilitate comparative behavioral analysis.

Comparative Rationale

The contrast between these two locomotion techniques enables a focused investigation into how movement realism and bodily engagement influence memory and spatial cognition in VR. Both methods are well-established in immersive application design and research, supporting the relevance of findings to broader fields such as education, cognitive training, and narrative-based virtual environments.

4.2.8 Environment

The virtual environment is designed as a stylized apartment complex consisting of two distinct living units: Apartment 1 and Apartment 2. Each apartment features uniquely furnished and clearly delineated rooms, enabling participants to form robust spatial associations using the MoL. The layout and interior design promote natural navigation and spatial exploration, with a variety of object placement surfaces and easily recognizable room types.



(a) Apartment 1 – kitchen and hallway view

(b) Apartment 2 – living area and window view

Figure 1: Screenshots of the living rooms from the two virtual apartments. Each living room feature a distinct layout to support unique spatial encoding.

A total of twelve placement zones are distributed across various rooms and surfaces within the two apartments. Each zone is visually marked by a glowing yellow cylinder, signaling that the area is available for object placement during the Association and Recall phases. The placement zones themselves are interactable and designed to span multiple room types and spatial orientations, encouraging broad spatial engagement and supporting memory encoding through environmental variety. The full layout is as follows:

Table 1: Placement Zones in the Virtual Environment.

Zone ID	Apartment	Room / Area	Surface / Placement
Placement Zone 1	Apartment 2	Double Bedroom (right)	Nightstand
Placement Zone 2	Apartment 1	Double Bedroom	Dresser
Placement Zone 3	Apartment 2	Bathroom	Sink Unit
Placement Zone 4	Apartment 2	Living Room	Coffee Table
Placement Zone 5	Apartment 1	Bathroom	Toilet Seat
Placement Zone 6	Apartment 2	Double Bedroom (left)	Bookshelf Box
Placement Zone 7	Apartment 1	Living Room	Work Desk
Placement Zone 8	Apartment 1	Dining Room	Dining Table
Placement Zone 9	Apartment 1	Entrance	Bench
Placement Zone 10	Apartment 2	Kitchen Area	Stove Top
Placement Zone 11	Apartment 1	Living Room	Side Table
Placement Zone 12	Apartment 2	Single Bedroom	Bed

Each placement zone features an interactable glowing yellow cylinder that registers object placement and enables the system to log where participants position each item within the environment. A total of twelve zones are evenly distributed across the two apartments, with six zones per unit. These zones are intentionally placed across varied room types and surface locations to promote comprehensive spatial exploration and to minimize reliance on simplistic heuristics. Importantly, the environment does not present an obvious linear route across all twelve zones, as this could allow participants to adopt alphabetical or sequential placement strategies, undermining the intended memorization task. Instead, their spatial arrangement is designed to engage participants with a range of directions, depths, and memory anchors throughout the environment.

This spatial design draws on spatial memory theory and cognitive map research, which highlight the importance of landmarks and environmental cues in supporting memory encoding and recall in both physical and virtual environments [Jeung et al., 2023, Lew, 2011, Kitchin, 1994]. Each placement zone is situated to act as a navigational anchor, allowing participants to link objects to distinct locations. By distributing the zones across visually and structurally unique rooms and surfaces, the environment simulates the kind of landmark-rich context shown to facilitate the formation of spatial associations in MoL tasks.

The two apartments are connected by a long hallway, which participants traverse after completing the starting area. This transitional path introduces the spatial structure of the environment and encourages a sequential experience of movement, whether physical or virtual, before engaging in the memory task.

4.2.9 Object Pool

The experimental object pool consisted of twelve visually distinct and thematically varied 3D models, deliberately selected to discourage simple mnemonic grouping strategies (e.g., by color, shape, or theme) and instead promote spatially grounded memory encoding. To reduce automatic associations with the domestic setting of the virtual environment, common household items were excluded. Assets were sourced from free repositories, primarily the **Unity Asset Store** and **TurboSquid**, and each model was tested and optimized to ensure correct rendering and interaction in VR. In addition, a representative 2D icon for each object was included in the user interface, taken directly from the corresponding asset package to ensure visual consistency.

The final set of items includes:

Figure 2: The twelve objects included in the experimental object pool. Items were selected for visual and thematic distinctiveness while intentionally excluding common household items to reduce the influence of pre-existing associations.

The placement system is configured to support both the Association and Recall stages of the experiment, with tailored interaction mechanics for each.

In the Association Phase, when participants approach a placement zone (within approximately one meter), the inventory user interface appears automatically in front of them. This interface displays twelve items as labeled buttons with corresponding images, arranged in a randomized order that is unique to each participant.

Participants use the ray from the left controller, along with the trigger input, to select an item. Once selected, the item appears in the participant's right hand. Only one item can be held at a time; selecting a different item replaces the one currently held.

If a participant exits the placement zone without confirming the placement, the item is automatically reset and removed from view. To confirm a placement, participants aim their right controller at the glowing yellow cylinder and press the trigger. This action causes the item to disappear from their hand and updates the on-screen progress indicator (for example, "3/12 items placed").

If a participant wishes to change a previously placed item, they can re-enter the corresponding zone and press the secondary trigger. This resets the item, reopens the inventory interface, and allows them to select a new object for that zone.

The inventory is randomized uniquely for each participant to prevent reliance on button position or layout. This design encourages participants to use deliberate, spatially anchored memory strategies rather than visual repetition or interface familiarity.

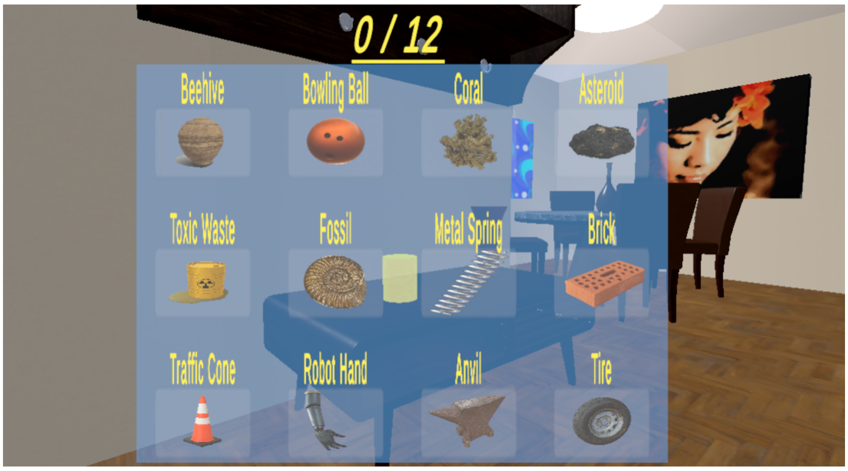


Figure 3: Inventory UI during the Association Phase. Participants select from 12 labeled buttons with images, presented in a randomized order unique to each participant.

Each placement zone provided immediate visual feedback to guide the process. When available, a glowing yellow cylinder signaled that the zone was empty and ready for placement. Once an object was placed, the glow disappeared and the item appeared on the surface, replacing the cylinder. This system offered clear confirmation of successful placement, supported progress tracking, and reinforced the spatial associations being formed. Figure 4 illustrates this feedback cycle.

(a) Placement zone before placing an item (glow visible)

(b) Placement zone after placing an item (glow removed)

Figure 4: Placement Zone 4 in the second apartment (living room, coffee table). Left: the zone before item placement, showing the glowing yellow cylinder indicating it is available. Right: the same zone after successful placement of the 'Traffic Cone' object.

In the Recall Phase, the inventory interface is simplified to display only item names, without visual previews. Upon entering a placement zone, participants are prompted to select the item they believe was originally placed in that location. The inventory order is reshuffled once again, differing from both the participant's original configuration and the order used by others. This design discourages recognition-based strategies and promotes reliance on memory-based reasoning. Once an item is selected, it is locked in and cannot be reset, encouraging deliberate and confident decision-making.

The placement and inventory systems are closely integrated and configured to align with the objectives of each phase: fostering spatial exploration and associative encoding during the Association Phase, and emphasizing recall accuracy and commitment during the Recall Phase.

Figure 5: Inventory UI during the Recall Phase. Participants select from twelve labeled buttons without images, presented in a randomized order unique to each participant.

Zone 1

Zone 2

Zone 3

Zone 4

Zone 5

Zone 6

Zone 7

Zone 8

Zone 9

Zone 10

Zone 11

Zone 12

Figure 6: Placement Zones 1–12, each positioned in a distinct area of the virtual apartment. The spatial layout is designed to facilitate deliberate encoding and retrieval during the experiment.

4.2.10 Pre- and Post-Session Questionnaires

To complement the behavioral data and gain insight into participants' subjective experience and cognitive strategies, participants complete brief questionnaires before and after the VR session.

Pre-Session Questionnaire (1 minute)

After reading the information sheet and signing the informed consent form, participants complete a brief pre-session questionnaire prior to entering the VR session or beginning the Association phase. The questionnaire gathers basic demographic and baseline data, including:

- Name (coded into Participant ID)
- Age
- Gender
- Prior experience with VR technology, rated on a 1–5 Likert scale

This demographic information serves to characterize the sample's diversity and to examine potential correlations between prior VR experience and task performance.

Post-Session Questionnaire (5 minutes)

After completing the Recall Phase, participants reflected on their experience and cognitive strategies using a combination of Likert-scale and open-ended questions. All Likert-scale items were rated on a 5-point scale (1–5), with the anchors adapted to the content of each question. These measures included:

- How confident are you that you correctly remembered most of the item–location pairings?
- To what extent were you able to form meaningful associations between the objects and their locations in the VR environment?
- How mentally demanding did you find the task of remembering and recalling item–location pairings?
- During the recall task, did you feel you always knew where you were in the VR memory palace and how to navigate to each place?
- Did you experience any discomfort or disorientation while using the VR system?
- What helped you remember the items best (if anything)? (open-ended)
- Did you use any strategies to help remember the object locations? If so, please describe them. (open-ended / multiple choice with "Other" option)
- Was there anything you found particularly easy or difficult about remembering and recalling where you placed the objects in the VR environment? (open-ended)

This subjective feedback contextualizes individual performance outcomes and provides insights into how participants engage cognitively and physically with the virtual environment. Combined with in-game analytics that capture object placements, time spent per zone, locomotion condition, recall accuracy, and interaction patterns, this approach offers a comprehensive understanding of participant behavior and strategic differences between the two locomotion conditions.

4.3 Design and Measures

4.3.1 Design Overview

A between-subjects design is employed, with twenty-four participants randomly assigned to one of two locomotion conditions—Walking-in-Place or Teleportation—resulting in twelve participants per group. Each participant completes two primary experimental phases, Association and Recall, embedded within a broader five-phase session that also includes Introduction, Distraction, and Debrief phases to facilitate familiarization, cognitive interference, and study closure, respectively.

Participants are randomly assigned to one of the following locomotion conditions:

- **Teleportation:** Participants move instantaneously through the environment by pointing and clicking on a destination.
- **Walking-in-Place (WIP):** Participants simulate natural locomotion through rhythmic head and hand movement, creating a physically engaging form of virtual navigation.

Each participant completes two sequential phases:

- **Association Phase:** Participants explore a virtual apartment and assign twelve distinct objects to spatially distributed placement zones, thereby forming personalized item-location associations.
- **Recall Phase:** Participants attempt to recall and reassign each object to its original location using an inventory interface that displays only item names without visual previews, thereby testing memory independent of recognition cues.

4.3.2 Locomotion Conditions

Walking-in-Place Condition

In the *Walking-in-Place* condition, participants navigate the virtual environment by physically simulating walking through rhythmic movements of the head, legs, and hands. This method aims to replicate a more embodied and naturalistic form of locomotion, allowing participants to move in their chosen direction through active bodily engagement. Walking-in-Place is selected to investigate its potential influence on spatial cognition and memory processes.

Teleportation Condition

In the *Teleportation* condition, participants move through the virtual environment using a controller-based interface. They point to a destination and instantly teleport to that location, adjusting their orientation by physically rotating their bodies. This technique enables efficient traversal of space but does not provide continuous visual flow or proprioceptive cues.

Hypotheses

- **H1:** Participants using Walking-in-Place will recall more correct item–location associations *than those using Teleportation*.
- **H1a:** They will spend more time in both the Association and Recall phases *than Teleportation participants*, reflecting more deliberate exploration or increased cognitive involvement.

- **H1b:** They may exhibit fewer item resets during the Association phase *than Teleportation participants*, consistent with the assumption that embodied movement encourages more intentional encoding.

These hypotheses are grounded in literature suggesting that embodied locomotion promotes stronger spatial awareness *compared to teleportation*. By mimicking real-world walking, Walking-in-Place facilitates the formation of mental maps and enhances memory retrieval through bodily motion and environmental interaction. In contrast, teleportation, lacking continuous self-motion cues, is expected to fragment spatial continuity and hinder the construction of a coherent mental representation of the environment *relative to WIP*.

4.3.3 Independent and Dependent Variables

This study investigates how different locomotion techniques affect memory encoding and retrieval within a virtual reality memory palace. It specifically examines whether walking-in-place enhances recall performance and fosters a more embodied experience compared to teleportation. The study also considers whether participants' familiarity with virtual reality influences task performance and subjective experience. The overarching aim is to explore the cognitive and experiential impact of embodied navigation in immersive environments, using both behavioral data and self-reported measures.

Two independent variables are examined. The primary independent variable is locomotion technique, manipulated between subjects. Participants are randomly assigned to either a Teleportation or a Walking-in-Place condition. This design facilitates the analysis of how the physical and cognitive demands of each navigation method influence spatial memory and presence.

The secondary independent variable captures prior familiarity with virtual reality, assessed through a pre-session Likert-scale item. This measure accounts for potential differences in prior VR exposure that may affect participants' performance and engagement with the task.

Dependent variables are derived from three sources: in-game behavioral metrics, item-level placement logs, and post-experiment questionnaire responses.

Behavioral Metrics

The metrics are derived per participant from the structured gameplay logs. These include the duration of the Association Phase, the duration of the Recall Phase, and the total task time. Additional measures include the number of item resets during the Association Phase, the number of correctly recalled items during the Recall Phase, and the overall recall accuracy, expressed as the percentage of items correctly matched to their original locations.

Placement Log Data

Item-level data are recorded for each placement interaction, including the task phase (Association or Recall), the specific zone where the item is placed, and the name of the selected item. This dataset enables detailed analysis of navigation patterns, zone-specific recall behavior, repeated placements, and consistency in item-location mapping across both phases.

Post-Experiment Questionnaire

Participants complete a post-task questionnaire assessing several subjective dimensions, including perceived cognitive load, use of mnemonic or spatial strategies, and perceived immersion and presence during the task. These self-reported measures complement the behavioral data by providing insight into how participants experience the task and manage recall and navigation internally.

Together, these dependent variables capture both objective performance and subjective experience, offering a comprehensive view of how locomotion influences spatial memory, immersion, and overall task engagement.

4.4 Procedure

Each participant completes a standardized five-phase procedure: Introduction, Association, Distraction, Recall, and Debriefing. The full session lasts approximately 60 minutes. During this time, participants receive instructions, explore the virtual environment to place items (Association), take a short break (Distraction), attempt to recall their placements (Recall), and finally reflect on the experience (Debriefing).

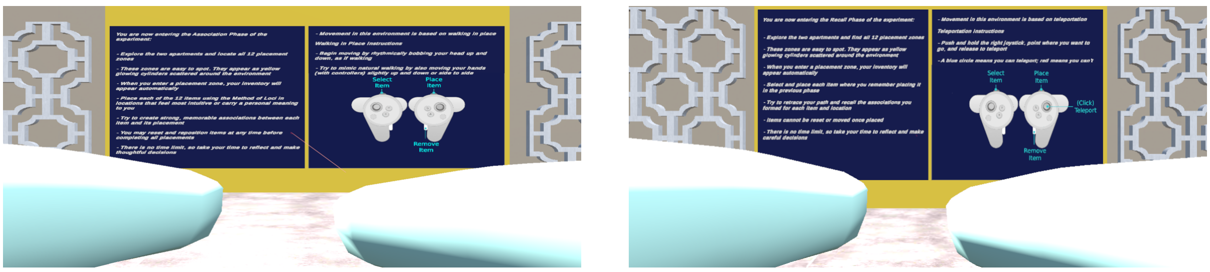
4.4.1 Introduction Phase

Participants are welcomed and introduced to the study. They receive an information sheet outlining the purpose of the research and the nature of their participation. After reading the sheet, they provide informed consent by signing the consent form. A brief pre-questionnaire follows, capturing demographic information and background variables such as VR familiarity and navigation experience.

Participants are then randomly assigned to one of two experimental conditions: Walking-in-place or teleportation. Before beginning the main task, they are introduced to the VR setup and practice their assigned locomotion method to ensure they are comfortable navigating the virtual environment.

4.4.2 Association Phase

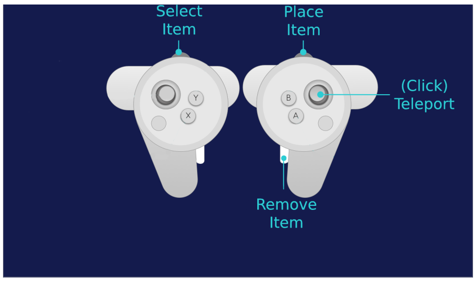
Before starting the Association phase, participants are placed in a VR instruction room within the virtual environment. In this space, they view an instruction screen that outlines the current task, available controls, and their assigned locomotion condition (Walking-in-Place or Teleportation). Participants are given time to practice their assigned movement method in a dedicated hallway area before entering the main apartment complex. This onboarding process ensures familiarity with VR navigation prior to the start of the memory encoding task.



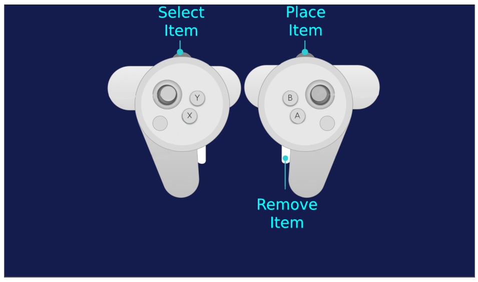
(a) Teleportation instructions (b) Walking-in-place instructions

Figure 7: Instruction screens shown to participants during onboarding, based on their assigned locomotion condition. The panels explained the movement method and corresponding controller inputs.

When participants enter the virtual environment, they are presented with visual instruction panels tailored to their assigned locomotion condition. As shown in Figure 7, participants in the teleportation condition receive guidance on using the thumbstick to navigate, while those in the walking-in-place condition are instructed on movement through rhythmic head-bobbing. The instruction screen also outlines the experiment's objectives and explains how to select, place, and reset items within the environment.



(a) Teleportation controller mapping



(b) Walking-in-place controller mapping

Figure 8: Controller instruction screen displayed during the onboarding sequence. The mappings illustrate the primary input methods for navigation, item selection, placement, and reset functionality.

As shown in Figure 8, participants are provided with visual guides outlining the controller layout for their assigned locomotion condition. These panels clarify which buttons are used for movement, object selection, placement, and reset functions.

This phase functions as the memorization session and lasts approximately 20 minutes. Participants enter the virtual environment and complete a memory task based on the Virtual Method of Loci (VMoL).

Twelve distinct items are presented in the virtual space. Participants are instructed to freely explore the environment, select a placement zone for each item, and form a personal association between the item and its chosen location. They are encouraged to select locations they believe will facilitate memory. Items can be reset or repositioned at any time, and the session is self-paced to support deliberate encoding strategies.

4.4.3 Distraction Phase

To prevent active rehearsal and support memory consolidation, a verbal distraction task followed the Association Phase. The task included two verbal fluency components:

- Reciting the alphabet paired with consecutive numbers (e.g., A1, B2, C3, etc.).
- Naming two animals per letter, beginning with A and continuing sequentially, typically reaching H depending on the participant's pace.

Participants are instructed to perform the task quickly and continuously. The duration is fixed at five minutes and remains consistent across all participants.

4.4.4 Recall Phase

In this phase, participants re-enter the same virtual environment, now devoid of visible items. Their task is to recall and reassign each object to the location where they believe it was originally placed during the Association Phase.

Participants navigate the environment and complete all 12 placements. Unlike in the Association Phase, items cannot be reset or moved once assigned, emphasizing the accuracy of memory retrieval. The phase lasts approximately 15 minutes and is used to assess spatial memory performance based on correct item-location matches.

The inventory interface is adapted to increase cognitive demand by reducing visual recognition cues. Items are presented as a randomized list of names only, without images. Interaction with placement zones remains proximity-based (within approximately 1 meter), but selected items are automatically assigned to the zone without appearing in hand. Once placed, items are locked in and cannot be changed. As in the Association Phase, a black screen with closing instructions appears upon completion of all 12 placements.

4.4.5 Debriefing Phase

After completing the Recall Phase, participants are invited to share how they feel and are offered water or a brief rest. They then complete a short post-questionnaire designed to capture reflections on their experience, strategies used, and perceived cognitive demands.

Following this, participants are debriefed on the purpose of the study, which investigates how different forms of VR locomotion may influence memory for object-location associations. Any remaining questions are addressed, and participants are thanked for their time and contribution.

4.5 Ethical Considerations

Ethics Approval

This study receives formal ethical approval from the Media Technology Board of Examiners at Leiden University. The submitted Ethics Assessment Application Form outlines the research protocol, potential risks, and mitigation strategies in detail. The accompanying checklist and signed approval confirm that all procedures comply with the university's ethical standards and adhere to Dutch legislation governing research with human participants. The study is assessed as low risk and approved for implementation in its proposed form.

Informed Consent

Prior to participation, all individuals are presented with an Information Sheet explaining the study's objectives, procedures, estimated duration, potential risks, and data handling practices. Participants are informed that participation is voluntary and that they may withdraw at any time without consequence.

After reviewing this information, participants sign an Informed Consent Form confirming their understanding of the study and their willingness to participate. The form also outlines how their data will be used and how anonymity will be preserved. Consent is obtained before any data collection begins, including the pre-session questionnaire and VR interaction.

Confidentiality and Data Protection

To ensure participant privacy, each individual is assigned a unique anonymous identifier. This identifier is used in all data logs and files in place of names or other personal information. No personally identifiable data are collected at any stage of the study, and none are included in reports, presentations, or publications.

All data, including VR interaction logs and questionnaire responses, are securely stored on password-protected computers and encrypted drives accessible only to the research team. The data management procedures adhere to Leiden University's data protection policies and comply fully with GDPR regulations governing the privacy and security of research participants.

Debriefing and Participant Rights

At the conclusion of the session, participants receive a comprehensive debriefing that outlines the study's purpose, research questions, and the specific condition to which they were assigned. This process includes addressing any questions or concerns to ensure full transparency and participant comprehension.

Participants sign two copies of the debriefing form: one is retained by the researcher for documentation, and the other is provided to the participant for their own records. The form includes the researcher's contact information and specifies a one-month period during which participants may request the removal of their data from the study.

Participants are also informed that they may request a summary of the final research findings once the study has been completed and submitted.

4.6 Data Analysis

This study investigates whether the type of locomotion, specifically Walking-in-place versus Teleportation, influences spatial memory performance in a virtual memory palace. The central hypothesis (H1) proposes that embodied movement enhances memory encoding, resulting in improved recall accuracy. To evaluate this, the analysis focuses on participants' ability to recall object and location associations after navigating the environment using their assigned locomotion method. Additional behavioral and subjective measures are included to contextualize performance and explore potential underlying mechanisms, including differences in pacing, confidence, or interaction style that may accompany embodied navigation.

Data Preparation and Aggregation

Each session was logged in real time using a custom Unity-based tracking system that recorded locomotion condition, anonymized participant ID, task phase, timestamps, zone ID, and item name. Using Python (`pandas`), these raw logs were processed into participant-level metrics, including total recall accuracy, phase durations (Association and Recall), and reset frequency, defined as repeated placements within the same zone during the Association phase. These behavioral indicators offered insight into task engagement and decision-making during encoding (see Appendix 9 for the full analysis workflow and log structure).

Behavioral data were then merged with responses from the pre- and post-session questionnaires to construct a comprehensive dataset. Pre-session data captured demographic variables (e.g., age, gender) and prior VR experience, rated on a 5-point ordinal scale. Post-session responses included ratings of confidence, association strength, mental demand, spatial orientation, and VR comfort, each converted to a 5-point scale.

Reset frequency was interpreted as a behavioral proxy for uncertainty or strategic revision during the encoding process and was later analyzed to assess condition-based differences in placement behavior.

Strategy Coding

Open-ended responses concerning memory strategies were thematically coded based on emergent patterns (e.g., spatial anchoring, storytelling) and categorized into binary indicators of strategy use. A detailed summary of these strategies is presented later in the results section. These strategy indicators were used descriptively to explore trends in memory performance. These thematic categories reflected strategy types described in prior MoL research, such as spatial anchoring (linking objects to distinct environmental features), semantic elaboration (creating narratives or personal associations), and mental walkthroughs (rehearsing paths or placements). By classifying participant strategies according to these patterns, the analysis was better positioned to interpret individual differences in recall performance within the framework of embodied cognition, which emphasizes that memory is shaped by spatial interaction and sensorimotor experience.

Analytical Strategy

The primary analysis tested whether recall accuracy differed significantly between Walking-in-Place and Teleportation participants. Given the small sample size ($N = 24$) and possible non-normality in recall scores, both parametric (independent samples t-test) and non-parametric (Mann–Whitney U test) approaches were used to ensure robustness against distributional assumptions.

Additional comparisons assessed reset frequency, phase durations, and subjective ratings to provide a broader behavioral profile for each condition. Individual differences in VR familiarity, reported mnemonic strategy use, and spatial orientation were also considered as covariates or descriptive moderators of performance.

Zone-level differences were evaluated using chi-square tests of independence to identify spatial contexts (e.g., specific rooms or surfaces) that may have been remembered more effectively under one condition. To further investigate performance variability, correlational analyses (Pearson or Spearman, as appropriate) were conducted to examine relationships between subjective self-reports (e.g., confidence, VR familiarity) and objective outcomes (e.g., recall accuracy, task duration).

Scatter plots were used to visualize relationships between recall accuracy and other variables, helping to explore behavioral patterns not captured by inferential tests alone. These visualizations helped assess whether task pacing or engagement style was associated with memory performance across conditions.

All data preprocessing, variable computation (e.g., reset frequency, phase durations), and statistical analyses (e.g., t-tests, Mann–Whitney U tests, chi-square tests, and correlation analyses) were conducted in Python using the `pandas`, `scipy`, and `statsmodels` libraries.

While recall accuracy served as the primary outcome measure, secondary analyses of behavioral and subjective metrics provided additional context to inform interpretation. Given the modest sample size ($N = 24$), all statistical results were interpreted with caution, with emphasis placed on effect sizes and observed trends.

Methodological Rationale

This mixed-methods approach reflects the complex, multidimensional nature of spatial memory in virtual reality environments. While statistical comparisons highlight group-level effects, visual and correlational analyses offer insight into individual differences, behavioral strategies, and the potential role of sensorimotor engagement. Grounded in theories of embodied cognition, this framework assumes that memory formation depends not only on visual input but also on how individuals move and interact within the environment.

Data Cleaning and Standardization

To ensure consistency across participants, several standardization procedures were applied. Placement zones were categorized by apartment, room, and surface type based on a fixed layout. The five-minute interval between the Association and Recall phases was excluded from duration calculations. Likert-style items were coded on a 1–5 ordinal scale, and open-text responses describing memory strategies were thematically coded. A binary variable indicating whether a strategy was used was added for further analysis. VR familiarity, as reported by participants, was encoded as follows:

- 1 – Never used VR
- 2 – Tried VR once or twice
- 3 – Some experience
- 4 – Frequent use
- 5 – Very experienced

Data were inspected for inconsistencies, such as duplicate placements or missing entries. One participant was excluded due to experiencing disorientation and discomfort during the Association phase, and another canceled prior to their scheduled session, resulting in a final sample of 24 participants. No extreme outliers were identified that warranted removal.

Experimental Constraints

Given the scope and technical depth of the experiment, which involved the development of a custom VR environment and data logging system, the study was limited to 24 participants. While relatively small, this sample was sufficient to allow statistical comparisons between the two conditions. All participant data were pseudonymized to ensure privacy.

Together, these analytical procedures provided a multifaceted view of how locomotion influences spatial memory, setting the stage for the findings presented in the next section.

5 Results

Data collection for this study took place between June 16 and July 2, 2025, spanning a total of 17 days. Sessions were hosted at three separate locations: the VR Lab (Room 2.5.25) in the Sylvius Building in Leiden, the Study Space Lab in The Hague, and the Study Space/Lab in Utrecht. These locations were comparable in terms of size, layout, and environmental conditions. Each environment was quiet and free from distractions, allowing participants to concentrate fully on the task. Moreover, the physical settings were neutral and unfamiliar, minimizing the potential for prior associations and supporting the intended novelty of the virtual experience.

A total of 26 participants were recruited for the study. One participant canceled before their scheduled session, and another had to be excluded after experiencing significant disorientation and discomfort during the Association Phase of the experiment. This resulted in a final sample of 24 participants whose data were used for analysis.

5.1 Participants

The final sample included 24 participants: 13 identified as female, 10 as male, and 1 as non-binary/other. Ages ranged from 20 to 57 years, with a mean age of approximately 27 years.

Familiarity with virtual reality was self-reported on a scale from 1 (not familiar at all) to 5 (very familiar). Reported scores ranged from 1 to 3, with no participants indicating high or very high experience. This suggests limited prior exposure to virtual environments across the sample.

Participants were randomly assigned to one of two experimental conditions:

- **Teleportation:** 12 participants (7 male, 5 female)
- **Walking-in-place:** 12 participants (3 male, 8 female, 1 non-binary/other)

Condition	Male	Female	Non-binary or other	Total
Teleportation	7	5	0	12
Walking-in-place	3	8	1	12
Total	10	13	1	24

Table 2: Participant gender distribution by condition

Each participant completed a single session that lasted approximately 60 minutes, following the standardized five-phase protocol described in the Procedure section.

5.2 Descriptive Analysis

This section provides a summary of participant performance and behavioral metrics across the two locomotion conditions: *Teleportation* and *Walking-in-place*. The aim is to objectively present the collected data without interpretation.

Recall Performance and Task Difficulty

Participants were instructed to recall and place 12 objects in their original locations. Recall accuracy was measured by the number of correct object–location matches, with a maximum possible score of 12.

A total of 13 out of 24 participants achieved a perfect score. Four participants scored below 10. The distribution is presented in Table 3.

Recall Score (out of 12)	Number of Participants
12	13
10	4
9	2
8	1
7	1
5	1
3	2

Table 3: Distribution of recall scores across all participants

Two participants scored markedly lower than the rest (3/12), but these were retained in the analysis as they did not violate protocol or demonstrate signs of disengagement. Their inclusion aligns with an intention to preserve the ecological validity of the sample and avoid post hoc exclusion bias. Furthermore, no a priori criteria for outlier exclusion were established.

Condition-Based Behavioral Differences

To contextualize behavioral differences and understand how locomotion method influenced task execution, descriptive metrics were calculated for each locomotion condition, including recall accuracy, number of resets during the Association Phase, and phase durations. Table 4 summarizes these metrics for both groups.

Total task duration is defined as the sum of Association and Recall phase durations, representing the total time participants actively engaged in the two VR task phases.

Measure	**Teleportation (n = 12)**	**Walking-in-place (n = 12)**
Mean Recall Score (out of 12)	9.42 ± 3.34	10.58 ± 2.31
Mean Number of Resets	2.33 ± 1.61	0.83 ± 1.99
Association Phase Duration (s)	487.25 ± 156.26	594.00 ± 264.58
Recall Phase Duration (s)	260.25 ± 59.43	348.75 ± 112.71
Total Task Duration (s)	747.50 ± 157.83	942.75 ± 345.80

Table 4: Descriptive metrics by condition (reported as mean ± standard deviation)

Note: Association Phase duration, Recall Phase duration, and Total Task Duration are reported in seconds.

Participant Memory Strategies

Building on the observed performance metrics, participants also reported the memory strategies they employed during the experiment via a post-task questionnaire. A thematic analysis was conducted to identify recurring strategy types. Table 5 summarizes the most commonly reported approaches, along with descriptions and illustrative examples.

Table 5: Participant-reported memory strategies with descriptions and examples

Strategy	Description	Example from Participant
Story-based Recall	Creating a narrative or scenario to link items and locations meaningfully.	"I made up a story that connected all the items. I was roleplaying a family living there."
Spatial Anchoring	Placing objects where they intuitively belonged within the room's context.	"I placed the items where they felt natural, like furnishing an apartment."
Emotional Association	Linking objects to personal memories or emotional significance.	"Some objects reminded me of my parents' home, like how they decorate with fossils."
Visual Matching	Associating an object's appearance with environmental features or colors.	"The fossil just looked like it belonged in the bathroom. The asteroid matched the black table."
Route Repetition	Using the same walking path or spatial navigation to trigger memory recall.	"I followed the same path again and remembered where I placed things the first time."
Verbal Relabeling	Renaming items to create simpler or more personally meaningful labels.	"I didn't use the given names. I called the nuclear barrel 'toxic waste' and the asteroid a 'vase'."

Further breakdowns of interaction-level metrics, including total placements, resets, durations, and recall accuracy, are provided in Table 6. These data report the raw values observed for each locomotion condition.

Table 6: Descriptive statistics for key behavioural metrics per condition. Recall accuracy is reported as a proportion correct out of 12 items.

Condition	Participants	Total Placements	Resets	Association Phase Mean (s)	Recall Phase Mean (s)	Recall Accuracy
Teleportation	12	172	28	487	260	0.78
Walking-in-Place	12	154	10	594	349	0.88

Table 6 summarizes the number of participants, total placements, resets, mean durations for the Association and Recall phases (in seconds), and mean recall accuracy per locomotion condition. Both groups consisted of 12 participants. The Teleportation group recorded 172 placements and 28 resets, with Association Phase Mean of 487 seconds and Recall Phase Mean of 260 seconds, achieving a recall accuracy of 0.78. The Walking-in-Place group recorded 154 placements and 10 resets, with Association and Recall Phase Means of 594 and 349 seconds respectively, and a recall accuracy of 0.88.

To explore trends beyond group-level averages, visual analyses were conducted to examine individual variability and time–accuracy relationships.

Participant Experience Ratings

Participants also rated their experience using a 5-point Likert scale across several subjective dimensions. These included perceived clarity of instructions, task difficulty, and overall engagement. These subjective ratings were based on custom Likert-scale items developed specifically for this experiment, targeting perceived cognitive load, spatial orientation, and engagement. Table 7 reports the mean scores and standard deviations for each condition.

Table 7: Participant Likert-scale experience ratings (Mean ± SD)

Question	Teleportation (Mean ± SD)	WIP (Mean ± SD)
Confidence in recall	3.67 ± 1.37	4.08 ± 1.38
Ability to form associations	3.75 ± 0.97	3.83 ± 0.72
Mental demand	2.67 ± 0.89	2.50 ± 0.90
Spatial orientation in VR	3.83 ± 0.83	4.00 ± 0.85
Discomfort / VR sickness	1.75 ± 0.97	1.50 ± 0.52

Figure 9 presents recall accuracy for each of the 12 placement zones, separated by locomotion condition. The WIP group demonstrated higher accuracy in 7 zones, the Teleportation group in 2 zones, and both conditions performed equally in 3 zones (Zones 1, 9, and 12).

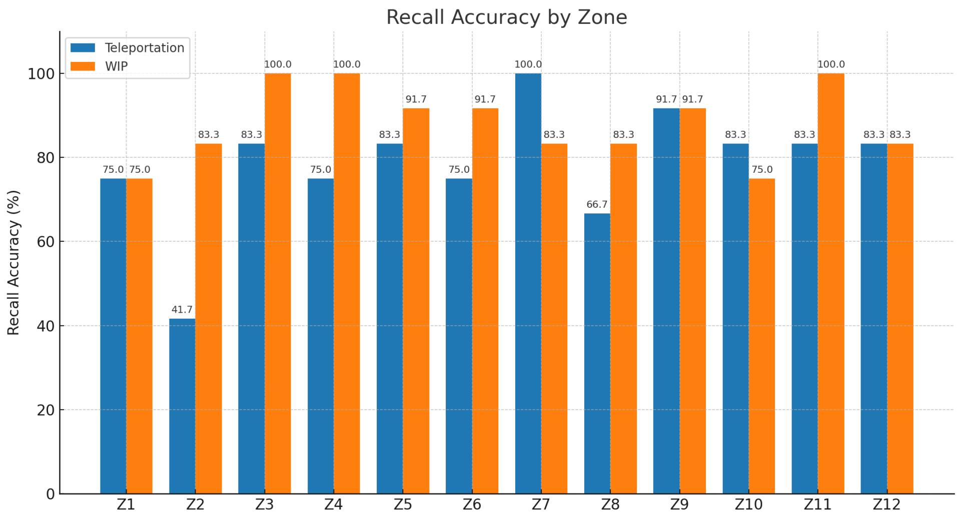


Figure 9: Recall accuracy as a function of total task duration, color-coded by locomotion condition.

Statistical Modeling

Table 8 summarizes the regression coefficients, standard errors, t-values, and p-values for the model predicting recall accuracy from locomotion condition and VR familiarity. The model included two predictors: WIP condition and VR familiarity. The coefficient for WIP was

$\beta = 1.17$ (SE = 1.27), $t = 0.92$, $p = 0.34$, indicating a positive but non-significant trend. VR familiarity was not a significant predictor ($\beta = 0.15$, SE = 0.86, $t = 0.18$, $p = 0.85$).

Table 8: Linear regression predicting recall accuracy

Predictor	**β Coefficient**	**SE**	**t**	**p-value**
Intercept	9.09	1.35	6.75	<0.001
WIP Condition	1.17	1.27	0.92	0.34
VR Familiarity	0.15	0.86	0.18	0.85

While none of the predictors reached statistical significance, it is worth noting that the modest sample size ($N = 24$) may have limited statistical power to detect small or moderate effects. To further examine group-level differences, two additional statistical tests were conducted.

The linear regression model showed a positive, though non-significant, effect of WIP ($\beta = 1.17$, $p = 0.34$). Complementary t-test and Mann–Whitney U test analyses yielded non-significant results as well ($p = 0.331$ and $p = 0.360$, respectively; see Table 9). While these tests do not provide evidence for a statistically robust difference, they underscore the challenge of detecting subtle effects in small samples.

Table 9: Statistical comparison of recall accuracy between locomotion conditions

Test (WIP vs. Teleportation)	**Test Statistic**	**p-value**
Independent Samples t-test	$t = -0.99$	.331
Mann–Whitney U test	$U = 57.0$	.360

To assess potential differences in recall accuracy between the two locomotion conditions, both an independent samples t-test and a Mann–Whitney U test were conducted. The t-test yielded $t(22) = -0.99$, $p = .331$, with $n = 12$ per group. The non-parametric Mann–Whitney U test resulted in $U = 57.0$, $p = .360$, with $n_{WIP} = 12$ and $n_{Teleportation} = 12$. These analyses were performed to complement the regression model and to ensure robustness across statistical methods. While the regression model did not reveal a statistically significant effect of locomotion condition on recall accuracy, these descriptive patterns provide a consistent directionality aligned with the study's core hypothesis and contribute valuable context for interpreting condition-related differences. Interpretation of these results is provided in the discussion section.

Visual Patterns

Figure 10 displays a scatter plot of recall accuracy (y-axis) as a function of total task duration in seconds (x-axis). Each data point corresponds to an individual participant, with Teleportation participants represented by yellow circles and Walking-in-Place participants represented by red triangles. The x-axis ranges approximately from 450 to 2000 seconds, while the y-axis spans from 30% to 100% accuracy. Most Walking-in-Place participants are clustered near the upper range of accuracy, with a wider range of total durations. Teleportation participants are primarily concentrated between 450 and 750 seconds in total duration.

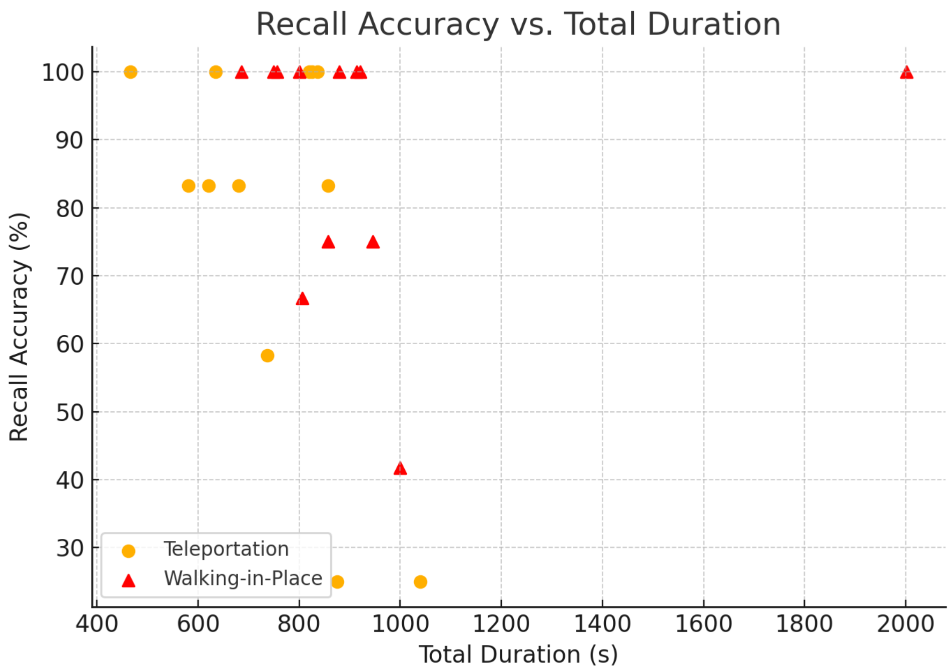


Figure 10: Recall accuracy as a function of total task duration, color-coded by locomotion condition.

Note: Total task duration represents the sum of Association Phase duration and Recall Phase duration, measured in seconds.

This spread indicates that Walking-in-Place participants generally exhibit higher recall accuracy with a wider range of total task duration (sum of Association and Recall phase durations), suggesting variability in engagement time, whereas Teleportation participants cluster at shorter durations and lower accuracy.

Figure 11 shows a scatter plot comparing Association Phase duration (x-axis) and Recall Phase duration (y-axis) for each participant. Teleportation participants are indicated by yellow circles, while Walking-in-Place participants are shown as red triangles. Association durations range approximately from 300 to 1400 seconds, while Recall durations range from about 150 to 600 seconds. The data points are distributed across both axes, with most Teleportation participants clustered between 300 and 700 seconds for Association Phase and 150 to 350 seconds for Recall Phase. Walking-in-Place participants span a wider range on both axes, including the longest recorded durations in both phases.

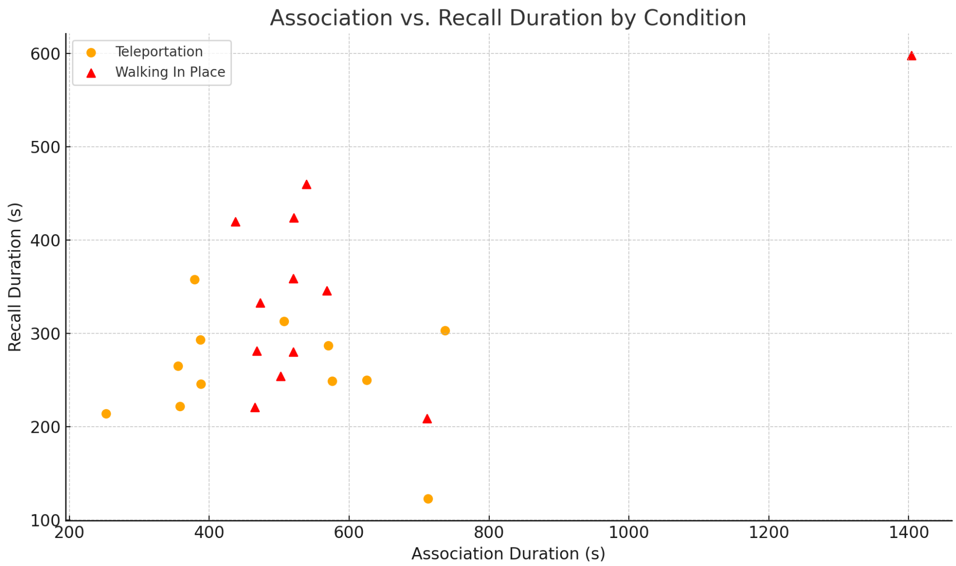


Figure 11: Association Phase duration vs. Recall Phase duration for each participant, color-coded by locomotion condition.

The distribution shows greater variability in the durations of the Association and the recall phases among participants who walk in the place, which may reflect different strategies or levels of comfort with the novel locomotion method.

5.3 Testing the Hypotheses

This section evaluates the three hypotheses guiding the present study. The main hypothesis (H1) posited that participants using Walking-in-Place (WIP) would recall more correct item–location associations than those using Teleportation. Sub-hypothesis H1a predicted that WIP participants would spend more time during the task phases, reflecting deeper exploration and cognitive involvement. Sub-hypothesis H1b proposed that WIP participants would reset items less frequently, reflecting greater decisiveness and confidence in their memory encoding.

Main Hypothesis (H1): Higher Recall Accuracy in WIP Condition

The hypothesis that participants in the WIP condition would demonstrate superior recall performance received partial support. WIP participants had a higher mean recall score ($M = 10.58$, $SD = 2.31$) compared to those in the Teleportation group ($M = 9.42$, $SD = 3.34$), and their overall recall accuracy ratio was also higher (0.88 vs. 0.78). Although non-significant, participants in the Walking-in-Place group recalled on average one more item correctly than those in the Teleportation group, a trend in the hypothesized direction.

To statistically evaluate this pattern, a linear regression model (Table 8) was conducted with locomotion condition and VR familiarity as predictors. The analysis showed a positive but non-significant effect for the walking-in-place condition ($\beta = 1.17$, $p = .34$), and VR familiarity was also not a significant predictor ($\beta = 0.15$, $p = .85$). Group comparison tests (independent-samples t-test and Mann–Whitney, Table 9) likewise failed to reach significance ($p = .331$; $p = .360$), suggesting no statistically reliable difference in recall accuracy between the two conditions, likely due in part to the modest sample size and generally high overall recall scores (i.e., ceiling effects).

Despite the lack of statistical significance, several descriptive trends aligned with the hypothesized advantage for WIP. Zone-level accuracy data revealed that WIP participants outperformed their Teleportation counterparts in 7 of the 12 placement zones, with equal performance in 3 zones and higher Teleportation accuracy in only 2. Furthermore, visual analyses (Figure 10) showed a clustering of WIP participants toward both higher accuracy and longer engagement durations, suggesting a more consistent and potentially more reflective task engagement profile.

It should be noted that the modest sample size ($N = 24$) limited the statistical power to detect small or moderate effects. Even so, the descriptive patterns consistently pointed in the same direction: Walking-in-Place (WIP) participants achieved higher recall accuracy, made fewer item resets, and outperformed teleportation in most spatial zones. These trends, although not statistically significant, suggest that WIP encouraged more deliberate and embodied engagement with the task, consistent with embodied cognition theory, which emphasizes the role of active movement in strengthening spatial encoding.

Sub-Hypotheses H1a and H1b

H1a and H1b were treated as exploratory sub-hypotheses and therefore not tested inferentially. Given the modest sample size, analyses were focused on the primary outcome (recall accuracy, H1). Secondary measures such as task duration and reset frequency were instead examined descriptively to provide context and generate directions for future research.

Sub-Hypothesis H1a: Longer Task Engagement in WIP Condition

Although not formally tested, descriptive results for H1a suggested that WIP participants spent more time on task, reflecting deeper cognitive processing. Participants in the WIP group spent more time during both the Association Phase ($M = 594.00$ s, $SD = 264.58$) and Recall Phase ($M = 348.75$ s, $SD = 112.71$) compared to those in the Teleportation condition (Association: $M = 487.25$ s, $SD = 156.26$; Recall: $M = 260.25$ s, $SD = 59.43$). Total task duration was also longer in the WIP group ($M = 942.75$ s, $SD = 345.80$) relative to the Teleportation group ($M = 747.50$ s, $SD = 157.83$).

These temporal differences suggest a pattern of extended engagement in the WIP condition, consistent with the idea that embodied navigation invites a more reflective or deliberate interaction style. Visual inspection of scatterplots (Figures 10 and 11) showed that WIP participants tended to cluster toward both longer durations and higher recall accuracy. In contrast, the Teleportation group displayed greater variability, including outliers with low recall despite extended task durations.

The relationship between time and accuracy therefore remains ambiguous: while WIP appears to support richer encoding strategies, it may also require more time due to physical or interactional complexity.

Sub-Hypothesis H1b: Fewer Resets in WIP Condition

Similarly, H1b was explored descriptively and indicated that WIP participants reset items less frequently during the Association Phase. WIP participants recorded fewer resets ($M = 0.83$) compared to the Teleportation group ($M = 2.33$).

This behavior may reflect more intentional encoding or stronger memory confidence, particularly when considered alongside WIP participants' higher accuracy trends, longer engagement durations, and higher self-reported confidence ($M = 4.08$ vs. 3.67). Participants in the WIP group also reported greater perceived spatial orientation ($M = 4.00$ vs. 3.83), consistent with embodied cognition theories that link bodily movement to spatial memory representations.

Although reset behavior was not statistically tested, the consistency of this trend across descriptive, subjective, and behavioral measures suggests that embodied navigation fostered greater decisiveness in item placement.

6 Discussion

The results revealed consistent but non-significant trends in favor of the Walking-in-Place (WIP) condition, particularly in recall accuracy, task duration, and item resets. This section interprets these findings in light of existing literature and theoretical frameworks, particularly those related to spatial memory, embodied cognition, and VR learning environments.

What We Found

Descriptive results indicated a consistent trend favoring the Walking-in-Place (WIP) condition. Participants in this group demonstrated higher average recall accuracy and completed fewer item resets compared to those in the teleportation group. Zone-level analysis showed higher accuracy for WIP participants in 7 out of 12 spatial zones, equal performance in 3 zones, and lower performance in 2 zones. These trends align with the hypothesis that embodied locomotion strengthens memory, even if the small sample made it difficult to establish firm statistical evidence (see Results). This resonates with findings by [Ruddle and Lessels, 2006], who reported that continuous movement in VR improved spatial updating compared to teleportation, suggesting that even modest forms of embodied navigation provide encoding benefits.

Why Movement Matters

Both groups achieved high recall scores, suggesting the task was accessible and potentially limited by ceiling effects. However, consistent differences still emerged between the two groups. WIP participants tended to achieve higher accuracy and required fewer resets, suggesting they may have encoded associations more deliberately and confidently, consistent with embodied cognition theory. This interpretation is consistent with embodied cognition accounts [Chrastil and Warren, 2015; Proffitt, 2006], which demonstrate that active movement yields richer spatial learning than passive observation. Similarly, [Plancher et al., 2010] showed that active navigation in virtual environments produced stronger episodic recall than passive conditions.

These observed group differences point to potential advantages for embodied interaction, particularly in initial encoding and spatial decision-making. Yet the statistical tests did not confirm a reliable effect, likely due to the small sample size, making it difficult to detect subtle differences. WIP participants also spent longer on tasks, reflecting the added effort of embodied navigation.

Beyond accuracy and duration, differences in how participants managed item resets also hinted at distinct strategic approaches, discussed in the next section.

How People Encoded and Strategies Used

In addition to performance-based metrics, participants' self-reported strategies provide further insight into the encoding and recall process. WIP participants more often described their memory as following a path, route, or journey, suggesting that locomotion helped them construct coherent spatial narratives. In contrast, some teleportation users reported a more fragmented or visually oriented approach.

Comparable strategy differences are evident in spatial cognition: locomotion methods shape both navigation strategies and the type of spatial representations formed. Continuous, body-based movement tends to support more stable, path-based representations, whereas discontinuous or disembodied navigation encourages reliance on visual landmarks. This aligns with [Waller and Greenauer, 2007], who found that body-based sensory cues enhanced directional estimation, and with [Kelly and McNamara, 2008], who showed that egocentric experience in virtual environments interacts with structural cues to shape spatial memory.

Participants in the teleportation condition performed more resets than those in the WIP group. This difference could be attributed to the locomotion method itself. Teleportation, with its swift and flexible nature, may have allowed participants to experiment more freely, knowing they could revisit zones quickly and make changes without much consequence. In contrast, WIP required users to physically walk back to a placement zone to reset an item. This added effort likely made participants more mindful, calculated, and deliberate with their initial placement decisions, resulting in fewer resets. The physical investment involved in WIP may have encouraged the formation of stronger spatial associations and more solidified mental maps.

Self-reported experience ratings further reinforce these observations. WIP users rated their confidence in recall, spatial orientation, and ability to form associations higher than teleportation users. They also reported slightly lower levels of cognitive load and VR-related discomfort. Together, these patterns offer indirect support for H1a, suggesting that embodied movement may facilitate stronger spatial encoding through more deliberate navigation, confidence in placement, and the formation of spatial narratives.

Contextual Effects and Zone-Level Nuances

The effects of locomotion were not uniform across spatial zones. While WIP participants generally performed better overall, teleportation showed advantages in certain areas, and some zones yielded equal performance. This variability highlights that the benefits of embodied navigation are not categorical but context-dependent.

For example, in zones with repetitive or ambiguous layouts, WIP participants performed more accurately, suggesting that proprioceptive cues helped disambiguate spatial features. In contrast, teleportation showed slight advantages in simpler zones, where reduced sensorimotor demands may have streamlined performance.

These zone-level differences suggest that embodied movement is particularly beneficial in environments with ambiguous or easily confusable spatial cues, whereas teleportation may be equally effective in straightforward layouts. Rather than offering a uniform advantage, the impact of locomotion appears to depend on the interplay between task demands and environmental features. This resonates with our earlier review of [Bozgeyikli et al., 2016], who noted that teleportation trades immersion for efficiency, often at the cost of fine-grained spatial learning. Our findings extend this by showing that embodied navigation may compensate under higher spatial ambiguity. This was evident in our data, where WIP participants showed stronger performance in zones with repeated layouts, suggesting that embodied cues helped resolve spatial overlap, while teleportation showed slight advantages in simpler zones where reduced sensorimotor demands streamlined performance. Taken together, these differences highlight a practical trade-off: embodied movement supports disambiguation in complex layouts, while teleportation may optimize efficiency in simpler environments.

Behavioral Patterns

These duration differences are unpacked further in the behavioral analyses. As shown in Figures 10 and 11, participants in the walking-in-place (WIP) condition generally showed higher recall accuracy and longer task durations compared to those in the teleportation condition. Importantly, these patterns were not simply a function of time spent on the task. Instead, the clustering of WIP participants toward both longer durations and stronger recall performance suggests that embodied movement may have supported more deliberate and spatially grounded strategies.

This extended engagement appeared to reflect more deliberate navigation and memorization strategies, rather than mere inefficiency. The contrast between conditions was also evident in pacing across the Association and Recall phases. In the WIP condition, steadier and more consistent pacing suggests that embodied movement fostered a rhythm of engagement that supported systematic encoding and retrieval. By contrast, teleportation participants showed greater variability, with some completing phases quickly and others extending their time without corresponding improvements in accuracy.

Together, these behavioral trends indicate that the mode of navigation shaped not only memory outcomes but also the temporal dynamics of task engagement. The embodied demands of WIP encouraged a more sustained style of exploration, whereas teleportation often produced fragmented or uneven engagement. These observations highlight behavioral differences that extend beyond the statistical outcomes alone.

Exploratory Observations and Strategy Use

Strategy reports reinforce this distinction. These contrasts align with participants' reported strategies (see Section "How People Encoded"), where teleportation users emphasized visual anchors and WIP participants described embodied paths and spatial narratives. Taken together, these patterns suggest that locomotion not only influenced outcomes but also shaped the type of spatial representation participants relied on.

These findings provide preliminary evidence of a practical trade-off: while embodied movement fosters deeper encoding, it may not always be optimal in contexts where speed or efficiency is prioritized. This creates opportunities for future exploration of hybrid locomotion designs that balance cognitive benefits with practical constraints.

Contributions

At a theoretical level, this work adds to research on embodied cognition by demonstrating that locomotion methods in VR do more than simply move users through space—they shape the way spatial information is encoded and recalled. Walking-in-place encouraged participants to form richer, path-based narratives, while teleportation often led to more fragmented strategies. These findings highlight how sensorimotor cues support memory within virtual adaptations of the Method of Loci. At a practical level, the results offer guidance for the design of VR learning and mnemonic tools. By showing that embodied locomotion can enhance recall accuracy and promote stronger spatial associations, this work suggests that movement interfaces should be treated not just as technical design choices, but as cognitive ones. Educators, trainers, and designers of memory-support systems can leverage embodied navigation to foster deeper engagement and improve learning outcomes.

Broader Implications and Future Directions

The observed benefits of embodied interaction in VR suggest that even modest physical movement may shape how associations are formed and recalled. Together, these findings nuance embodied cognition accounts [Chrastil and Warren, 2015; Proffitt, 2006] by showing that not all forms of movement are equally beneficial; rather, their value depends on task context and environmental complexity. They also extend VR memory research (e.g., Krokos et al., 2019; McCabe, 2015) by illustrating how locomotion design itself shapes mnemonic strategies.

These findings reinforce the theoretical value of embodied cognition in virtual environments and point to the importance of continued exploration. While Section 8 outlines specific design and methodological priorities, future research should also consider how user agency, environmental complexity, and locomotion types interact to shape both spatial learning and the subjective experience of memory navigation.

Ultimately, our study highlights that how we move in VR is not just a technical choice but a cognitive variable that shapes memory itself.

7 Limitations

This study has several limitations that should be acknowledged.

First, the reliance on relatively small physical spaces constrained the realism of the locomotion-based condition. While Walking-in-Place (WIP) effectively simulates movement, it does not replicate natural ambulatory motion. Techniques such as Redirected Walking (RDW), which subtly manipulate the virtual environment to steer users without their awareness, could provide a more ecologically valid alternative. Future studies should explore the feasibility and cognitive impact of RDW in memory-focused VR tasks.

Second, the modest sample size ($n = 24$) and the generally high recall performance across participants raise the possibility of a ceiling effect. Because most participants performed at a relatively high level, differences between conditions may have been compressed, making it harder to detect statistically significant effects even when consistent trends were present. The limited sample size, constrained by the scope of a Master's thesis, further reduced statistical power. Future work should address this by increasing both sample size and task complexity, which would help to lower ceiling effects and improve sensitivity to condition-specific differences.

Third, although the WIP condition introduced embodied interaction, its implementation did not involve full-body locomotion or spatial displacement. The limited realism could have either muted or exaggerated the observed cognitive benefits. Incorporating room-scale tracking or more naturalistic movement systems may provide a better test of embodied memory theories. Moreover, the specific Walking-in-Place (WIP) implementation in this study relied on head-bobbing detection. While this enabled simulated locomotion within limited physical space, several participants reported it as distracting or unnatural. This may have interfered with immersion and introduced variability in how effectively the embodied condition supported memory encoding. Future work should test alternative WIP implementations—such as controller-based stepping gestures or inertial sensor–driven gait recognition—to evaluate whether more naturalistic designs preserve cognitive benefits while reducing distraction.

Fourth, the experimental environment comprised three visually similar apartments. While this design choice allowed controlled comparison across zones, it may also have introduced perceptual interference, particularly for teleportation users. Future work should test more varied or semantically rich spatial contexts to clarify how environmental features interact with different locomotion methods. In addition, the artificial nature of the task and the controlled experimental setting may limit ecological validity. While these constraints support internal validity, they reduce generalizability to everyday memory tasks in dynamic real-world environments.

Although VR familiarity and task duration were included as covariates, other individual differences such as spatial ability, attention control, or working memory capacity were not measured. Pre-task assessments of these traits could clarify how individual cognitive profiles mediate the effects of embodied VR learning. Additionally, the study only measured immediate recall performance. Future research should assess long-term memory retention to better understand the durability of embodied learning effects.

Finally, this study employed a between-subjects design, which helps prevent carryover effects but introduces greater inter-individual variability. A within-subjects design could offer higher sensitivity by controlling for participant-level differences, although it may require additional counterbalancing measures.

8 Future Work

To build on these results, future research should:

- Increase task complexity to mitigate ceiling effects;
- Test additional locomotion modalities such as arm-swing systems, omnidirectional treadmills, or setups that include knee or leg tracking sensors;
- Refine Walking-in-Place implementations: Explore alternatives to head-bobbing (e.g., controller stepping, inertial sensors, or foot-tracking) to reduce distraction and improve ecological validity;
- Compare active versus passive locomotion to isolate the cognitive impact of agency in embodied interaction;
- Investigate the use of larger physical spaces or implement techniques such as Redirected Walking (RDW), which subtly steer users within limited real-world boundaries to simulate larger virtual environments;
- Vary spatial environments and object semantics;
- Collect self-reports of memory strategies and administer standardized spatial ability tests (e.g., mental rotation or spatial orientation tasks) to better understand how individual cognitive profiles influence encoding and recall under different locomotion conditions;
- Examine physiological markers of engagement and stress;
- Explore combinations of locomotion types to optimize usability and performance.

Design Refinements and Strategy Considerations

Post-task feedback revealed that participants employed diverse memory strategies, including personal associations, spatial narratives, and object-function reasoning. However, several patterns suggest opportunities to refine task design and reduce strategy-based biases:

- **Discourage linguistic and categorical strategies**: Participants may have relied on item names to group or place objects alphabetically or by semantic category (e.g., all 'stone-like' items together or all 'traffic-related' items together). Future iterations could hide names during the Recall Phase, use abstract or randomized labels, or vary the timing of item presentation to reduce reliance on linguistic encoding.

- **Limit visual grouping strategies**: Visually or thematically similar objects (e.g., fossil, asteroid, coral) may have encouraged clustering by color or shape. Selecting more diverse items across dimensions such as material, function, and emotional salience can help reduce visual redundancy.

- **Restrict visible inventory**: Showing only one or two items at a time, rather than the full set, could discourage batch placement strategies and promote more deliberate encoding.

- **Include distractor items**: Adding a few visually similar but irrelevant objects (e.g., 3 distractors among 12 target items) could help measure discriminability and reduce reliance on elimination or process-of-elimination strategies.

- **Standardize exposure time**: Equalizing item exposure times across participants, or by room or phase, could improve control over encoding conditions.

- **Introduce distinct spatial environments**: Participants reported confusion due to visually similar apartment layouts. Future designs should differentiate environments through layout, decor, and lighting to aid disambiguation and spatial anchoring.

- **Explore time constraints**: Introducing optional or mild time limits could assess how embodied encoding functions under cognitive pressure while preserving exploratory freedom.

- **Code participant strategies**: Open-ended feedback revealed rich variations in memory strategies. Future studies should incorporate structured interviews or formal content analysis to investigate how locomotion affects strategic encoding.

- **Leverage game analytics**: The current system logs item interactions, resets, and scene transitions. These data could be further analyzed to identify behavioral markers of spatial encoding, confusion, or embodied engagement.

- **Embed narrative or dialogue (optional)**: A lightweight narrative structure or contextual dialogue could enhance immersion and facilitate memory by providing semantic hooks.

These refinements would strengthen experimental control while preserving ecological validity, enabling more precise investigation of the cognitive mechanisms underpinning embodied memory.

9 Conclusion

This thesis examined how different locomotion methods, teleportation and Walking-in-place, influence memory within a virtual reality memory palace. The results revealed consistent trends favoring Walking-in-place group across recall accuracy, task duration, and reset behavior, though these differences were not statistically significant, likely due to the limited sample size and possible ceiling effects in recall performance. Even so, the patterns suggest that embodied locomotion supports more deliberate encoding, stronger spatial associations, and more confident recall strategies compared to teleportation.

These findings contribute to research on embodied cognition by showing that locomotion in VR is not a neutral technical choice but a cognitive variable that shapes how spatial information is encoded and recalled. Walking-in-place participants more often described their recall as path-based and narrative-driven, while teleportation users relied on more fragmented, visually anchored strategies. This aligns with theoretical accounts of embodied interaction, where active movement strengthens spatial memory by engaging sensorimotor cues.

At a practical level, the results underscore the importance of locomotion design in VR learning and mnemonic tools. Interfaces that encourage embodied navigation may foster richer engagement, deeper encoding, and improved recall accuracy, particularly in tasks requiring spatial associations. Designers of educational VR systems, training environments, and cognitive support tools should therefore treat locomotion not merely as a usability concern but as a central element of cognitive design.

In summary, this study highlights that how users move through virtual environments fundamentally shapes their memory of those spaces. While further research with larger samples is needed to confirm these effects, the consistent trends observed here reinforce the value of embodied navigation as a design principle. Locomotion in VR should be recognized not just as a means of traversal but as an integral factor in how memory is formed, experienced, and recalled.

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Appendix

Participant Materials

The following documents were provided to participants as part of the ethical approval process and participation protocol.

- Participant Information Sheet
- Informed Consent Form
- Debriefing Sheet

Information Sheet

Name of the Student:	Tudor Drobota
Affiliation:	Media Technology MSc, Leiden University
Name of the Supervisor(s):	Dr. Maarten Lamers and Dr. Ineke van der Ham
Research Title:	Cognitive Voyages: Navigating Virtual Spaces

Introduction
My name is Tudor Drobota, and I am a master's student in the Media Technology program at Leiden University, supervised by Dr. Maarten Lamers and Dr. Ineke van der Ham. For my graduation project, I am conducting a study that explores how people interact with and remember information in virtual reality (VR) environments.

This research focuses on memory and spatial orientation in VR. Participants will explore a virtual environment, place objects at specific locations, and later try to remember where those objects were placed. The study is based on the Method of Loci (MoL), a well-established memory technique that involves associating information with specific spatial locations. We are investigating how this strategy works when applied within a VR setting.

Your participation will contribute to research at the intersection of psychology and immersive technology. The insights may help improve the design of VR tools for education, training, and cognitive support. The study follows strict ethical standards, and your privacy, safety, and comfort will be ensured throughout the process.

Purpose of the research
This research investigates how exploring and interacting within virtual reality environments influences memory and spatial understanding. The study aims to gain insights into memory related cognitive processes.

Voluntary Participation
Your participation in this study is completely voluntary. You have the freedom to decide whether to partake in the research or not, without any obligation. Your consent is important to us, and we are here to answer any questions or concerns you might have regarding your participation.

Right to Withdraw
You have the right to withdraw your consent at any time within one month of providing it. Withdrawing your consent will not have any adverse consequences, and you are not required to justify your decision. If you decide to withdraw, any data collected from you will be excluded from the study results and will be securely disposed of.

Procedures
Upon your arrival, you will receive a briefing on the study's objectives and your role in the research. You will be asked to sign an informed consent form to confirm your understanding and agreement to participate.

Before starting the experiment, you will first complete a short questionnaire collecting basic demographic information, including your age, gender, and previous experience with virtual reality.

To ensure that everyone feels comfortable and confident using the VR equipment, you will receive a brief familiarization session introducing the setup and guiding you through safe and intuitive interaction with both the equipment and the virtual environment.

The experiment consists of several tasks designed to assess memory and spatial cognitive abilities through interactive VR experiences.

After the VR tasks, you will complete a brief questionnaire to share your experience and any discomfort or disorientation you may have felt. The session concludes with a debriefing where you can ask any further questions and discuss your experience.

You are encouraged to ask for clarifications at any time during the experiment. Our team is here to ensure you understand and are comfortable with all aspects of the study.

Potential Risks and Discomforts
Participating in VR research may include some inherent risks, such as the potential for motion sickness, eye strain, or a sense of disorientation. To mitigate these risks:

- Before beginning the experiment, all participants will receive a brief introduction and hands-on demonstration to ensure they understand how to use the VR equipment and navigate the virtual environment.
- A researcher will monitor you throughout the session to ensure your safety and comfort.
- Should you feel uncomfortable, nauseous, or disoriented at any point, you will be able to inform a staff member immediately, pause the experiment and appropriate measures (like a chair and water) will be provided to help you.
- You have the right to pause or stop participating at any moment during the experiment if you feel uncomfortable continuing for any reason. There will be no negative consequences for deciding to stop, and your decision will be fully respected.
- The entire session, from arrival to departure, is designed to be completed within approximately 60 minutes, depending on your engagement and the specifics of the session.

Reimbursements
As a token of our appreciation for your participation in this study, we are pleased to offer you a choice of complimentary coffee or tea. Please note that while we do not provide monetary compensation for participation in graduation research, we value your time and contribution to this important research. The provision of coffee or tea is our way of thanking you, ensuring you have a pleasant experience during the study session.

Privacy
For the purpose of this research, we will be collecting a range of data to understand and analyse participant behaviour and performance within a virtual reality (VR) environment. This includes:

- Personal Information, such as demographic information including participant ID, gender, age, familiarity with VR, and other relevant details to tailor and analyse the study.
- In-game analytics will include general measures such as session duration, task completion time, and participant interactions with objects and locations in the virtual environment.
- This data is used to evaluate overall performance and engagement during the experiment.

Steps are taken to anonymize and protect all personal data collected during the research. Only the research team will have access to this data, ensuring your privacy is maintained. Access to this data is strictly limited to the research team, safeguarding your personal information, and ensuring that your privacy is maintained throughout the process of this research.

Retaining and Sharing data

Once collected, all data will be pseudonymized to further protect participant identities. Any dissemination of the research findings, whether in academic papers or presentations, will utilize only anonymized data. After the project is completed, all data will be securely transferred to the Media Technology archive at Leiden University. Any future sharing of data will be in anonymized form unless explicit consent is provided.

Sharing the Results

The primary dissemination of results will be through academic papers and the thesis, which might be published in relevant scientific journals and presented at conferences. This ensures that the research community can review and build upon the findings. All shared data will be anonymized to protect participant identities.

Who to Contact

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Informed Consent Form

For participating in Media Technology MSc graduation project research
Cognitive Voyages: Navigating the Impact of Locomotion on Memory within Virtual Reality Memory Palaces, conducted by Tudor Drobota supervised by Dr. Maarten Lamers and Dr. Ineke Van Der Ham at Leiden University

I confirm that I have been clearly informed about the nature and method of the research, as described in the information sheet. My questions have been answered satisfactorily.

I agree to participate in this research freely. I know that I can stop my participation at any time. If my research results are to be used in scientific publications, or made public in any other way, this will be done completely anonymously, unless I give my consent to exceptions below by marking the checkboxes.

Optional Consent for Use of Research Material
The following are entirely optional and only applicable if such materials are collected.

☐ I consent to having my responses quoted in research publications. I understand that my (real) name and any other direct identifiers will not be used.

If I would like any further information about the study, now or in the future, I can contact Tudor Drobota (telephone: *+31 684800681*, e-mail: *tudor.drobota97@gmail.com*) and Maarten Lamers (telephone: *+31 71 527 7033*, e-mail: *m.h.lamers@liacs.leidenuniv.nl*).

If I have any complaints about this research, I can contact the supervisor of this research (name, surname, email) or the secretary of the Ethics Committee for Mathematics and Natural Sciences of Leiden University (*ethicscommittee@science.leidenuniv.nl*).

Name, Surname: ……………………….

Location and date: …………………………………………………………………….

Signature: …………………………………………………………………….

De-briefing

Thank you for your participation in this research. This study aims to explore how different locomotion techniques in virtual reality (VR) environments, may affect learning, spatial memory, and cognitive functions. By examining these impacts, we hope to provide insights that could enhance the design of VR systems for educational, training, and therapeutic applications.

Right to withdraw data

You may choose to withdraw the data you provided during the research. If that is the case, please contact me not later than 1 month after participating in this research.

If you have questions

The main researcher conducting this study is Tudor Drobota This research is supervised by Maarten Lamers at Leiden Institute for Advanced Computer Science (LIACS), Leiden University. Please ask any questions you have now. If you have questions later, you may contact Tudor Drobota at tudor.drobota97@gmail.com or at (+31) 68 48 00 681.

If you have any questions or concerns regarding your rights as a research participant in this study, you may contact the supervisor Dr. Maarten Lamers at m.h.lamers@liacs.leidenuniv.nl or (+31) 71 52 77 033 or secretary of the Ethics Committee for Mathematics and Natural Sciences of Leiden University (ethicscommittee@science.leidenuniv.nl).

If you would like to receive a copy of the final report of this study or a summary of the findings when it is completed, please feel free to contact the student.

Your signature below indicates that you have been debriefed, and have had all of your questions answered.

___________________________	_________________________	__________
Name of Researcher	Signature	Date
___________________________	_________________________	___________
Name of Participant	Signature	Date

Please sign both copies, keep one and return one to the researcher.

Pre-Session Questionnaire

The following data were collected from each participant prior to starting the experiment:

1. Participant Name
2. Age
3. Familiarity with VR

Post-Session Questionnaire

The following questions were administered after participants completed the Recall Phase:

1. How confident are you that you correctly remembered most of the item-location pairings?
2. To what extent were you able to form meaningful associations between the objects and their locations in the VR environment?
3. How mentally demanding did you find the task of remembering and recalling item-location pairings?
4. During the recall task, did you feel you always knew where you were in the VR memory palace and how to navigate to each place?
5. Did you experience any discomfort or disorientation while using the VR system?
6. What helped you remember the items best (if anything)?
7. Did you use any strategies to help remember the object locations? If so, please describe them.
8. Was there anything you found particularly easy or difficult about remembering and recalling where you placed the objects in the VR environment?

Custom Scripts

The following custom scripts were implemented to support the experimental system. They were designed in a modular fashion and adapted where necessary for both the Association and Recall phases.

- **InventoryManager:** Handles item instantiation, despawning, and selection from the inventory.
- **PlacementManager:** Controls placement zones, validates correct placements, and manages occupancy states.
- **RecallPlacementManager:** Manages item selection and placement during the Recall Phase; compares recall placements with ground truth.

- **PlacementZone:** Defines individual placement zone behaviour, including highlighting, occupancy checks, and reset handling.
- **RecallPlacementZone:** Recall-specific version of placement zones, enabling text-based item selection.
- **ResetButton:** Implements item reset functionality tied to zone colliders (only functional inside zones).
- **Walking-In-Place-Movement / HeadBobMovement:** Implements head-bob locomotion, translating vertical oscillations into forward motion.
- **TeleportationLocomotion:** Configures and manages teleportation movement using the XR Interaction Toolkit.
- **DataManager:** Logs trial data (placements, timestamps, accuracy, condition, etc.) to Google Sheets/CSV.
- **ConditionManager:** Assigns experimental condition (Teleportation vs. Walking-in-Place) and maintains consistency across scenes.
- **SceneController:** Manages transitions between scenes/phases (Association → Recall).
- **UIManager:** Controls visibility and states of inventory buttons, disables/enables buttons based on item usage.
- **FadeManager:** Provides fade-in/fade-out transitions between phases and after task completion.
- **HighlightManager:** Controls visual glow/feedback of placement zones when items are required or zones are empty.
- **XROriginAutoAlign / CharacterControllerDriverWrapper:** Ensures correct alignment of XR Origin and Character Controller, prevents desynchronization between camera and collider.
- **SnapToGround:** Keeps the player aligned to ground surfaces, preventing floating or phasing through geometry.
- **LoggingUtilities:** Provides helper functions for formatting log entries and ensuring consistency in exported datasets.

Association Phase Instructions

Instructions Text

- Explore the two apartments and locate all 12 placement zones.
- Placement zones appear as yellow glowing cylinders scattered around the environment.
- When you enter a placement zone, your inventory will appear automatically.

- Place each of the 12 items using the MoL in locations that feel intuitive or personally meaningful.
- Try to create strong, memorable associations between each item and its placement.
- You may reset and reposition items at any time before completing all placements.
- There is no time limit, so take your time.

In-Game Screenshot

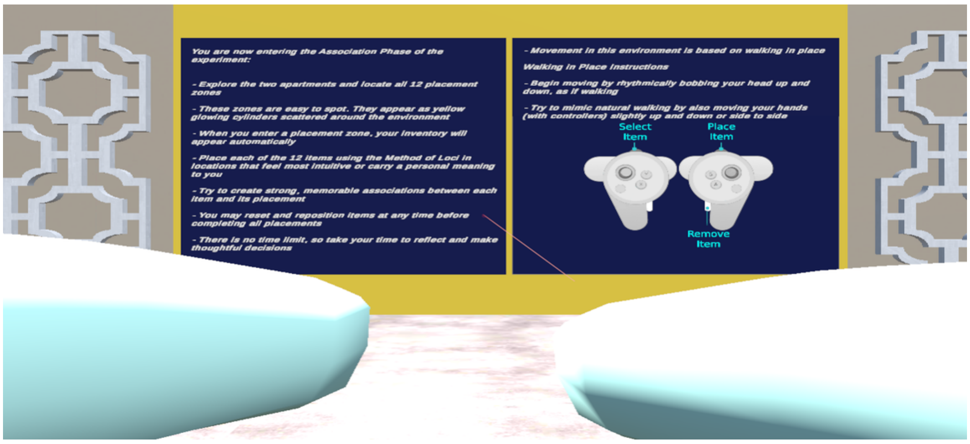

Figure 12: In-game instruction panel for the Association Phase, reproduced here with added details alongside the full instruction text.

Recall Phase Instructions

Instructions Text

- Explore the two apartments and find all 12 placement zones.
- Placement zones appear as yellow glowing cylinders scattered around the environment.
- When you enter a placement zone, your inventory will appear automatically.
- Select and place each item where you remember placing it in the previous phase.
- Try to retrace your path and recall the associations you formed.
- Items cannot be reset or moved once placed.
- There is no time limit, so take your time to reflect and make careful decisions.

In-Game Screenshot

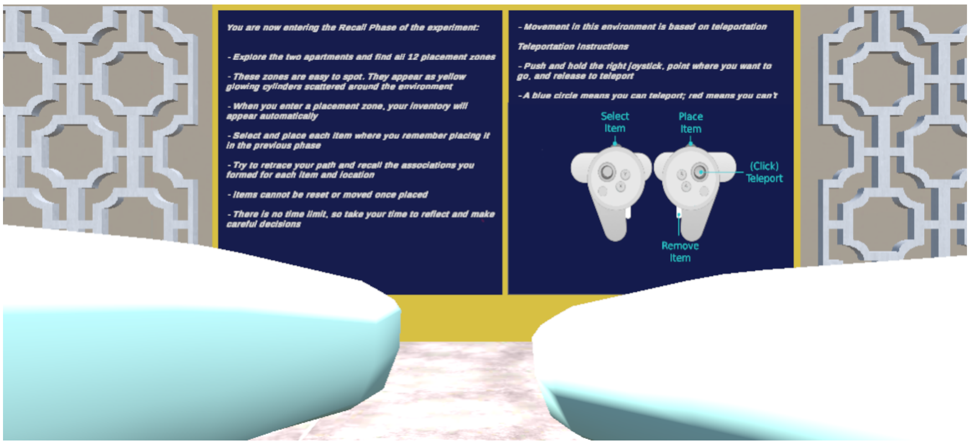

Figure 13: In-game instruction panel for the Recall Phase, reproduced here with added details alongside the full instruction text.

Analysis Workflow (Python)

To ensure reproducibility and transparency, all log data exported from Unity was cleaned and analyzed using Python. The following workflow summarizes the main steps of the analysis process:

1. Import raw CSV logs (placements, resets, timestamps).
2. Remove test sessions and incomplete data.
3. Calculate per-participant metrics (e.g., durations, resets, accuracy).
4. Aggregate data by condition (Teleportation vs. Walking-in-Place).
5. Generate descriptive statistics and visualizations.
6. Conduct inferential tests:
    - Welch's t-test for comparing group means without assuming equal variances.
    - Mann–Whitney U test as a non-parametric alternative for robustness.
7. Export summary tables for reporting.

These tests were chosen due to the relatively small sample size and the possibility of unequal variances between conditions.

Log Output

Example of Collected Participant Data

The following illustrates the full set of data collected from one participant (ID = 1, Teleportation condition). This example shows the level of detail captured per session.

1. **Condition:** Teleportation
2. **Participant ID:** 1
3. **Timestamp:** 2025-06-16 10:58:10
4. **Age:** 20
5. **Gender:** Male
6. **Familiarity with VR:** 2 (out of 5)
7. **Association Duration (s):** 252
8. **Recall Duration (s):** 214
9. **Total Duration (s):** 466
10. **Number of Resets:** 1
11. **Items Recalled:** 12
12. **Total Recall Accuracy:** 100%
13. **Zone Matches:** All 12 zones correctly recalled (Yes for Zones 1–12).
14. **Post-Session Responses:**
    (a) Confidence in remembering item–location pairings: 4
    (b) Confidence in ability to form meaningful associations: 4 (out of 5)
    (c) Mental demand: 3 (out of 5)
    (d) Orientation/navigation confidence: 4 (out of 5)
    (e) Discomfort/disorientation: 1 (out of 5)
    (f) What helped most: *Personal memory trick*
    (g) Strategy: *"I made associations between objects and their location. For example, I placed the beehive in the first since honey is food ans the dining table is a place where people eat."*
    (h) Easy/difficult: *"I found the process moderately difficult, as the objects are not common for an apartment."*

Aggregated Results by Condition

The detailed logs (see example in the previous section) were cleaned and aggregated across all participants. To support transparency, Table 10 presents descriptive statistics for the two experimental conditions. This represents the refined dataset at the condition level, summarizing placements, resets, task durations, and recall accuracy.
Note. Due to privacy and anonymity considerations, the full dataset is not included here but can be made available upon reasonable request to the author.

Table 10: Descriptive statistics for key behavioural metrics per condition. Recall accuracy is reported as a proportion correct out of 12 items (Reproduced).

Condition	Participants	Total Placements	Resets	Association Phase Mean (s)	Recall Phase Mean (s)	Recall Accuracy
Teleportation	12	172	28	487	260	0.78
Walking-in-Place	12	154	10	594	349	0.88

Variable Definitions

- ParticipantID: unique anonymous identifier
- Condition: Teleportation or Walking-in-Place
- Phase: Association or Recall
- PlacementZone: Zone label
- Item: Item name
- Accuracy: Correct/Incorrect
- Timestamp: System log time
- Post-session questions were coded on 1–5 Likert scales where applicable; open-ended responses were thematically coded

Supplementary Materials

The Unity project files, experimental setup, and analysis scripts used in this thesis are available at: https://github.com/drobotatudord/Cognitive-Voyages-Thesis-Project