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Examining the Effects of Teleportation on Semantic Memory of a Virtual Museum Compared to Natural Walking

Zubin Datta Choudhary[1], Laura Battistel [2], Raiffa Syamil[1], Hiroshi Furuya[1],
Ferran Argelaguet[3], Gerd Bruder[1] and Greg Welch[1]

[1]University of Central Florida, Orlando, USA
[2]CIMeC, University of Trento, terraXcube, Eurac Research, Italy
[3]Inria Rennes, Rennes, France

Abstract

Over the past decades there has been extensive research investigating the trade-offs between various Virtual Reality (VR) locomotion techniques. One of the most highly researched techniques is teleportation, due to its ability to quickly traverse large virtual spaces even in limited physical tracking spaces. The majority of teleportation research has been focused on its effects on spatial cognition, such as spatial understanding and retention. However, relatively little is known about whether the use of teleportation in immersive learning experiences can effect the acquisition of semantic knowledge — our knowledge about facts, concepts, and ideas — which is essential for long-term learning. In this paper we present a human-subjects study to investigate the effects of teleportation compared to natural walking on the retention of semantic information about artifacts in a virtual museum. Participants visited unique 3D artifacts accompanied by audio clips and artifact names. Our results show that participants reached the same semantic memory performance with both locomotion techniques but with different behaviors, self-assessed performance, and preference. In particular, participants subjectively indicated that they felt that they recalled more semantic memory with walking than teleportation. However, objectively, they spent more time with the artifacts while walking, meaning that they learnt less per a set amount of time than with teleportation. We discuss the relationships, implications, and guidelines for VR experiences designed to help users acquire new knowledge.

CCS Concepts

• ***Human-centered computing*** → ***Empirical studies in HCI; Virtual reality;***

1. Introduction

Virtual Reality (VR) has long been used for educational and learning applications [Bri91]. In these applications, VR is frequently used to support knowledge acquisition [MMDR20], which in turn primarily involves semantic memory [MHS03]. Semantic memory is important for a wide range of cognitive functions including understanding language, recognizing objects, recalling learned concepts, and integrating new information [SC02]. Semantic memory can also be affected by other cognitive and psychomotor activities, such as actions taken during memory acquisition [Bar16]. VR, while affording access to virtual environments useful for learning and memory development, features numerous interactions and locomotion techniques that are not seen in the real world, raising the question of how the cognitive and psychomotor processes involved in each may impact semantic memory outcomes.

VR locomotion techniques allow users to move through virtual spaces that do not match, or are larger than, users' physical tracking spaces. A wealth of research exists that has investigated the trade-offs between selection of different locomotion techniques for a given VR experience [MWM22]. For example, teleportation techniques, which are unique to VR, offers clear advantages in limited physical spaces. Users' can traverse large virtual spaces instantaneously, and could allow users to access more information in a shorter period of time. It is not clear, however, how this faster traversal may impact users' ability to acquire and recall new semantic memories. On the other hand, natural walking techniques in VR induces higher ratings of presence (feeling "in" the VR environment) and user preference [LJKM*17], supporting the idea that VR experiences can improve learning by providing engaging and immersive learning experiences [HMEW21]. Despite a large amount of work covering each locomotion techniques and VR educational experiences, the direct relationship between specific locomotion techniques and the cognitive processes impacting semantic memory is not well understood [AVS21].

In this paper, we present a human-subjects study ($N = 22$) aimed at understanding the effects of two of the most commonly studied VR locomotion techniques — natural walking and teleportation [MWM22] — on users' semantic memory. We prepared a virtual museum in which participants were tasked to visit and learn the semantic details of different artifacts. This included specific details from the visuals of the 3D objects, accompanying audio clips, and artifact names. To assess semantic memory, we administered recall questionnaires immediately after the museum experience and again 24 hours later. Additionally, to study participants' exploratory behaviors, we tracked their movement and eye gaze during the experience.

The results of our experiment show that participants were able to demonstrate the same level of semantic memory recall performance using both locomotion techniques, despite exhibiting significantly different behaviors in each condition. Furthermore, participants rated their perceived performance and preference higher for natural walking than for teleportation. Thus, although participants' semantic memory outcomes may not have been objectively different, they came away feeling better about their learning experience overall when using natural walking compared to teleportation. On the other hand, participants objectively completed the virtual museum tasks faster in the teleportation condition, meaning that teleportation yielded better task performance metrics compared to natural walking. In other words, traversing the space faster and spending less time with the exhibits did not result in decreased semantic memory outcomes as otherwise might have been assumed. These results help to clarify the direct tradeoffs that need to be considered when choosing locomotion techniques for a new VR learning experience.

The remainder of this paper is structured as follows. Section 2 provides an overview of related work. Section 3 describes our experiment. The results are presented in Section 4 and discussed in Section 5. Section 6 concludes the paper.

2. Related Work

In this section we discuss the literature forming the theory behind semantic memory, factors affecting its acquisition, and how VR locomotion techniques may impact semantic memory.

2.1. Semantic Memory

Our long-term memory as individuals is largely classified into implicit and explicit memory [GS85]. Implicit memories are those acquired without necessity or conscious recollection, such as can observed through the priming effect [PRR90]. Explicit memories, on the other hand, are those remembered consciously in reference to a specific learning event [Sch87]. Explicit memory has classically been further divided into episodic and semantic memories [T*72]. Loosely defined, episodic memory concerns temporal experiences and semantic memory concerns symbols, meaning, and relations. Educational outcomes, such as learning scientific theories or historical facts, can thus be considered outcomes concerning semantic memory. Although semantic memory was originally suggested to be context-free [Bar16], i.e. where you learned it and what you were doing when you learned it have no impact on your recall, more recent work posits that semantic memory incorporates sensorial and actional information in addition to abstract, semantic information [Kum21]. For instance, the physical stimulation of using a kitchen utensil becomes part of the semantic memory of what a kitchen utensil is. Prior work has also demonstrated that actions taken during memory acquisition may affect the retention of the memory, such as the photo-taking-impairment effect where subjects are less likely to remember objects if they photograph them compared to if they only observed them [Hen14], with other work suggesting that the act itself of taking a photo may impair memory encoding [SS18].

In VR, even simple actions such as walking are altered due to an increase in cognitive load by simply being in VR [JKTS19]. Therefore, it is reasonable to expect that semantic memory outcomes of learning experiences would be affected by VR factors, although empirical results are scarce. Prior works do address the effects that VR factors can have on memory concepts similar to long-term semantic memory. Smith reviewed the impacts of VR on *episodic* memory, including factors such as immersion and interactivity [Smi19]. Ragan et al. demonstrated that manipulating field of view in an immersive virtual environment significantly affected short-term procedural memory [RSKB10]. In education, where long-term semantic memory is key to desired outcomes, VR has been primarily studied for its effects on motivation and engagement [KLRWP17]. A review by Hamilton et al. reveals that most studies concerning VR for use in pedagogy utilize multiple choice questions measuring recall of information, though the studies are not designed to investigate the effects of VR factors on semantic memory acquisition [HMEW21]. In this work, we directly investigate the impacts of VR experience design on semantic memory outcomes. In particular, we focus on the effects of VR on semantic memory by investigating the relationship between choice of VR locomotion technique and semantic memory recall of content from a virtual museum experience.

2.2. VR Locomotion Techniques

Limited physical tracking environments place constraints on the VR locomotion techniques that users can rely on to explore VR environments that can vary widely in size and shape. Different techniques address different constraints and present their own advantages and limitations. Natural walking, for example, offers the most natural and familiar mode of locomotion to users but is also limited by mismatches between virtual and tracking environment sizes as well as difficulties in providing users with sensory stimuli to accompany the walking motion [NSSN18]. Another locomotion technique, point-and-teleport, instantly moves users to a location that they point and select [BRKD19]. Point-and-teleport offers the ability to quickly travel long distances but precludes interactions that involve the locomotion itself, such as obstacle courses, and may not be suitable for paths that would require many teleportation interactions, such as moving along a tight curve. Both real walking and point-and-teleport are among the most well-researched VR locomotion techniques in the literature [MWM22], but numerous other types of locomotion techniques have been examined, with techniques largely falling into the categories of walking-based, steering-based, selection-based, manipulation-based, and automated [LJKM*17].

With the variety of locomotion techniques in literature comes a variety of metrics used to investigate them. A review by Martinez et al. showed that metrics represented in VR locomotion literature include travel performance, usability, subjective experience, preference, and cognitive performance, among other categories [MWM22]. Using these metrics, prior work has demonstrated advantages and trade-offs to using specific locomotion techniques. For example, point-and-teleport techniques allow users to move across space faster compared to natural walking, but natural walking techniques elicit higher subjective preference and presence ratings [SSH20]. In addition, Checa et al. suggested participants who toured a historical city using teleportation may miss important information on environmental context compared to participants who used a gamepad [CB20]. Other works address other cognitive ability outcomes, including effects on memory [MWM22]. These mostly focus on evaluating the effect of locomotion technique on *spatial understanding* and *spatial memory*, such as by administering pointing tasks after participants traveled between waypoints [LLS18].

Furthermore, spatial understanding and memory make up only a portion of cognitive development that a VR application may target, especially in education and training contexts. For example, VR has been used to create virtual museum experiences to teach historical content to users [KTD17], in which case users' semantic memory outcomes would be more important than spatial ones to judge the effectiveness of the experience. Although there have been many education and training VR applications, typically their evaluation is understandably limited to their specific learning outcomes [XLA*21], leaving it unclear how users' learning and memory from the experiences could have been impacted had different locomotion techniques been used.

The work discussed above would suggest that the advantages of natural walking would support semantic memory outcomes, while teleportation would not since its strengths in faster space traversal do not directly support semantic memory acquisition. In this paper we present an experiment where we compare semantic memory recall outcomes between virtual museum experience using natural walking and point-and-teleport locomotion techniques to shed light on whether these factors directly impact the development of semantic memory.

3. Experiment

3.1. Participants

We recruited 23 participants from our university community, 16 male, 6 female and 1 non-binary, ages between 23 and 44, $M = 26.81$, $SD = 4.99$. All of the participants had normal or corrected-to-normal vision, 3 wore glasses and 2 wore contact lenses during the experiment. None of the participants reported any visual or vestibular disorders, such as color or night blindness, dyschromatopsia, or a displacement of balance. 20 participants had used a VR Head-Mounted Display (HMD) before, amongst which 19 were familiar with teleportation in VR. The participants were either students or non-student members of our university community who responded to open calls for participation, and received monetary compensation for their participation. The on-site experiment took participants on average 50 minutes to complete and the recall questionnaires (which were distributed 24 hours later) took average 15 minutes to complete.

3.2. Materials

3.2.1. Hardware and Physical Setup

As shown in Figure 1, participants donned the Meta Quest Pro HMD [Met24], which provides a field of view of up to 96 degrees, and a native resolution of 1800×1920 per eye at a refresh rate of 90 Hz. The Meta Quest Pro Light Blocker was attached to the HMD to provide a complete VR experience, blocking the real world view. The HMD uses an inside-out tracking system, which included a tracked controller that participants held in their dominant hand and used for input during the experiment. Additionally, participants wore Logitech G Pro VR Headphones [Log24], characterized as full bandwidth with passive noise cancellation. All rendering was done directly on the HMD. We developed the audio-visual environment we used in this experiment in the Unity Engine version 2021.3.f1.

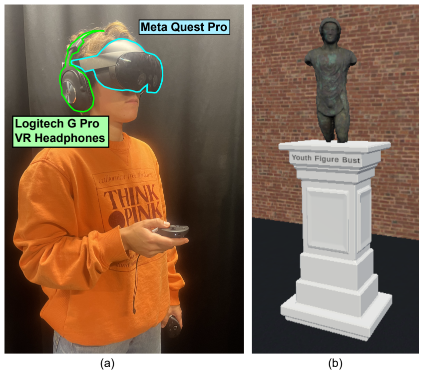


Figure 1: *(a) Annotated photo showing a participant completing the experiment, wearing a Meta Quest Pro HMD and Logitech G Pro VR Headphones, while holding the controller in their dominant hand. (b) Artifact presented on a pedestal which includes the title and an audio description (clip played as participant approaches the artifact) to supplement its visual appearance.*

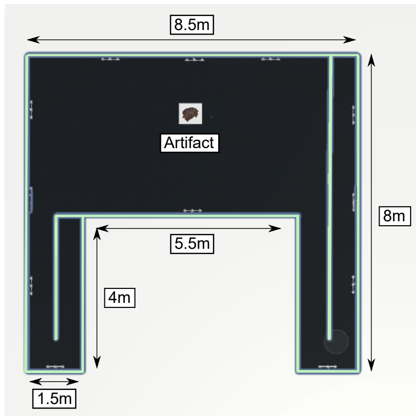


Figure 2: *Annotated picture showing the top down view of the virtual museum, consisting of a* 8.5 *m* ×8 *m central space and two corridors on each side of* 1.5 *m* ×4 *m.*

3.2.2. Virtual Museum Environment

The virtual museum environment was designed as a U-shaped space replicating the dimensions of our laboratory's physical space (refer to Figure 2). The central area measured 8.5 meters long by 8 meters wide, with corridors on either side, measuring 1.5 meters wide by 4 meters long. The virtual ceiling height was set at 7 meters, ensuring ample vertical space. This configuration allowed users to physically navigate the virtual environment without encountering any physical obstructions.

A general best practice in real museums is to have clear sightlines of the artifact with the least amount of distractions to other artifacts. This enables visitors to have distinct and unobstructed views of an artifact. To simulate this in our experiment, we wanted to create an illusion of users' moving into different rooms with a single artifact in the middle. Hence we used a simple impossible spaces paradigm [SLF*12], consisting of two arrangements Please refer to Figure 6 in the Supplementary Materials for a description.

3.2.3. Virtual Museum Artifacts

In this experiment, ten distinct artifacts, all high-poly 3D models with high quality textures, were presented on white pedestals. Two artifacts served as training stimuli for participants. The remaining eight were divided into two sets (Set A and Set B). During each of the two main trials for a given locomotion technique, participants encountered one of these sets. Each artifact included a *title* and an *audio description* to supplement its *visual appearance*.

3.2.3.1. Visual Appearance: The artifacts were all resized to a standard dimension of approximately $0.5 \times 0.5 \times 0.5$ meters, regardless of their original size and orientation (standing or lying flat). This addressed potential bias arising from prior research by Serrell et al. [Ser97], which suggests that viewers dedicate more time to examining larger exhibits compared to smaller ones. To ensure optimal viewing for users of varying heights, the pedestals dynamically adjusted their height to position the artifacts at a comfortable level for title and artifact observation. Despite the size standardization, each artifact retained its visual distinctiveness in terms of color, pose (e.g., standing, kneeling), and the presence of unique features (e.g., a golden crown on a figure). This aligns with research by Brady et al. [BKA11, BKAO13], which suggests that these object properties (color, pose, and unique features) are independently stored within our visual memory.

3.2.3.2. Text Titles: Titles, or labels, can facilitate user's not only to descriptively learn more about an artifact, but also can increase attention on the artifact itself [BP93]. Each title consisted of 2-3 words and was positioned on the top of the pedestal, below the artifact. For optimal visibility, the text employed a high-contrast color scheme (dark text on a light background) with a large enough font size.

3.2.3.3. Audio Descriptions: They are played once as the user approaches an artifact, averaged 30-35 words in length, corresponding to an average audio clip duration of 15-20 seconds. Research by Litwak et al. [Lit96] suggests that optimal listening comprehension and memory retention are achieved with descriptions under 50 words. The content focused on the artifact's creation date, its region of origin, and a unique fact, deliberately omitting physical details and the artifact's title.

3.3. Methods

3.3.1. Study Design

We ran a within-subjects design study to investigate the effects of two locomotion techniques, *natural walking* and *teleportation* on users' recall at two periods of time after the VR experience – *immediately after* and *24 hours later*.

For *natural walking*, we used a one-to-one mapping between our real and virtual space to preserve distances and angles of a user's movement. For instance, when the participant walks one meter, the virtual scene is simultaneously translated one meter as well.

For *teleportation*, we implemented the point-and-teleport technique [BRKD19]. Participants can point a raycast onto the museum floor by holding the grip button on their controller and then pressing the trigger button to teleport to the destination. To minimize physical movement, a circle with a radius of 0.5 meters was displayed on the floor, directly underneath the participant. They were instructed to only rotate within the circle and remain physically inside it.

In total, each participant experienced the virtual museum twice with a unique set of artifacts, one for each locomotion technique. The were tasked to learn semantic details about every artifact in the museum. Recall questionnaires were administered *immediately* and *24 hours* after the experience. We counterbalanced the order of the locomotion techniques and artifact sets for each participant.

3.3.2. Procedure

Upon arrival, participants read through a brief description of the study procedure and consent form, and were asked to give their verbal consent to participate in the experiment. Participants were informed that the experiment involved virtual museum exploration and artifact learning via two locomotion techniques: natural walking and teleportation. Each technique would be used in separate main trials. Before each main trial, participants completed a corresponding training session within the virtual environment to familiarize themselves with the locomotion technique. Following each main trial, a recall questionnaire was administered. To assess delayed recall performance, two additional recall questionnaires were presented 24 hours later.

3.3.2.1. Training Session: The training session was designed to familiarize participants with each locomotion technique (natural walking or teleportation) before the main trials. In the training scenario, participants encountered two artifacts (compared to four in the main trials). The experimenter provided instructions on navigating between the artifacts. As they visited each artifact, they were instructed to focus on the title, visual appearance, and the audio description of the artifact. For natural walking training, the goal was to ensure participants felt comfortable physically navigating the virtual museum. Initially, participants were instructed to walk slowly. As comfort increased, they were encouraged to gradually reach their natural walking pace. During teleportation training, participants learned how to teleport and remain physically within a designated circle on the floor to minimize physical movement. Following the initial training phase, participants completed a practice recall questionnaire. This questionnaire mirrored the format and question types of the main recall questionnaires but presented different artifacts. Given the within-subjects design (all participants experienced both conditions), the practice questionnaire aimed to mitigate first-time answer effects.

3.3.2.2. Main Trial: Each participant completed two main trials. Each trial featured a unique set of four artifacts (either Set A or Set B) and utilized a different locomotion technique (natural walking or teleportation). The order of artifact set and locomotion technique was randomized and counterbalanced across participants. The experimenter remained uninvolved during the main trials to encourage natural exploration within the virtual museum. Upon completion of a main trial, participants immediately answered a recall questionnaire. Following the second and final main trial, in addition to the immediate recall questionnaire, participants completed a post-experiment questionnaire and provided demographic information. They received half of the compensation upfront and were informed of additional recall questionnaires to be completed 24 hours later for the remaining compensation, which would be distributed via email. They took an average 50 minutes time to complete both trials and questionnaires, while they took an average of 10 minutes time to complete the delayed recall questionnaires.

3.4. Measures

3.4.1. Recall Performance Measurements

Explicit semantic memory is commonly evaluated using questions that exercise recall of information on a targeted topic – questions categorized as recognition, cued recall, and free recall [HG12]. Recognition memory can be tested by asking subjects to differentiate between an old stimulus, i.e. something that has been seen or learned already, from a new stimulus, i.e. something that has not been seen or learned [She67]. Cued recall can be tested by providing a cue prompting the memory retrieval, such as a category, e.g. recalling the word "train" can be cued with a category cue of "form of transport" [FC77]. Lastly, free recall can be tested by providing stimuli and prompting recall without providing cues, e.g. presenting a list of words then asking the subject to recall as many words from that list as possible [MJ62]. We employ questionnaire measures that cover all three question types to assess recall performance.

Each main trial presented participants with four artifacts. Subsequently, participants completed a recall questionnaire that comprised six distinct question types presented in the following sequence. The sequence ensured that no question provided clues for subsequent questions. The six question types included free recall and order tests, which required participants to remember the experience as a whole. The remaining tests were cued recall and recognition types (see Section 2), focusing on details about individual artifacts, and each correct response was scored a point (1), while incorrect responses were scored with no points (0).

1. ***Free Recall Test:*** This free recall test asked participants to write down everything they remembered about the artifacts from their experience. This included the title of the artifacts and information obtained from the visual appearance and the audio description. Responses were scored by two raters (Inter-Rater Reliability = 0.83) and disagreements were addressed by a third rater.
2. ***Name Recognition Test:*** This recognition test consists of the names of the four artifacts randomly intermixed with four more names of other artifacts that were not part of the experience but that were artifacts participants could plausibly have seen. They would see one name at a time, and answer *(1) I observed this artifact*, OR, *(2) this artifact was not part of my experience*.
3. ***Audio Detail Test:*** This is a cued recall test in which participants were asked about details obtained from the audio description of an artifact, and given four multiple-choice response options. The question could be about the the artifact's creation date, its region of origin, or a unique fact. One audio detail question was asked for every artifact.
4. ***Visual Detail Test:*** This is a cued recall test in which participants were asked about a visual detail of an artifact and given four multiple-choice response options. The visual details asked were either about the color, or the state of the artifact. Based on Brady et al.'s work [BKAO13], it suggests independent storage of the above object properties in our memory. One question per set required participants to view the artifact from the back. Two questions per set were about the color of the artifact, and in total two visual detail questions were asked for every artifact.
5. ***Variation Test:*** This is a recognition test in which participants were presented 4 picture variations of an artifact and asked to select the one they visited. All variations were similar in terms general shape and subject, and differed in terms of color or a semantic change (for example, a sword replaced with a spear). One variation test was asked for every artifact.
6. ***Order Test:*** The titles of all four artifacts were randomized and presented to the participants in a list. They were tasked to order them from the first seen to the last seen artifact. Responses were scored based on the discrepancy between the participant's chosen order and the correct order. A maximum score of 1 was awarded for the correct order of all four artifacts. For each incorrectly placed artifact, 0.25 points were deducted, resulting in a minimum score of 0.

Following each recall question, participants rated their confidence in the accuracy of their responses using a 7-point scale ranging from -3 (Not Confident) to 3 (Extremely Confident). A lower score indicated that the participant believed they were guessing. Additionally, the time taken to respond to each recall question was logged.

After completing a main trial, participants provided self-reported performance evaluations. They rated their perceived performance on a 7-point scale ranging from -3 (Extremely Poorly) to 3 (Extremely Well) and were encouraged to elaborate on their reasoning. After completing both trials, participants were asked a comparative preference question: "Considering memory performance, which locomotion technique (natural walking or teleportation) did you find preferable? Please explain your reasoning."

3.4.2. Tracking Data

Participants were tasked to visit all artifacts and learn semantic details about them. Knowledge acquisition requires users to actively explore the artifact, so we tracked their movement and eye gaze behavior. To do this, during the experiment, raw tracking data was collected at 60 Hz, one frame every 16.67 milliseconds. In each frame, the timestamp, the 6DOF (i.e., position and rotation) of the headset, and eye interactions were recorded.

In the conventions of Unity game engine, the three positional dimensions are denoted as X, Y, and Z. The Y-axis represents the vertical direction, with positive values corresponding to upwards movement. The Z-axis dictates the forward and backward movement, while the X-axis handles lateral movements, positive values indicating rightward motion. The three rotational dimensions are denoted as yaw, pitch, and roll. Yaw describes rotation around the Y-axis, akin to turning left or right. Pitch, on the other hand, refers to the up-down tilting motion along the X-axis, similar to nodding your head. Finally, rolling an object along its longitudinal axis, analogous to tilting a barrel on its side, is represented by Roll, which corresponds to the Z-axis.

In terms of eye interactions, we recorded interactions with two regions of interest (ROIs): the *current artifact model* and the *title of the artifact*. Within Unity game engine, we added box colliders to both the artifact and the title. We then logged every frame where the eye gaze raycast intersected with these ROIs. The Meta Quest Pro's eye tracking is capable of an average accuracy of 1.652° with a precision of 0.699° (standard deviation) and 0.849° (root mean square) for a visual field spanning 15° [WBR23].

3.5. Hypotheses

In this experiment, our null hypothesis H_O posits that there is no effect due to locomotion technique, while the alternative hypothesis (H_A) assumes the presence of an effect due to locomotion technique. Additionally, we propose two hypotheses — H_1 posits that natural walking would benefit semantic memory compared to the non-natural technique of teleportation, and H_2 posits that the faster exploration enabled by teleportation might enhance memory by facilitating information gathering.

4. Results

We analyzed the responses with repeated-measures analyses of variance (RM-ANOVAs) and Tukey multiple comparisons with Bonferroni correction at the 5% significance level. We confirmed the normality with Shapiro-Wilk tests at the 5% level and QQ plots. Degrees of freedom were corrected using Greenhouse-Geisser estimates of sphericity when Mauchly's test indicated that the assumption of sphericity was not supported. As an effect size, we report the partial eta squared (η_p^2), whereby a value of 0.01 is considered a small effect, 0.06 a medium effect, and 0.14 a large effect [Coh92]. Analysis was done using IBM SPSS 29.0.0.0 and the box-plots were prepared using R version 4.4.0.

4.1. Recall Measurements

In this section, we present our analysis between two locomotion conditions and two periods of recall time on participants' objective recall performance and their self-assessed recall performance.

4.1.1. Recall Performance

Figure 3 (a) shows participants' objective recall performance with RM-ANOVA statistical test results in Table 2 (Supplementary Material) and Bayesian analysis test results in Table 1.

We perform two analyses on participants' recall scores, frequentist approach using a RM-ANOVA and a Bayesian statistics approach. The RM-ANOVA assumes the null hypothesis is true and a significant p value would reject the null hypothesis, whereas Bayesian statistics does not make that assumption, and provides a probability of evidence for all hypotheses.

Our RM-ANOVA results revealed no significant influence of locomotion technique on participants' recall performance across any of the recall measurements. However, a significant decline in performance was observed 24 hours later compared to immediate recall. This main effect was consistent for 3 tests: audio detail test $F(1,21) = 6.407$, $\boldsymbol{p = 0.019}$, $\eta_p^2 = 0.234$, visual detail test $F(1,21) = 5.172$, $\boldsymbol{p = 0.034}$, $\eta_p^2 = 0.198$, and order tests $F(1,21) = 12.165$, $\boldsymbol{p < 0.001}$, $\eta_p^2 = 0.419$. Furthermore, no interaction effect was detected between locomotion technique and the period of time, suggesting independent contributions of these factors to recall performance, please refer to the complete statistical test results in Table 2 in the supplementary material.

Our Bayesian analysis computed the posterior probability of both the null and alternative hypotheses. This approach proves useful in combination with the classic frequentist approach. In this experiment, the null hypothesis (H_O) posits that there is no effect due to locomotion technique, while the alternative hypothesis (H_A) assumes the presence of an effect due to locomotion technique. According to Rafferty et al. [Raf99], posterior probability values greater than 0.99 suggests very strong evidence for that hypothesis, followed by probability between 0.95 and 0.99 suggesting strong evidence, between 0.75 and 0.95 suggesting positive evidence, between 0.50 and 0.75 suggesting weak evidence and smaller than 0.50 suggesting poor evidence. From Table 1, out of our six measurements, five suggest positive evidence and one suggest weak evidence for our H_O. Overall both analyses suggest that locomotion techniques did not or had a minimal effect on participants' recall performance.

Table 1: *Bayesian Statistical Approach: H_O (Null Hypothesis) there is no effect due to the type of locomotion technique. H_A (Alternative hypothesis): there is an effect due to the type of locomotion technique.*

Measure	P(H_O)	P(H_A)
Free Recall	0.71 (Weak)	0.29 (Weak)
Name Recognition	0.90 (Positive)	0.10 (Poor)
Audio Detail	0.83 (Positive)	0.17 (Poor)
Visual Detail	0.90 (Positive)	0.10 (Poor)
Variation	0.89 (Positive)	0.11 (Poor)
Order	0.89 (Positive)	0.11 (Poor)

4.1.2. Self-Assessed Performance and Preference

Figure 3 (b) shows participants' Self-Assessed recall performance with the complete statistical test results in the Supplementary Materials Table 3.

Our results show a significant effect of locomotion technique on participants' Confidence $F(1,21) = 48.93$, $\boldsymbol{p < 0.001}$, $\eta_p^2 = 0.730$ and Self-Assessed recall performance $F(1,21) = 6.407$, $\boldsymbol{p = 0.019}$, $\eta_p^2 = 0.234$. Participants exhibited preference when walking compared to teleportation. However, response time per recall question remained unaffected by the type of locomotion. Regarding the period of time between VR experience and recall assessment, participants were significantly more confident in their responses when the recall questionnaire was administered immediately following the VR experience than 24 hours later. This effect was not observed for response time or overall perceived performance. Finally, no significant interaction effects were detected between locomotion technique and the period of time, suggesting potentially independent contributions of these factors to Self-Assessed recall performance.

In terms of preference amongst the two locomotion techniques, 17 participants out of 22 preferred walking over teleportation.

4.2. Tracking Data

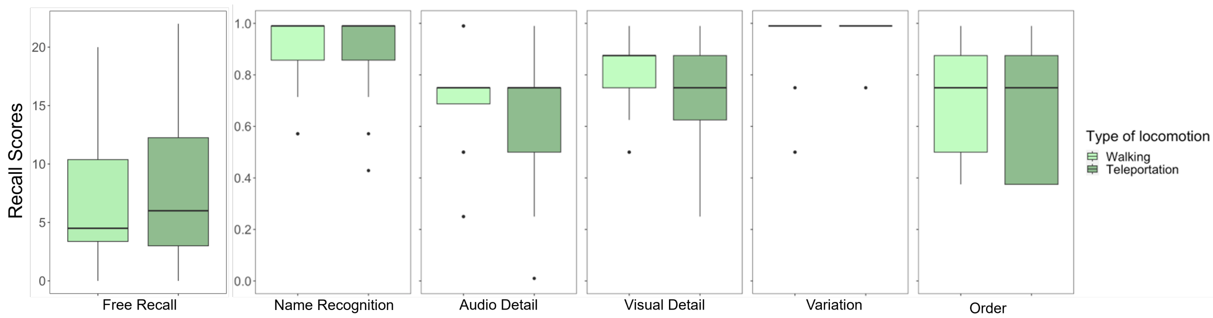
From participants' tracking data, we extracted the following three measures–total time spent, *time spent around artifacts*, and *time spent looking at the artifact or the title*. Total time spent looking at artifacts or titles refers to the overall duration participants eye gaze raycast intersects the ROI. Time spent around artifacts captures the amount of time a participant remained within 2 meters from the center of an artifact. A heatmap distribution of participants' movements (see Figure 5) visually confirms that participants spent most of their time close to the artifacts, within 2 meters. Lastly, by analyzing participants' eye gaze behavior, we determined the time spent looking directly at the artifacts or their titles.

We found a significant effects of locomotion on all three measures with walking taking significantly longer time than teleportation. Total time spent: $F(1,21) = 18.57$, $\boldsymbol{p < 0.001}$, $\eta_p^2 = 0.47$; Time spent near artifact: $F(1,21) = 10.42$, $\boldsymbol{p = 0.004}$, $\eta_p^2 = 0.33$; Time spent looking at the artifact or title: $F(1,21) = 0.11.43$, $\boldsymbol{p = 0.003}$, $\eta_p^2 = 0.35$.

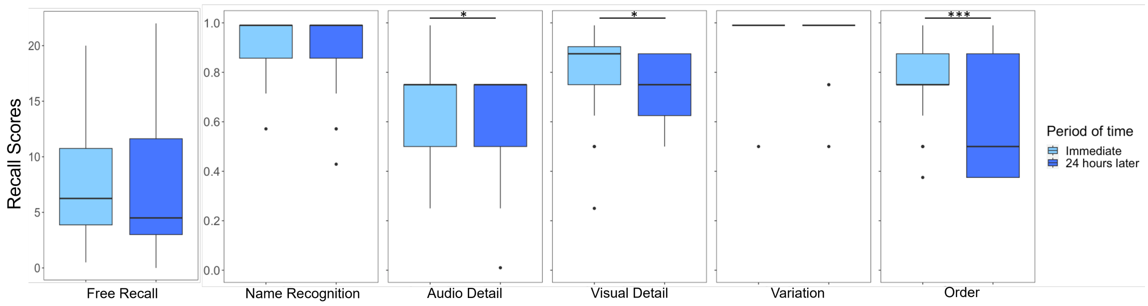
5. Discussions

In this section, we summarize the main findings and discuss implications for the use of walking or teleportation on users' semantic memory. We also mention the limitations of our experiment.

Our main finding, as detailed in Section 4.1, showed participants were able to demonstrate the same level of semantic memory recall



(a) Locomotion vs Recall Performance Box Plots



(b) Period of Time vs Recall Performance Box Plots

Figure 3: *Experimental results for our objective and subjective recall performance. The x-axes show the different recall measures. The y-axes show the participants' recall scores with the free recall scores* $\in [0,\infty)$ *and the rest* $\in [0,1]$. *Higher scores the better recall performance. The vertical error bars indicate the standard error. The horizontal bars and asterisks indicate statistical significance* ($*$ $p<0.05$; $***$ $p<0.001$)*.*

performance using both locomotion techniques, despite exhibiting significantly different behaviors in each condition. For educational or training virtual experiences, these findings would suggest that users can likely choose between walking or teleportation without a noticeable difference in their ability to retain semantic memory, given they have unlimited time for both techniques. This result stands in contrast to the initial hypotheses presented in Section 3.5. Our null hypothesis H_0 assumed no effect due to locomotion technique, while alternative hypothesis H_A assumes the presence of an effect. Two statistical approaches were employed: a frequentist approach and a Bayesian approach. The p-value obtained from the frequentist approach represents the probability of observing the obtained data, assuming the null hypothesis is true. Conversely, the Bayesian approach focuses on estimating the likelihood of each hypothesis being true given the data. In the frequentist approach, we observed high p values and low effect sizes, as demonstrated in Table 2. This suggests that the null hypothesis could not be definitively rejected and the recall scores did not significantly differ based on locomotion technique. Similarly in the Bayesian analysis, the likelihood of evidence showed in Table 1 supports our null hypothesis. While not statistically significant, our box plots in Figure 3 visually show a trend. In the free recall test, users who teleported performed slightly better than those who walked, while the opposite pattern emerged for the visual detail and order tests. Overall, interestingly, our results show no or a weak effect of locomotion technique on immediate semantic memory.

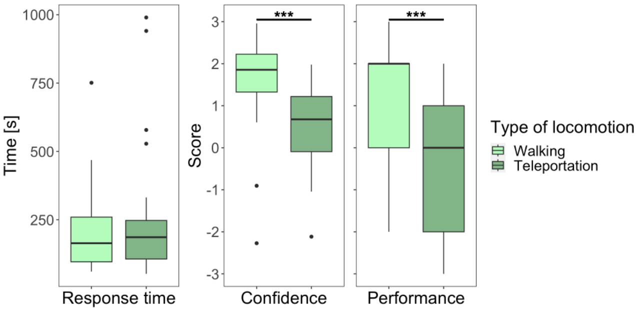
An additional factor considered in the study was the time delay between the virtual experience and the recall questionnaire (immediate vs. 24 hours). Participants performed significantly worse on three out of the six recall tests when the questionnaire was administered 24 hours later. This aligns with existing research demonstrating a decline in recall performance over time. Notably, statistical tests involving both factors did not reveal any interaction effects, further supporting the null hypothesis.

These findings are intriguing, and we believe they are due to different effects interacting with one another. Firstly, from a performance point of view, H_2 predicted that due to the instantaneous nature of teleportation, participants' would be able to access more information in less time. In our study, refer Section 4.2, participants significantly spent less total time, time near artifact, and time looking at the artifact when teleporting than walking. Anecdotes by P1 and P2 support this:

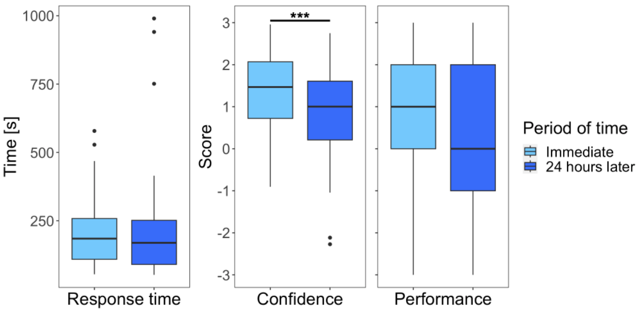
> P1: *"Teleportation allowed me to traverse faster..."*
>
> P2: *"Biggest reason was that walking forced me to stay in the room longer... "*

While faster travel may be useful in accessing information quicker some participants expressed concern about being distracted by teleportation while explicitly learning. An anecdote by P19 expressed:

> P19: *"... I needed to think about where exactly to click to observe the sculptures well, while during walking I moved naturally without actively thinking about locomotion. I felt like there were more interruptions during tele-*



(a) Locomotion vs Subjective Performance Box Plots



(b) Period of Time vs Subjective Performance Box Plots

Figure 4: *Experimental results for our objective and subjective recall performance. The x-axes show the different recall measures. The y-axes show the participants' recall scores with the time* $\in [0,\infty)$ *and the rest* $\in [-3,3]$*. Higher scores the better recall performance. The vertical error bars indicate the standard error. The horizontal bars and asterisks indicate statistical significance* ($***$ p$<$0.001)*.*

portation locomotion and as if my mind was not occupied as much with remembering as with dealing with the system."

In summary, users' teleporting achieved the same level of semantic recall performance compared to natural walking in less time.

Secondly, H_1's prediction was based on earlier research indicating that VR users' experience a greater sense of presence and favor natural walking over unfamiliar locomotion techniques [LJKM*17]. This was supported by our findings (see Section 4.1.2) regarding the participants' self-assessed performance and preferences. However, participants expressed concern due to their inability to see the real world when walking in room scale VR. Despite our efforts to familiarize participants, anecdotes from participants P1 and P6 suggest that the heightened vigilance added to their existing cognitive load and distracted them from learning.

P1: *"... When walking, I worried about bumping a wall and losing my train of thought."*

P6: *"I feel like while natural walking I felt like I needed to be a little more careful because I knew I could not see the real world. I feel like this added additional cognitive load that distracted me when initially listening to the audio descriptions ... "*

Third, some reasons could be due to our small participant pool or

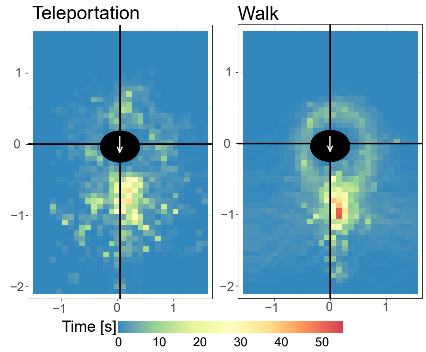


Figure 5: *Heat Map Distribution of participants' motion data. The longer the participant stayed at that location, the deeper the red color. The artifact is represented by the center (0,0), and the arrow points from the artifact forward. The x and y axes are in meters.*

participants' interpersonal differences, which have been shown to affect long-term memory [BU12].

Finally, from an application standpoint, our findings indicate that users can achieve comparable semantic memory performance using both locomotion techniques during a VR learning experience. Walking required significantly more time to achieve the same level of memory performance, indicating that teleportation may be preferable for time constraints. However, if users' preferences and self-assessed performance are taken into account, walking may provide a more present and engaging experience than teleportation while maintaining semantic memory.

6. Conclusion

In this paper, we present a comparative user study investigating the effects of teleportation compared to real walking on the retention of semantic information about artifacts in a virtual museum. Semantic information included the visual appearance of 3D objects, audio clips, and names. Recall tests were administered immediately and 24 hours after the museum experience. Firstly, our results show that participants achieved comparable semantic memory performance with both locomotion techniques. Secondly, participants spent significantly more total time, time near artifacts, and time spent looking at artifacts when they were walking than teleporting. Lastly, they indicated a higher self-assessed performance and preference for walking over teleportation. Overall, our findings indicate that during a VR learning experience, both locomotion techniques will achieve similar semantic memory recall. However, participants reached similar performances under different time spent engaging with the exhibits. This suggests that teleportation is recommended under time constraints. On the other hand, under no time and space constraints, walking can provide a more engaging learning experience.

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