MagicMap: Enhancing Indoor Navigation Experience in VR Museums

Xueqi Wang   Yue Li *   Hai-Ning Liang

School of Advanced Technology
Xi'an Jiaotong-Liverpool University

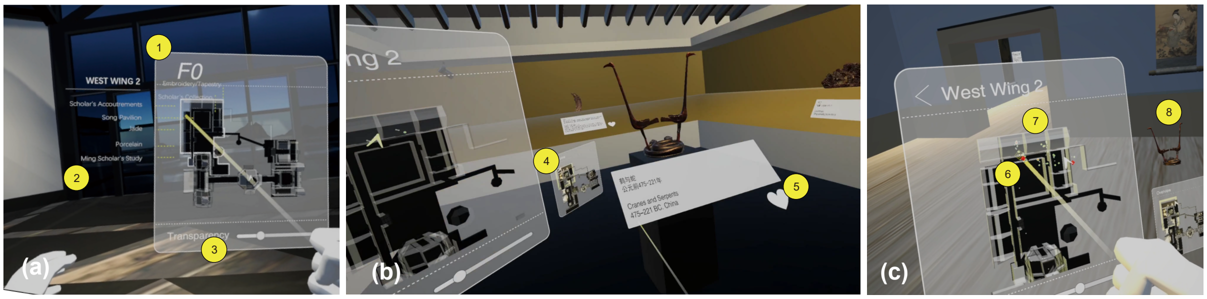

Figure 1: Demonstration of the use of MagicMap: (a) selecting an exhibition room to teleport, (b) entered the room to see museum collections, and (c) review annotations and visiting trace on the map. Features supported in MagicMap: ① 3D miniature of a museum on a 2D map interface, ② hover to show exhibition information, ③ slide to adjust the transparency of walls, ④ a multi-view interface showing details while keeping an overview at the corner, ⑤ button for annotating museum collections, ⑥ annotations (in red) displayed on MagicMap, ⑦ a heatmap (in yellow) showing the visiting traces (points), and ⑧ hover the annotation to view a miniature of annotated objects.

Abstract

Museum visitors are typically advised to follow trajectories planned by curators. Nevertheless, the diverse locomotion techniques available in Virtual Reality (VR) offer various navigation methods that are unattainable within physical museum spaces. Interestingly, these techniques have rarely been explored within museum settings. Our study aims to investigate appropriate navigation methods in VR museums. We first conducted a study in a virtual reconstruction of a local museum with the following navigation methods: a 2D mini-map, a World-in-Miniature (WiM) system, and a WiM map. Our results showed that the WiM map with a point-and-select interaction technique outperformed the other two regarding ease of learning, reduced workload, lessened motion sickness, and greater user preferences. Based on the findings, we improved the WiM map and introduced MagicMap. It builds upon the WiM map and translates the curatorial principles of museum visiting into a hierarchical menu layout. Our further evaluation showed that MagicMap supported prolonged engagement in VR museums, enhanced system usability and overall user experience, and reduced users' perceived workload. Our findings have implications for the future design of navigation systems in VR museums and complex indoor environments.

Index Terms: Human-centered computing—Human computer interaction (HCI)—Interaction paradigms—Virtual reality; Human-centered computing—Human computer interaction (HCI)—HCI design and evaluation methods—User studies

1 Introduction

Navigation is a fundamental activity in real and virtual environments [69]. As one of the most basic tasks in Virtual Reality (VR), navigation includes locomotion and wayfinding components [24]. With the development of eXtended Reality (XR) technologies, navigation-related research has proliferated rapidly. Navigation in open areas and outdoor environments has garnered significant attention in research and has been explored across a wide range of scenarios and contexts [37, 42, 68, 69]. Comparatively, navigation within complex indoor environments such as museums has been less explored, although it has always been an important research area whose findings can be applied to many other real-world scenarios [21, 63].

Our study aims to improve the navigation experience in VR museums. Based on previous works on navigation methods, VR locomotion techniques, and museum studies, we identify an opportunity to combine a 2D mini-map and the World-in-Miniature (WiM) metaphor to support effective navigation in VR museums. Inspired by navigation methods studied in related works, we first designed a WiM map. We created a virtual reconstruction of a local museum, based on which we conducted a within-subjects experiment ($n = 24$) to evaluate the use of three navigation methods: 2D mini-map, WiM, and WiM map. Participants were guided through a series of tutorials and were asked to perform two tasks: an object collection task and a map drawing task. This study serves to answer **RQ1**: *Can interactive maps (WiM and WiM map) better support users' navigation in complex indoor VR environments, compared to 2D mini-maps?* We found that (1) interactive maps (WiM and WiM map) facilitate more efficient navigation in VR museums than a 2D mini-map; (2) WiM map showed a greater perceived performance and lower perceived workload than WiM and 2D mini-map; (3) Compared to WiM, participants found the WiM map easier to learn and required fewer movements of the dominant hand; and (4) WiM map also caused less motion sickness (nausea and disorientation) than the 2D mini-map.

The results and participants' feedback led us to see the strong potential of the WiM map to support effective navigation and allowed us to gain some insights into its improvements. Thus, we optimized the WiM map design and proposed a novel navigation system, MagicMap (see Figure 1). The design of MagicMap included features that improved the accuracy of locomotion and the ease of wayfinding. To evaluate its use in VR museums, we populated the environment with 106 museum collections distributed across 11 exhibition rooms. The second study ($n = 24$) comparing the WiM map and the MagicMap provided answers to our **RQ2**: *Do*

*Corresponding author: yue.li@xjtlu.edu.cn

MagicMap's features improve users' navigation experience in VR museums, compared to WiM map? An improved system usability, enhanced user experiences, prolonged engagement in museum visits, and a reduction in workload were shown in the results.

Our work demonstrates the following contributions to VR, human-computer interaction, and cultural heritage research. (1) We identified from related works that the design of the WiM map based on a 2D mini-map and WiM could potentially contribute to VR navigation. (2) We empirically evaluated the effectiveness of the aforementioned three navigation methods in supporting indoor navigation. (3) We introduced a novel navigation system, MagicMap, for VR museums that integrates WiM based on 2D user interface control, supporting scalable map navigation and personal meaning-making. Study results showed that MagicMap was able to support improved navigation experiences for VR museum visitors. (4) We showed that the design of MagicMap can be directly taken into future VR museum systems. In the meantime, the features supporting precise locomotion and intuitive wayfinding are transferable and scalable to other complex indoor navigation scenarios. (5) Our research underscores the importance of addressing complex indoor environments in navigation research, particularly in the context of VR museums. We provide design guidelines for researchers and practitioners to explore more effective navigation solutions.

2 Related Work

In recent decades, VR has increasingly been used for museum visits, transforming the way heritage is experienced and making museums more accessible. To contextualize our research on navigation within VR museums, we examine research related to navigation in both physical museums and virtual museums. Subsequently, we provide an overview of VR navigation research, focusing on its relevance and applicability in the context of VR museums.

2.1 Effects of Navigation on Museum Experiences

Bitgood [6] highlighted the importance of navigation to visitors' museum experience: it determines what they see and do and, ultimately, what they experience and learn in museums. While research on navigation-related experiences in VR museums is currently limited, there is a greater body of research on such experiences in physical museums. Therefore, in this section, we draw insights from both physical museums and VR museums to inform our work.

2.1.1 Navigation within Physical Museums

When discussing navigation within museums, we often need to look into wayfinding, as real-world locomotion typically involves physical walking. Previous research has highlighted that wayfinding can pose challenges for both museum curators and visitors [52]. It can be particularly tricky due to the complex layouts of museum interiors [53]. Therefore, aiding visitors in both their physical and cognitive orientation is of paramount importance [6]. The conventional method is to provide visitors with a paper map prior to their visits or at key junctures within the museum [29]. Various research has reported the positive effect of maps on visitors' experiences. For instance, a study conducted at the Birmingham Zoo showed that visitors with handheld maps tended to explore more of the exhibition compared to those without maps [6]. Similarly, a study at the St. Louis Science Center revealed that visitors equipped with maps stayed three times longer and expressed higher levels of satisfaction with their visit compared to those without guide maps [6].

With the development of information and communication technologies, researchers explored ways to streamline the cognitive effort required for navigation. For example, digital devices enabled continuous updates of "you-are-here" markers on virtual maps. A notable example of adopting such a navigation approach is MusA [53]. It utilizes vision-based indoor positioning to provide real-time spatial positioning on a map, allowing users to select specific collections (landmarks) and receive guidance to their destination (route) via handheld devices. More recently, Augmented Reality (AR) handheld devices and head-mounted displays (HMDs) have become more affordable [3,7] and can be integrated into the exploration of physical spaces. In summary, these studies on navigation in physical museums confirmed the importance of navigation for visitors' museum experiences and showed strong potential of digital solutions to support indoor wayfinding.

2.1.2 Navigation within VR Museums

In contrast to navigation within physical museums, navigation in VR museums involves more than just wayfinding: locomotion also plays a vital role. Several commercial VR museum applications are available on various digital distribution services and storefronts, such as Steam and the Meta Quest Store. In this section, we explore how different navigation methods impact user experiences based on some example applications and identify the existing research gaps.

In general, navigation can be broadly divided into discrete or continuous, and, depending on how it is provided, it can impact users' experience and cognitive processes [38, 39, 62, 71]. Our literature review shows that almost all commercial VR museum applications adopted a discrete locomotion technique: point and teleportation [11]. Typical examples are *The Kremer Collection VR Museum*[1], *VR Museum Tour Grand Collection*[2], *Mona Lisa Beyond The Glass*[3], and *Smithsonian American Art Museum*[4]. Point and teleportation enables fast travel between locations [65], reducing travel time and increasing efficiency while causing less motion sickness compared to continuous locomotion [11,44]. Consequently, it has become the standard in many VR applications [34,51]. Due to its popularity, it is widely used in VR museums. However, previous research also showed that point and teleportation tends to cause disorientation and negatively affects the sense of spatial awareness [50,65]. Meanwhile, scholars in museum studies have a consensus that the museum space plays a significant role in the subsequent process of meaning construction and interpretation [54]. The visiting paths are also closely related to the storytelling. Thus, the issue of spatial awareness should be addressed in a VR museum if the point and teleportation technique is adopted.

Unlike discrete locomotion, continuous locomotion techniques often perform better in supporting spatial awareness. However, they can also lead to more motion sickness [44, 45, 61, 70], which can be severe in many users, thereby negatively affecting their overall experience. Real walking, although ideal, requires a large or tracked physical space, which is not always practical or feasible [10]. To overcome these issues, researchers have proposed continuous locomotion techniques such as redirected walking [57], zooming [36], or walking-in-place [46]. These techniques use walking-based workarounds to facilitate continuous locomotion in a virtual environment [41]. However, these approaches have their own limitations and complexities, such as the need for additional devices and significant efforts to set up. Some approaches, such as bicycle riding [46], are not suitable for VR museum scenarios.

Among the very few VR museum applications that supported wayfinding, *The VR Museum of Fine Arts*[5] offers users a 2D handheld leaflet that shows the layout of the museum before the visit. Apart from this example, most commercial designs of VR museums offered nearly no support for wayfinding. This signifies a significant opportunity for research in wayfinding design within VR museums.

To summarize, there are substantial research opportunities in VR museum navigation. The locomotion techniques available on commercial VR devices are largely restricted to point and teleportation.

[1] https://store.steampowered.com/app/774231/The_Kremer_Collection_VR_Museum/

[2] https://store.steampowered.com/app/1484150/VR_Museum_Tour_Grand_Collection/

[3] https://store.steampowered.com/app/1172310/Mona_Lisa_Beyond_The_Glass/

[4] https://store.steampowered.com/app/1087320/Smithsonian_American_Art_Museum_Beyond_The_Walls/

[5] https://store.steampowered.com/app/515020/The_VR_Museum_of_Fine_Art/

Such discrete locomotion techniques may disrupt spatial awareness, while continuous locomotion methods can lead to motion sickness. Navigation methods in VR museums need to be better designed to adopt appropriate locomotion techniques and support wayfinding. Consequently, our work aims to seek opportunities to improve navigation (locomotion and wayfinding) in VR museums.

2.2 Map and World-in-Minature in Virtual Environments

The review of related works in the previous section showed that a 2D map is one of the most common wayfinding aids in both physical and VR museums. Its positive effect on experience in physical museums has been widely acknowledged [6]. However, Lütjens et al. [40] highlighted that using 2D maps in an inherently 3D VR environment can present cognitive challenges to users. To address this issue, researchers have explored using 3D maps, also known as World-in-Miniature (WiM). It was first introduced by Stoakley et al. [58] as a handheld scaled-down replica of the virtual environment.

As a 3D map, WiM can support intuitive wayfinding. Berger and Wolf [5] demonstrated that users can gain an overview of the environment and a clear understanding of landmark locations compared to using a 2D map. They stated that WiM can offer detailed information and richer interactions [5]. Many researchers have used WiM as a tool to enhance users' understanding of virtual environments. For example, Weissker et al. [64] used WiM to show participants the route they needed to follow in a virtual city. Zhang et al. [68] made WiM an auxiliary tool for virtual urban navigation, helping users annotate, locate their positions, and explore urban points of interest. Recently, researchers also explored the use of WiM as a spatial design tool [67]. Based on these example uses of WiM, it is likely to contribute to wayfinding and help mitigate the issue of spatial awareness during museum visits.

Traveling guided by a WiM is not new. Bowman et al. [10] argued that techniques used for travel and wayfinding should be integrated if possible, given that these two tasks are inherently linked. Using WiM as a locomotion technique, a small representation of the user, often in the form of a human figure, is placed within the WiM to indicate the user's position and orientation in the virtual world. Users can pick up and drop their representatives in the WiM to define routes or teleportation points. The system then executes the corresponding motions in the full-scale virtual environment. Berger and Wolf [5] compared WiM, continuous locomotion, and teleportation. They found that as a locomotion technique, WiM outperformed the other two techniques in velocity for long distances, providing users with the highest spatial knowledge while causing the slightest motion sickness. Danyluk and Willett [23] conducted a similar comparison of flight, teleportation, and WiM in a large outdoor environment. They concluded that WiM is less prone to motion sickness than flight and more efficient in getting an overview of the scene than teleportation.

3 Design Dimensions of the WiM Map in VR Museums

Two key findings were learned from the related works and motivated our design of the WiM map:

(1) It is a common approach to use handheld 2D maps as a wayfinding tool in physical and virtual museums.

(2) World-in-Miniature demonstrates great benefits in supporting efficient locomotion and wayfinding in VR environments.

Thus, we propose to combine the features and explore the use of a WiM map to enhance navigation in VR museums. Specifically, we aim to leverage the WiM map to improve the efficiency and precision of instant discrete locomotion techniques while mitigating potential VR-induced discomfort. Additionally, we seek to provide wayfinding support in VR museums to compensate for the loss of spatial awareness resulting from teleportation.

Danyluk et al. [22] proposed seven design dimensions for the WiM: size-scope-scale, abstraction, geometry, reference frame, links, multiples, and virtuality. Detailed descriptions of dimensions, along with examples, were presented in their paper. Here, we discuss the design of the WiM map in a VR museum context and explain the features we considered based on previous works.

The **size-scope-scale** dimension describes the physical dimensions of the miniature replica. Given the appropriateness of using a 2D handheld mini-map in museums, we thus defined a *building* **scope** design of the museum WiM that is scaled to fit a *small* **size** map (10-30 cm). Similar to the previous design of WiM with a *building* scope, we adopted a *just areas* abstraction. Regarding **geometries**, we kept the WiM in a cube shape. The **reference frame** of our WiM map design is *peripersonal* and sits on a *handheld* interface. While pointing and selecting a teleport point on the WiM map, a cursor is shown on the ground of the VR museum environment, indicating a **link** between the WiM and the environment. We did not include any **mutiples** because the design of the WiM map mainly aims to support locomotion and wayfinding, but not interaction with specific parts of the map itself (e.g., urban planning). Finally, we target a design for *headset VR*, the utterly immersive end of the **virtuality** dimension. In summary, we narrowed down the design space of the WiM map to a small handheld interface that presents museum building areas and shows a link between the WiM and the museum environment.

In addition, we consider some design solutions to address some challenges indicated in the related works. The first is **occlusion**. Truman et al. [60] identified occlusion as a significant challenge in the implementation of WiM. This challenge stems from obstacles within the virtual environment, such as walls, roofs, and furniture, obstructing users' views of certain parts of the interface. One approach is to remove or modify parts of the virtual environment (e.g., walls or roofs). However, it may not be suitable for our virtual museum setting, where the architectural structure plays a crucial role in the museum experience. Instead, we chose another method: adjusting the WiM's transparency [5]. By making the WiM map translucent, we aim to maintain the visual connection between the user and the virtual environment while mitigating the occlusion challenge posed by physical structures within the museum. We also considered the **display orientation** and the **locomotion interaction technique**, which determine how users interact with the WiM design. 2D mini-map and WiM vary in their display orientations. WiM is often displayed in a horizontal manner to support users' mental model of its orientation in relation to the physical environment. The common manipulation technique used in WiM locomotion required users to pick up and drop their miniature representations [22, 58, 60]. On the other hand, 2D handheld interfaces usually have a vertical display so that users can hold and read [13]. Such vertical layouts have been widely adopted in VR system controls, such as menu interfaces and web browsers, which facilitate intuitive point-and-select interactions such as raycasting. Recent works also explored the use of raycasting to realize instant teleportation in WiM, such as the Group WiM [17]. Thus, we designed the WiM map to match the ground of a museum WiM to a vertical display of a 2D mini-map, where users could teleport using point-and-select interactions. We also considered users' **postures** of using the WiM map. Previous work [13] indicated that a vertical layout with a wrist-based approach was found efficient for a 2D interface design in 3D spaces. Thus, we adopted this approach that required users to raise and bend their elbows to see the WiM map. Table 1 provides a summary of the three navigation methods.

4 Study 1: Map Navigation in Complex Indoor VR Environments

Considering the various design dimensions of map navigation systems, it is infeasible to follow a comprehensive factorial design to evaluate the effectiveness of each design dimension. Therefore, we conducted a focused comparative study to assess the WiM map design against two conditions that emerged from the review of related

Table 1: Comparing 2D mini-map, WiM, and WiM map.

	2D mini-map	**WiM**	**WiM map**
Map	2D image	3D model	3D model with 2D panel
Link	None	None	Cursor
Display	Vertical	Horizontal	Vertical
Posture	Elbow bent	Arm forward	Elbow bent
Teleport	None	Pick up and drop	Point and select

works and museum applications. Specifically, a 2D map is designed to simulate the most common way used in current VR museums, and WiM is implemented as how it is designed to show and interact with. We designed a three-condition within-subjects experiment to answer **RQ1**: *Can interactive maps (WiM and WiM map) better support users' navigation in complex indoor VR environments, compared to 2D mini-maps?* Our primary objective is to assess the overall effectiveness of each navigation technique in supporting general navigation tasks within complex indoor VR environments. We used a VR museum environment but did not include any museum collections in it. This decision was made to prevent potential confounding effects that could arise from the presence of museum collections and to focus solely on the evaluation of the navigation methods. Figure 2 illustrates the use of three navigation methods in the VR museum.

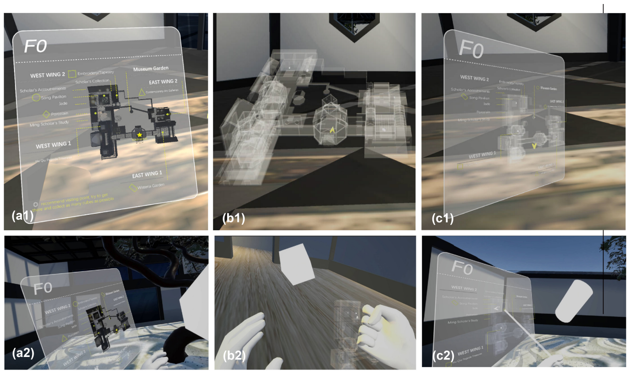

Figure 2: Screenshots showing the three navigation methods and how they were used in the VR museum scenario: (a1-2) hold and view a 2D mini-map; (b1-2) pick up and drop one's representation to teleport in WiM; and (c1-2) point and select to teleport using WiM map.

4.1 Apparatus and Implementation

We used a computer with an Intel Core i7-12700k CPU @ 3.60GHz, 32GB RAM, and a NVIDIA GeForce GTX 3080 graphics card with 4GB RAM. A Meta Quest 2 (1920×1832 resolution for each eye, 72 Hz refresh rate) with two controllers was used. The system was built using Unity (version 2021.3.32f1c1) under the 3D Universal Render Pipeline and the OpenXR package (version 1.4.2).

Commercial VR devices support steering as the most common continuous locomotion technique, while teleportation is the most popular discrete locomotion technique. Recent work has shown the benefits of the combined use of both steering and teleportation techniques [71]. Thus, we adopted both steering (moving speed: 1.4 m/s [43], turning speed: 60 degrees/s [2]) and teleportation (liner-instant, maximum distance: 18 m [41]) as the locomotion techniques and allowed users to switch between them at will.

We created 3D models of the Suzhou Museum using Autodesk Maya 2020 based on its public map, the virtual tours on the museum website, and some photos taken onsite (see Figure 3). The museum covers an area of about 10,700 square meters, with a construction area of more than 19,000 square meters. There are three floors for public visits. However, we did not consider multi-floor navigation at this stage and used only the ground floor for evaluation.

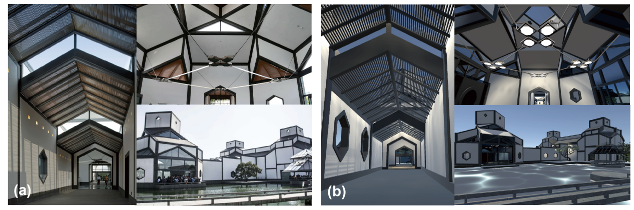

Figure 3: (a) Photographs of the Suzhou Museum; (b) screenshots of the VR museum in Unity.

4.2 Tutorial Scene and Experimental Tasks

4.2.1 Tutorial Scene

To mitigate the influence of unfamiliarity with the navigation methods, we prepared a tutorial scene that includes two parts: (1) how to steer, teleport, switch between locomotion methods, and change views, and (2) how to interact with the map and collect objects. In the first part, participants learned the operations of the locomotion techniques following step-by-step guidance pre-programmed into the system. After participants completed the locomotion tutorial, a maze was shown. Illustrations of the map controls and written instructions were included in the scene that guided them to use the map and collect three cubes in the maze.

4.2.2 Object Collection Task

Within each scene, participants were asked to explore the museum environment using the map and collect five target objects distributed in the scene. We did not include museum collections in the environment but used 3D geometries (cube, rhombus, cone, cylinder, and sphere) to focus on the effectiveness of navigation. Figure 4a shows an example scene with five target objects. To prevent learning effects, different locations of target objects were used in the three experimental sessions.

4.2.3 Map Drawing Task

After completing the object collection task, participants were asked to complete a map drawing task in a task environment showing a board textured with the layout of the VR museum and five blank spaces (see Figure 4b). The task design was inspired by [69]. Each task includes five correct answers and five distractors. Participants needed to select the correct screenshots of the target locations and match them with the corresponding blanks on the map. The task score (S) is calculated by dividing the number of correct selections (x) over the total number of blanks: $S = x/5$.

4.3 Procedure

Figure 5 illustrates the experimental procedure. Participants were first informed of the purpose of the study and signed a consent form. After that, they were asked to fill in the demographic questionnaire that included information about their gender, age, and dominant hand, as well as their familiarity with VR and the museum layout. Each experimental session started with the tutorial scene. After the tutorial training, participants explored the VR museum environment and completed the object collection and map drawing tasks. Next, they put off the VR headset and filled in a questionnaire. A Latin Square Design was followed to counterbalance the sequential effects [12]. After the three sessions, they were asked to rank the three navigation methods and discuss their experiences in a semi-structured interview. The experiment took ∼40 minutes in total. This study is approved by the University Ethics Committee of Xi'an Jiaotong-Liverpool University.

4.4 Variables and Hypotheses

The review of related works showed a potentially more significant learning cost of 3D manipulation techniques [10]. Previous re-

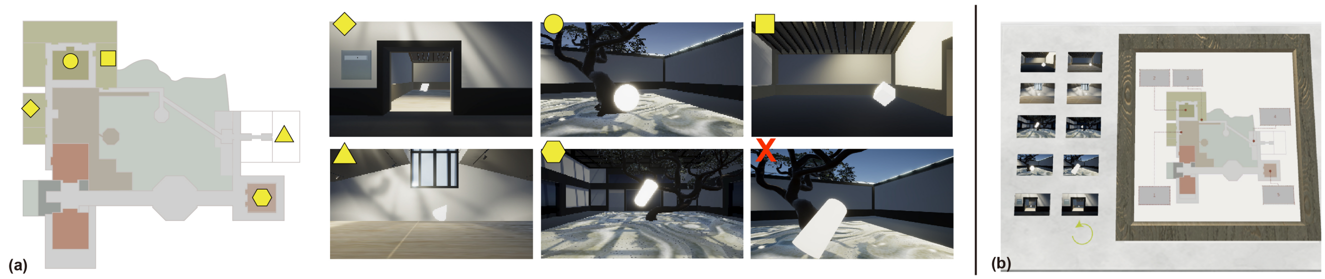

Figure 4: (a) An example object collection task scene with five 3D geometry shapes scattered around the VR museum. The screenshots show the first-person perspective views of the five target objects and an example distractor in (b) the corresponding map drawing task.

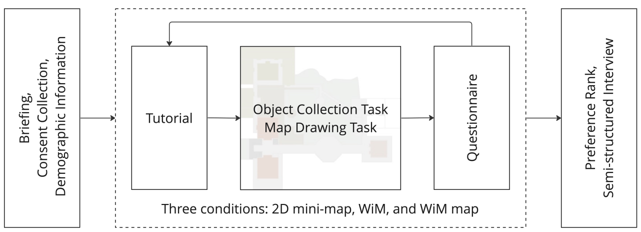

Figure 5: An illustration of the experimental procedure.

searchers found both the 2D mini-map and the WiM could improve users' navigation efficiency and spatial awareness [5,6]. In the meantime, we noted that instant teleportation reduces spatial awareness and presence but also alleviates motion sickness [9,64]. Thus, we hypothesize that there is a difference among 2D mini-map, WiM, and WiM map in users' perceived ease of learning (**H1a**), navigation efficiency (**H1b**), spatial awareness (**H1c**), perceived presence (**H1d**), perceived workload (**H1e**), perceived motion sickness (**H1f**), and preferences (**H1g**).

4.5 Measures and Scoring

4.5.1 System Logged Data

Our system logged objective data in the training session and the task sessions. Specifically, we recorded (1) **tutorial time**: the time spent to complete the tutorial tasks; (2) **object collection task time**: the time spent to complete the collection tasks; (3) **map drawing task time and accuracy**: the time spent to complete the map drawing task and the accuracy of the map drawing task, calculated by the number of correct answers over five (the total number of tasks); and (4) **hand and head movements**: the accumulated movement distance and rotation angle of two hands and the head during the task sessions.

4.5.2 Questionnaire Measures

We included four subjective measures. (1) **Presence** is measured using one question: *"I have a sense of being there"* [56], rated on a 7-point Likert scale; (2) **workload** is measured using the standard NASA Task Load Index [30] that includes six indicators: mental demand, physical demand, temporal demand, performance, frustration, and effort, with a total score ranging from 0 to 100 [28]; (3) **motion sickness** is measured using the Simulator Sickness Questionnaire (SSQ) [32] with 16 items, rating symptoms of nausea, oculomotor, and disorientation (none, slight, moderate, and severe). In addition, we invited participants to provide (4) **preference ranks** among three navigation methods.

4.5.3 Interview Questions

The semi-structured interview was guided by three questions: Q1: *Why did you rank the three methods this way?* Q2: *How would you plan your visit within a VR museum?* Q3: *Do you have any other comments or suggestions?*

4.6 Participants

This study involved 24 participants (13 male, 11 female) between 16 and 26 years old ($M = 21.17, SD = 2.12$). All participants are right-handed. Most of them ($N = 22$) had prior experience with VR equipment. On a scale from 1 to 5 (5 = extremely familiar), they were familiar with VR ($M = 3.29, SD = 1.08$) and slightly familiar with the layout of the local museum ($M = 1.88, SD = 1.03$). No participant asked to stop the experiment early.

4.7 Results

We used IBM SPSS Statistics for the data analysis. The normality of data distribution was assessed based on the Shapiro-Wilk test results, and the homogeneity of variances was assessed using Levene's tests. We performed one-way repeated-measures ANOVA and used the Friedman test when the data failed to meet the assumptions. We computed the effect size η^2 for one-way repeated-measures ANOVA, with threshold values of 0.01, 0.06, and 0.14 representing small, medium, and large effects, respectively. The effect size W for Friedman tests has threshold values of 0.10, 0.30, and 0.50 for the above-mentioned effect magnitudes. Figure 6 summarizes the analysis results. Pairwise comparisons showing statistical significance are marked in the figures ($*p < 0.05$, $**p < 0.01$, $***p < 0.001$).

4.7.1 System Logged Data

Tutorial Completion Time. A Friedman test showed a statistically significant difference in the time required to learn the three navigation methods, $\chi^2(2) = 11.93, p = 0.003, W = 0.25$. Post-hoc tests revealed that the time required to learn the WiM map was significantly less than the 2D mini-map ($p = 0.009$) and WiM ($p = 0.001$). The results support **H1a**: WiM map was easier to learn than 2D mini-map and WiM.

Object Collection Task. A Friedman test showed a statistically significant difference in the completion time of the collection task, $\chi^2(2) = 33.25, p < 0.001, W = 0.69$. Post-hoc tests revealed that the task completion time using the WiM map was significantly shorter than using the 2D mini-map ($p < 0.001$) and WiM ($p < 0.001$). The results support **H1b**: navigating using the WiM map was more efficient than using a 2D mini-map and WiM.

Map Drawing Task. No significant difference was found in the time required to complete the map drawing task ($\chi^2(2) = 0.06, p = 0.97, W = 0.001$) or the map drawing accuracy ($\chi^2(2) = 0.91, p = 0.63, W = 0.02$). **H1c** is not supported: perceived spatial awareness did not vary significantly.

Hand and Head Movements. Friedman tests showed statistically significant differences in users' right hand movement distance ($\chi^2(2) = 10.75, p = 0.005, W = 0.22$), head movement distance ($\chi^2(2) = 15.08, p = 0.001, W = 0.31$), left hand rotation ($\chi^2(2) = 10.58, p = 0.005, W = 0.22$), right hand rotation angle

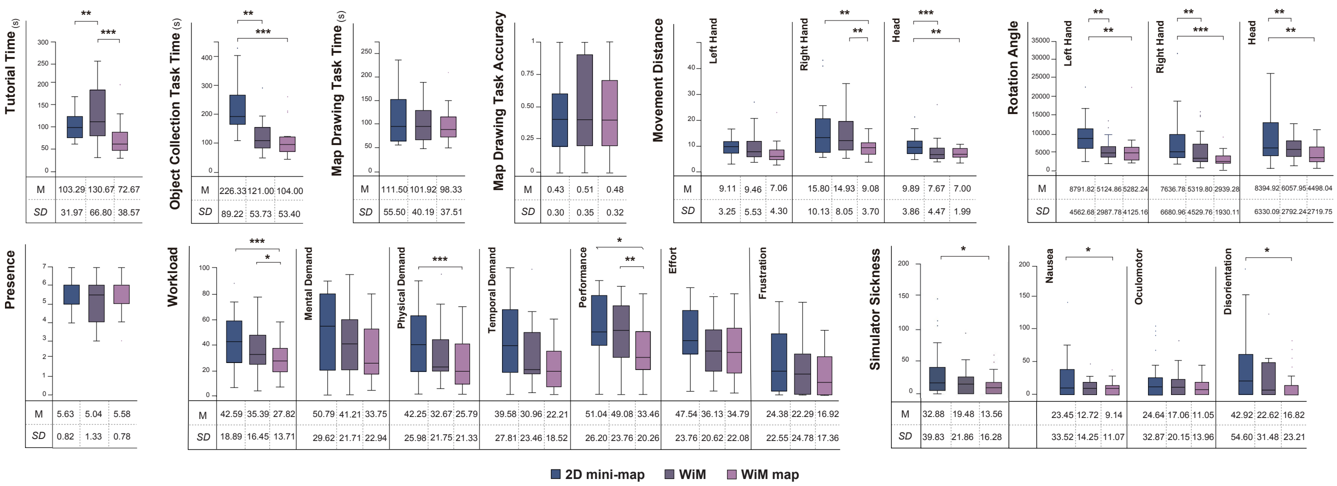

Figure 6: Box-plots and tables of descriptive statistics (means and standard deviations) showing the data analysis results in Study 1.

($\chi^2(2) = 17.58, p < 0.001, W = 0.37$), and head rotation angle ($\chi^2(2) = 10.58, p = 0.005, W = 0.12$) using the three navigation methods. Post-hoc analysis results are shown in Figure 6. The results showed support for **H1b**. The left hand movement distance had no significant difference ($\chi^2(2) = 5.58, p = 0.06, W = 0.12$).

4.7.2 Questionnaire Measures

Presence. No significant difference was found in participants' perceived presence using the three navigation methods, $\chi^2(2) = 4.28, p = 0.12, W = 0.09$. **H1d** is not supported.

Workload. We observed a significant effect of maps on perceived workload, $F(1,23) = 161.40, p < 0.001, \eta^2 = 0.88$. Post-hoc tests revealed that participants reported a significantly lower overall workload using WiM map than using 2D mini-map ($p < 0.001$) and WiM ($p = 0.043$). **H1e** is supported. Specifically, statistically significant differences were found in perceived physical demand ($\chi^2(2) = 12.59, p = 0.002, W = 0.26$), performance ($F(1,23) = 223.20, p < 0.001, \eta^2 = 0.91$), and effort ($F(1,23) = 118.57, p < 0.001, \eta^2 = 0.84$). Post-hoc analysis results are shown in Figure 6. No statistically significant difference was found in perceived mental demand ($\chi^2(2) = 4.98, p = 0.08, W = 0.10$), temporal demand ($\chi^2(2) = 4.11, p = 0.13, W = 0.09$), or frustration ($\chi^2(2) = 5.27, p = 0.07, W = 0.11$).

Motion Sickness. We observed a significant effect of maps on motion sickness, $\chi^2(2) = 7.92, p = 0.019, W = 0.17$. Post-hoc tests revealed significant differences between the 2D mini-map and WiM map ($p = 0.021$). **H1f** is supported: users' perceived motion sickness using the WiM map was significantly lower than the 2D mini-map. Specifically, statistically significant differences were found in the nausea ($\chi^2(2) = 8.316, p = 0.016, W = 0.173$) and the disorientation symptoms ($\chi^2(2) = 9.09, p = 0.011, W = 0.19$). Post-hoc tests revealed a significant difference between the 2D mini-map and WiM map in the nausea ($p = 0.030$) and the disorientation symptoms ($p = 0.025$). No statistically significant difference was found in the oculomotor symptoms, $\chi^2(2) = 2.56, p = 0.28, W = 0.05$.

Preference Rank. Fifteen participants preferred the WiM map the most, followed by WiM ($n = 5$) and 2D mini-map ($n = 4$). Fifteen participants ranked the lowest on the 2D mini-map, followed by WiM ($n = 8$) and WiM map ($n = 1$). This shows support for **H1g**.

4.7.3 Interview

In terms of preference (Q1), most participants ($n = 20$) favored interactive maps (WiM and WiM map) over the 2D mini-map. They found using the 2D mini-map tiring and disorienting, with one participant expressing frustration about following step-by-step movements in VR. Comparing the WiM to the WiM map, participants found the point-and-select interactions more intuitive than the drag-and-drop interactions ($n = 15$). For example, P22 commented on WiM that *"It's unnatural. I find it hard to pick it up and down to change my position."* In contrast, P6 found the drag-and-drop interaction playful, but he commented that *"my whole attention is on the map"*, which shows a distracting impact.

Regarding path planning in museums (Q2), participants tended to use *"the collections I like"* and *"the things I'm not interested in"* to describe how they use museum objects as landmarks to navigate in a museum. Most participants ($n = 21$) preferred planning their routes based on exhibits they liked, while the other three indicated they did not have a particular preference but followed the exhibition layout. Many participants ($n = 9$) also mentioned that they would avoid repeated routes in their visits.

Participants also provided suggestions for improving the navigation systems (Q3). Seven participants encountered visibility and readability issues with the translucent WiM map design under bright lights. They suggested keeping a solid background to address this concern. Two participants highlighted accuracy issues with selection and suggested map scaling as a means to improve precision. One participant suggested reducing the amount of text on the map.

In summary, participants' comments suggested that WiM map with point-and-teleport has the potential for further development. To optimize this, it was recommended to address issues related to 1) occlusion, 2) text display, and 3) scaling. Participants' feedback also indicated the need to 4) support personal meaning-making. Features such as annotations and traces are needed on the map to help them navigate based on preferred collections and avoid repeated routes.

5 Design of MagicMap

Based on the results of our first study, we improved the design of WiM map and developed MagicMap (see Figure 1). Table 2 summarizes the improvements and new features. We fixed some issues identified by participants. For example, we added a radio slider for users to **adjust the transparency** of the museum building abstractions. This was applied to the walls but not the floor for better clarity. We observed that many participants were confused about the wrist-based interaction with elbow bent and tended to use the **arm forward posture**. In addition, we added a **hover** interaction to avoid abundant text on the map and only show those of interest.

Table 2: Comparing WiM map and MagicMap.

	WiM map	**MagicMap**
Map	3D model	3D model
Display	Translucent, vertical	Adjustable transparency, vertical
Posture	Elbow bent	Arm forward
Teleport	Point and select	Point and select
Text on map	Show all	Hover to show
Map view	Overview only	Overview and details
Multi-view	None	Two views
Visiting trace	None	Heatmap
Annotation	None	Annotate collections

5.1 Enable Scalable Map View

The major improvement in MagicMap lies in the scalability of the **map view**. We explored the design space of map scaling to see how we can better support the view of map details. Several methods have been proposed to tackle this issue. Enlarging the entire 2D map interface was an option being denied as it was found to be intrusive and potentially overwhelming. Scaling and scrolling is another approach that has been used, which remains the size of the interface but changes the view of the WiM [60,66]. However, these techniques can be relatively complex to operate, and participants in previous studies have reported a learning curve of 10-15 minutes to master them [66]. Besides, Trueba et al. [59] proposed Dynamic Worlds in Miniature (DWiM), which automatically subdivides scenes into logical structures such as rooms, floors, and so on.

Our proposed WiM map differs from traditional WiM in its combined use with a 2D mini-map, making it natural to be aligned with the system control in 2D user interfaces [10]. Combining 2D interface features with the system control metaphor and the WiM map could be a novel way to make the map view scalable. We adopted this approach for the following reasons. From a developer's perspective, it simplifies the representation of museum environments. Museums have inherently clear structures in their architecture, and spatial layouts are logically shaped by curators. This logical structure can be directly translated into the virtual environment. Additionally, the 2D menu is well-suited for structuring a large number of functions [10]. It also allows us to incorporate explanatory text like a museum handheld leaflet. From a user's perspective, this approach leverages users' existing mental model of 2D interaction and minimizes the learning curve for users. Furthermore, interacting in two dimensions is generally easier and allows users to perform tasks such as selection and manipulation (e.g., point and teleport) with a higher level of precision [10]. In addition to the scalability in the map view, we also included a **multi-view** interface so that users can see both an overview and map details (see Figure 1).

5.2 Enhance Navigation and Support Meaning-Making

Museum visits often involve personal meaning-making, where users tend to create their own records during their visits. For example, during the interview of our first study, participants frequently mentioned their navigation strategies based on personal interests and experiences, such as *"the collection I like"* and *"the place I visited"*. Previous studies also found that some participants intentionally moved in specific paths to create some trails in a certain pattern [35]. Kleinermann et al. [33] emphasized the importance of allowing users to add personal meaning to the objects in the virtual environment and to the environment itself. In this way, users are more likely to stay engaged and immersed in the environment. Based on these findings, we incorporated the following features into MagicMap:

(1) **A heatmap showing visiting traces.** We added a heatmap to MagicMap, inspired by Kraus et al. [35]. They suggested using heatmaps in conjunction with a mini-map to support users' orientation in virtual environments when adopting the teleportation locomotion technique.

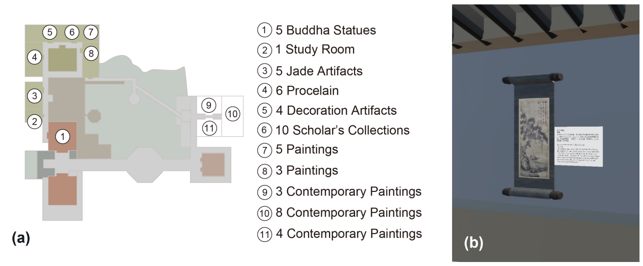

Figure 7: (a) The layout of exhibition rooms and the collections in the VR museum; (b) a screenshot of an example collection.

(2) **Annotation of collections to view and teleport.** We allow users to annotate collections within the VR museum. A heart-shaped annotation will appear on the MagicMap to represent the marked collection. Users can hover over the annotation to view a miniature representation of the collection and point to the annotation to teleport. This feature enhances navigation by allowing users to attribute personal meanings to specific collections within the museum. It also aids in memorizing locations and supports wayfinding.

6 Study 2: Evaluation of MagicMap in a VR museum

In this study, we included museum artifacts and simulated navigation in the museum with no specific navigation goals. We designed a two-condition within-subjects experiment to answer **RQ2**: *Do MagicMap's features improve users' navigation experience in VR museums, compared to the WiM map?*

6.1 Apparatus and Implementation

The apparatus used for the system development was the same as the previous study. The experimental scenes were populated with photo-realistic museum collections, maintaining consistency with the physical museum layout and their themed objects (see Figure 7a). Each scene has 53 museum collections (e.g., a painting, see Figure 7b) and a scene set up (i.e., a study room) distributed in 11 exhibition rooms. Different collections of the same types were used in the two experimental sessions to facilitate a valid comparison.

6.2 Experimental Tasks and Procedure

Instead of asking participants to perform object collection and map drawing tasks, we gave the following instructions: *Please explore the museum collections and use the map to help you navigate. You may stop the visit once you feel that you have visited all the exhibition rooms.* The study followed a similar procedure, as described in Section 4.3. The tutorial allowed participants to practice using the two locomotion techniques (steering and teleport) and familiarize themselves with the WiM map and the MagicMap. Participants freely explored the museum exhibition rooms using the WiM map and the MagicMap, after which they filled in questionnaires to evaluate their experiences. At the end of the experiment, participants discussed their preferences and provided suggestions in an interview. The experiment took $\sim$30 minutes in total.

6.3 Dependent Variables and Hypotheses

Following up on the previous study, we hypothesize that map systems will not have a significant impact on users' perceived presence (**H2a**). Compared to WiM map, MagicMap could reduce users' perceived workload (**H2b**) and motion sickness (**H2c**). In addition, it should be preferred by users (**H2d**), sustain prolonged engagement (time spent) (**H2e**), and have a better system usability (**H2f**) and greater user experience (**H2g**).

6.4 Measures and Scoring

The measures of **presence**, **workload**, **motion sickness**, and **preference** were the same as the previous study (see Section 4.5.1). In

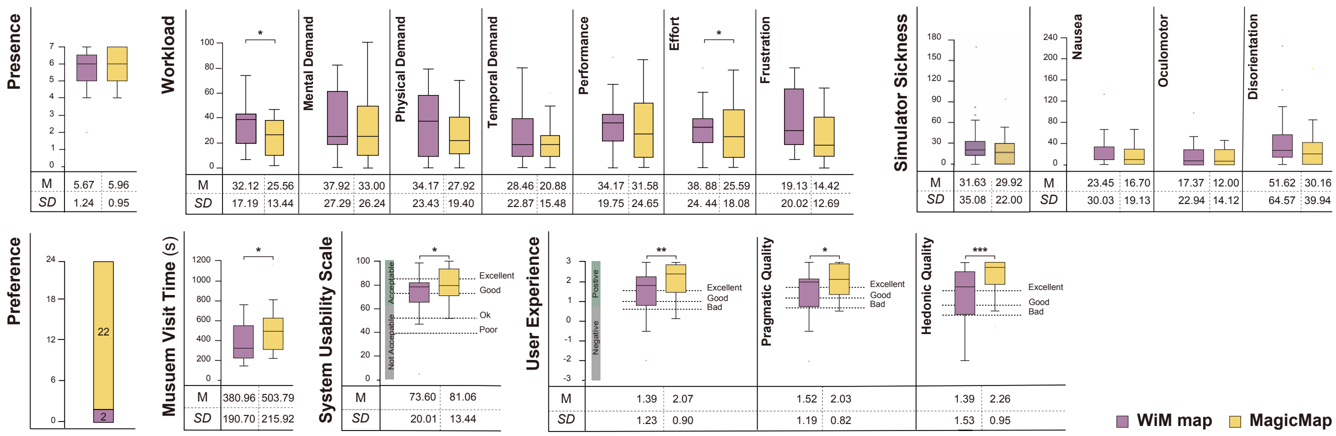

Figure 8: Box-plots and tables of descriptive statistics (means and standard deviations) showing the data analysis results in Study 2.

addition, we used system logs to record the **time** participants spent in the VR museum. Given that we did not include task settings in this study, we dropped the measures of task performance. Instead, we measured **usability** and **user experience** using the System Usability Questionnaire (SUS) [14] and the short version of the User Experience Questionnaire (UEQ-S). We invited participants to discuss their preferences (Q1) and give their suggestions (Q2) in the interview.

6.5 Participants

Twenty-four participants (12 male, 12 female) between 19 and 26 years old ($M = 22.58, SD = 2.43$) participated in the study. All participants are right-handed. Most of them ($N = 21$) have used VR before. They were familiar with VR ($M = 3.38, SD = 1.17$) and slightly familiar with the museum layout ($M = 2.04, SD = 0.91$). We found no significant effect of familiarity on the measured variables.

6.6 Results

We assessed the distribution and homogeneity of variances of our data to help determine the statistical tests to use. Paired sample t-tests were applied for data that met the test assumptions, and Wilcoxon signed-rank test was used otherwise. Figure 8 summarized the results. We computed the effect size d for paired sample t-tests, with threshold values of 0.2, 0.5, and 0.8 representing small, medium, and large effects, respectively. The effect size r for Wilcoxon signed-rank test has threshold values of 0.1, 0.3, and 0.5 for the above-mentioned effect magnitudes. Figure 8 shows the analysis results.

Presence. We observed no significant effect of maps on participants' perceived presence using the two navigation methods, $Z = -1.26, p = 0.21, r = 0.26$. **H2a** is supported.

Workload. Similar to Study 1, we observed a significant effect of maps on perceived workload, $t(23) = 2.53, p = 0.019, d = 0.43$. Participants reported a significantly lower overall workload using MagicMap than WiM map. **H2b** is supported. Specifically, we found statistically significant differences in perceived effort, $Z = -2.72, p = 0.006, r = 0.56$. No significant difference was shown in perceived mental demand ($Z = -0.88, p = 0.38, r = 0.18$), physical demand ($t(23) = 1.66, p = 0.11, d = 0.29$), temporal demand ($Z = -1.76, p = 0.08, r = 0.36$), performance ($t(23) = 0.49, p = 0.63, d = 0.12$), or frustration ($Z = -1.20, p = 0.23, r = 0.24$).

Motion Sickness. Wilcoxon signed-rank test showed no statistically significant difference in the reported symptoms of nausea ($Z = -0.83, p = 0.41, r = 0.17$), oculomotor ($Z = -1.39, p = 0.17, r = 0.28$), disorientation ($Z = -1.62, p = 0.11, r = 0.33$), or the overall motion sickness ($Z = -1.48, p = 0.14, r = 0.19$). **H2c** is not supported.

Preference Rank. Twenty-two out of 24 participants preferred to navigate in VR museums using the MagicMap. **H2d** is supported.

Museum Visiting Time. A Wilcoxon signed-rank test showed a statistically significant difference in the museum visiting time, $Z = -2.20, p = 0.028, r = 0.37$. **H2e** is supported: participants' prolonged engagement (time spent) was significantly greater using MagicMap than WiM map.

Usability. Both the median and the mean scores of WiM map and MagicMap fell within the suggested *acceptable* range [14], showing *good* usability. A Wilcoxon signed-rank test showed a significant difference in usability scores, $Z = -2.10, p = 0.036, r = 0.43$. Participants rated significantly higher usability for MagicMap than the WiM map. Thus, **H2f** was supported.

User Experience. A Wilcoxon signed-rank test showed a significant difference in the evaluation of user experience, $Z = -2.66, p = 0.008, r = 0.54$. Participants rated significantly higher for MagicMap than the WiM map on the overall user experience. Significant differences were shown for the pragmatic quality ($Z = -2.16, p = 0.031, r = 0.44$) and the hedonic quality ($Z = -3.52, p < 0.001, r = 0.72$). Both were rated higher for the MagicMap than the WiM map. The results support **H2g**.

Interview. Most participants ($n = 22$) showed strong preferences for the MagicMap (Q1). P20 and P15 favored the WiM map because they found it clear and straightforward to use. P20 explained that the WiM map required fewer operations, making it *"easy to use for more people, like children."* Participants who favored the MagicMap highly praised the use of annotations and traces. Most of them ($n = 20$) reported that they did not remember where they had visited when using the WiM map. P21 said *"I completely forgot where I have been before, so I just jumped around the museum with the map to confirm."* Only one participant (P7) explicitly stated that he could remember all visited locations without the assistance that MagicMap provided. P7 further expressed that *"I hesitated because MagicMap was information-overloaded for me. For example, this heatmap, I don't think I need it."* Three participants (P4, P9, and P14) commented that the scalable map design allowed them to point and select the map to teleport more accurately.

Participants commented highly on the MagicMap design when we asked for suggestions (Q2). Nevertheless, P11 reported that *"Sometimes I bumped into the wall when I teleport, which was uncomfortable."* This indicates the need for a preview of the target location before confirming the selection to ensure a smooth transition. In addition, four participants expressed unease when visiting a museum alone, especially around Buddha statues. P16 proposed adding "*fake tourists*" (i.e., virtual avatars) for accompanying. P18 suggested that *"It would be great if the heat map I saw was generated by everyone there!"* This indicates the need for social presence as an integral part of the museum visiting experience.

7 Discussion of Design Implications

Study 1 underscored the importance of interactive navigation tools and answered **RQ1:** the WiM map can better support users' navigation in complex indoor VR environments. The WiM map demonstrated greater ease of learning (**H1a**), shorter collection task time and reduced dominant hand movements (**H1b**), lower perceived workload (**H1e**), slighter perceived motion sickness (**H1f**), and greater preferences (**H1g**). However, we did not find significant differences in spatial awareness or presence. **H1c** and **H1d** were not supported. The results showed that participants had an overall medium accuracy in the map drawing tasks ($\sim$50%) when using all three techniques, suggesting room for improvement. Similar to the findings in [62], our results indicated that interactions with navigation tools may not have a significant effect on perceived presence.

Study 2 answered **RQ2** by showing that compared to the WiM map, MagicMap has improved users' navigation experience in VR museums. The evaluation results showed that presence is not significantly affected by the map systems (**H2a**), which is consistent with the finding in Study 1. Despite this, MagicMap demonstrated improvements in its reduced workload (**H2b**), greater user preference (**H2d**), prolonged engagement (**H2e**), and improved system usability (**H2f**) and user experience (**H2g**). Although motion sickness was not significantly improved (**H2c**, not supported), both the WiM map and the MagicMap showed very slight symptoms. Moreover, interview comments showed that some features of MagicMap, such as annotations and traces, contributed to users' spatial awareness. Those results signified the effectiveness of MagicMap in addressing key challenges faced in VR museum navigation.

MagicMap features a museum WiM attached to a 2D mini-map. Throughout our studies, we explored various map layouts, display approaches, and holding postures. The design of MagicMap embodies incremental integration of effective means reported in previous research, including multi-view, heatmap, and annotation, among others. While navigation in VR museums has not been extensively studied in the literature, our research contributes to filling this gap. The study showcases the effectiveness of MagicMap for indoor museum navigation and provides valuable insights into the advancement of navigation technique design. From our findings, we derive a set of design implications for future navigation techniques in VR museums or similar complex indoor environments.

- Static **2D mini-maps** may not work well in VR museums as users can get lost more easily in virtual environments [16], where navigation expectations differ from physical museums.
- Be mindful of the learning curve when incorporating **3D manipulation** into navigation systems. Aligned with previous work [10], using WiM with 3D manipulation had a higher workload than the WiM map with 2D control metaphor.
- Display **wrist vertical map** in an 'arm forward' posture. The 'elbow bent' posture illustrated in [13] was found to cause user confusion about the front and back of the map.
- Allow adjustable transparency of walls and roofs but keep a solid material for the ground. This helps solve the **occlusion** issue without disrupting the architecture. Avoid fully translucent WiM (e.g., [5]) under strong lights (e.g., spotlight).
- Use **system control metaphor** to **scale** the WiM or WiM-based map. Compared with previous scrolling and scaling methods [8, 60], which require 10-15 minutes to master, this approach requires much less learning time.
- If a map is designed for a complex indoor environment, provide **annotation** and **trace** functions for users to have personalized visits. These can act as landmarks and facilitate wayfinding.
- Give users options to **enable** information (e.g., hover to view) and **disable** functions to cater for individual preferences.
- Incorporate a **preview function** for long-distance teleportation, allowing users to recognize what they will encounter next and adjust their navigation accordingly.

8 Limitations and Future Work

This research has some limitations and room for future work. First, our sample primarily included young adults who are familiar with VR. This group of users have been identified as the primary audience for VR museums and the target users in promotional efforts [4,20,27,55]. Attracting young people via technological means was included in strategies aiming to address the declining number of young people visiting museums [19, 25, 31]. Despite this, the inclusion of other age groups and remote participants into the audience spectrum can be highly beneficial as well. Second, our comparisons in the first study were more exploratory than confirmatory. Although both steering and teleport were allowed in the 2D mini-map, it may be disadvantaged since it does not support long-distance teleportation from the map. Third, our VR museum was not a 1:1 replica of the physical museum. Further explorations involving actual collections and comparing navigation within physical museums could provide valuable insights. In addition, despite interview comments showing the potential effectiveness of MagicMap in supporting spatial awareness, this should be further validated using task measures. Fourth, we did not explore navigation in multi-floor environments, which are common in museums and other complex indoor environments such as shopping malls and schools. Given the scalability demonstrated in our MagicMap design, we plan to further improve the design by incorporating techniques for multi-floor 3D maps (e.g., [18, 48]) in our future work. Fifth, museum visiting is a social activity [26], but we only explored the single-person navigation experience. The observation of participants reporting strange feelings when visiting alone in the second study raises an interesting point about the potential impact of social interactions and collaborative navigation in VR museums. It is a valuable direction for future research to explore how user-generated content in the form of heatmaps and annotations can be leveraged in a collaborative context. Future work should also explore methods to enhance the teleportation experience with WiM-based systems, incorporating suggestions such as the teleportation preview mentioned by our participants. This could be combined or compared with other transition techniques (e.g., [1, 15, 47, 49]).

9 Conclusion

In this paper, we presented two studies focusing on improving navigation in Virtual Reality (VR) museums. The first study compared the effectiveness of three maps (2D mini-map, WiM, and WiM map) in guiding users through a VR museum. The findings highlighted the potential of the WiM map, demonstrating significant enhancement in ease of learning, efficiency, perceived workload, perceived motion sickness, and user preference. Building on participants' feedback for improvements and insights from previous research, we introduced MagicMap, a novel navigation system that leverages the WiM map as its foundation. Our results show that it helped address the challenges of navigating complex indoor VR environments with improved system usability and user experience, minimizing workload and enhancing prolonged user engagement. Participants' feedback in the interview also indicates its strength in supporting spatial awareness and wayfinding. Furthermore, we formulated initial design guidelines for map-based navigation systems in the context of VR museums. These guidelines serve as a valuable starting point for researchers and developers seeking to enhance the user experience of VR museum navigation. Future work can build upon these guidelines, validating and refining the design through user evaluations to continually improve navigation in VR museums.

Acknowledgments

This work is supported by the National Natural Science Foundation of China (62207022, 62272396), the Natural Science Foundation of the Jiangsu Higher Education Institutions of China (22KJB520038), and the Xi'an Jiaotong-Liverpool University (RDF-20-02-47).

REFERENCES

[1] D. Ablett, A. Cunningham, G. A. Lee, and B. H. Thomas. Point & Portal: A New Action at a Distance Technique For Virtual Reality. In *2023 IEEE International Symposium on Mixed and Augmented Reality (ISMAR)*, pp. 119–128. IEEE, 2023.

[2] I. B. Adhanom, N. Navarro Griffin, P. MacNeilage, and E. Folmer. The Effect of a Foveated Field-of-view Restrictor on VR Sickness. In *2020 IEEE Conference on Virtual Reality and 3D User Interfaces (VR)*, pp. 645–652, 2020. doi: 10.1109/VR46266.2020.00087

[3] J. Al Rabbaa, A. Morris, and S. Somanath. "MRsive: An Augmented Reality Tool for Enhancing Wayfinding and Engagement with Art in Museums". In C. Stephanidis, ed., *HCI International 2019 - Posters*, pp. 535–542. Springer International Publishing, Cham, 2019.

[4] S. Auffret. VR Opportunities, May 2017.

[5] L. Berger and K. Wolf. Wim: fast locomotion in virtual reality with spatial orientation gain & without motion sickness. In *Proceedings of the 17th International Conference on Mobile and Ubiquitous Multimedia*, pp. 19–24, 2018.

[6] S. Bitgood. *Attention and value: Keys to understanding museum visitors*. Routledge, 2016.

[7] J. L. Bitter, R. Dörner, Y. Liu, L. Rau, and U. Spierling. "Follow the Blue Butterfly – An Immersive Augmented Reality Museum Guide". In C. Stephanidis, M. Antona, and S. Ntoa, eds., *HCI International 2022 Posters*, pp. 171–178. Springer International Publishing, Cham, 2022.

[8] S. Boring, M. Jurmu, and A. Butz. Scroll, tilt or move it: using mobile phones to continuously control pointers on large public displays. In *Proceedings of the 21st Annual Conference of the Australian Computer-Human Interaction Special Interest Group: Design: Open 24/7*, pp. 161–168, 2009.

[9] D. Bowman, D. Koller, and L. Hodges. Travel in immersive virtual environments: an evaluation of viewpoint motion control techniques. In *Proceedings of IEEE 1997 Annual International Symposium on Virtual Reality*, pp. 45–52, 1997. doi: 10.1109/VRAIS.1997.583043

[10] D. Bowman, E. Kruijff, J. J. LaViola Jr, and I. P. Poupyrev. *3D User interfaces: theory and practice, CourseSmart eTextbook*. Addison-Wesley, 2004.

[11] E. Bozgeyikli, A. Raij, S. Katkoori, and R. Dubey. Point & teleport locomotion technique for virtual reality. In *Proceedings of the 2016 annual symposium on computer-human interaction in play*, pp. 205–216, 2016.

[12] J. V. Bradley. Complete Counterbalancing of Immediate Sequential Effects in a Latin Square Design. *Journal of the American Statistical Association*, 53(282):525–528, 1958. doi: 10.1080/01621459.1958.10501456

[13] E. Brasier, O. Chapuis, N. Ferey, J. Vezien, and C. Appert. ARPads: Mid-air Indirect Input for Augmented Reality. In *2020 IEEE International Symposium on Mixed and Augmented Reality (ISMAR)*, pp. 332–343, 2020. doi: 10.1109/ISMAR50242.2020.00060

[14] J. Brooke. SUS: a retrospective. *Journal of usability studies*, 8(2):29–40, 2013.

[15] G. Bruder, F. Steinicke, and K. H. Hinrichs. Arch-explore: A natural user interface for immersive architectural walkthroughs. In *2009 IEEE Symposium on 3D User Interfaces*, pp. 75–82. IEEE, 2009.

[16] J. Cao, Q. He, Z. Wang, R. LC, and X. Tong. DreamVR: Curating an Interactive Exhibition in Social VR Through an Autobiographical Design Study. In *Proceedings of the 2023 CHI Conference on Human Factors in Computing Systems*, pp. 1–18, 2023.

[17] V. Chheang, F. Heinrich, F. Joeres, P. Saalfeld, B. Preim, and C. Hansen. Group WiM: A Group Navigation Technique for Collaborative Virtual Reality Environments. In *2022 IEEE Conference on Virtual Reality and 3D User Interfaces Abstracts and Workshops (VRW)*, pp. 556–557, 2022. doi: 10.1109/VRW55335.2022.00129

[18] L. Chittaro, V. Gatla, and S. Venkataraman. The Interactive 3D Break-Away Map: a navigation and examination aid for multi-floor 3D worlds. In *2005 International Conference on Cyberworlds (CW'05)*, pp. 8 pp.–66, 2005. doi: 10.1109/CW.2005.88

[19] E. Ch'ng, S. Cai, F.-T. Leow, and T. E. Zhang. Adoption and use of emerging cultural technologies in China's museums. *Journal of Cultural Heritage*, 37:170–180, 2019. doi: 10.1016/j.culher.2018.11.016

[20] E. Ch'ng, Y. Li, S. Cai, and F.-T. Leow. The Effects of VR Environments on the Acceptance, Experience, and Expectations of Cultural Heritage Learning. *J. Comput. Cult. Herit.*, 13(1), feb 2020. doi: 10.1145/3352933

[21] D. Cosley, J. Baxter, S. Lee, B. Alson, S. Nomura, P. Adams, C. Sarabu, and G. Gay. A Tag in the Hand: Supporting Semantic, Social, and Spatial Navigation in Museums. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, CHI '09, p. 1953–1962. ACM, New York, NY, USA, 2009. doi: 10.1145/1518701.1518999

[22] K. Danyluk, B. Ens, B. Jenny, and W. Willett. A Design Space Exploration of Worlds in Miniature. In *CHI '21*. ACM, New York, NY, USA, 2021. doi: 10.1145/3411764.3445098

[23] K. Danyluk and W. Willett. Evaluating the performance of virtual reality navigation techniques for large environments. In *Advances in Computer Graphics: 36th Computer Graphics International Conference, CGI 2019, Calgary, AB, Canada, June 17–20, 2019, Proceedings 36*, pp. 203–215. Springer, 2019.

[24] R. P. Darken and B. Peterson. Spatial orientation, wayfinding, and representation. In *Handbook of virtual environments*, pp. 533–558. CRC Press, 2002.

[25] Department for Digital, Culture, Media Sports, UK. Sponsored Museums Performance Indicators 2015-16. 2017.

[26] E. Dim and T. Kuflik. Automatic Detection of Social Behavior of Museum Visitor Pairs. *ACM Trans. Interact. Intell. Syst.*, 4(4), nov 2014. doi: 10.1145/2662869

[27] S. Dominquez. How to Market Virtual Reality. *The Huffington Post. August*, 14, 2016.

[28] R. Grier. How high is high? A metanalysis of NASA TLX global workload scores. vol. 59, 10 2015. doi: 10.1177/1541931215591373

[29] S. Guo and X. Zheng. Research on the welcoming experience of the museum's arrival space. *Museum Management and Curatorship*, 0(0):1–17, 2022. doi: 10.1080/09647775.2022.2132994

[30] S. G. Hart. NASA Task Load Index (TLX). 1986.

[31] S. Iyengar, T. Bradshaw, and B. Nichols. 2008 Survey of Public Participation in the Arts. *National Endowment for the Arts*, 1, 2009.

[32] R. S. Kennedy, N. E. Lane, K. S. Berbaum, and M. G. Lilienthal. Simulator sickness questionnaire: An enhanced method for quantifying simulator sickness. *The international journal of aviation psychology*, 3(3):203–220, 1993.

[33] F. Kleinermann, O. De Troyer, C. Creelle, and B. Pellens. Adding semantic annotations, navigation paths and tour guides to existing virtual environments. In *Virtual Systems and Multimedia: 13th International Conference, VSMM 2007, Brisbane, Australia, September 23-26, 2007, Revised Selected Papers 13*, pp. 100–111. Springer, 2008.

[34] A. Kolesnichenko, J. McVeigh-Schultz, and K. Isbister. Understanding Emerging Design Practices for Avatar Systems in the Commercial Social VR Ecology. In *Proceedings of the 2019 on Designing Interactive Systems Conference*, DIS '19, p. 241–252. ACM, New York, NY, USA, 2019. doi: 10.1145/3322276.3322352

[35] M. Kraus, H. Schäfer, P. Meschenmoser, D. Schweitzer, D. A. Keim, M. Sedlmair, and J. Fuchs. A Comparative Study of Orientation Support Tools in Virtual Reality Environments with Virtual Teleportation. In *2020 IEEE International Symposium on Mixed and Augmented Reality (ISMAR)*, pp. 227–238, 2020. doi: 10.1109/ISMAR50242.2020.00046

[36] J.-I. Lee, P. Asente, and W. Stuerzlinger. Designing Viewpoint Transition Techniques in Multiscale Virtual Environments. In *2023 IEEE Conference Virtual Reality and 3D User Interfaces (VR)*, pp. 680–690, 2023. doi: 10.1109/VR55154.2023.00083

[37] H.-N. Liang, F. Lu, Y. Shi, V. Nanjappan, and K. Papangelis. Evaluating the effects of collaboration and competition in navigation tasks and spatial knowledge acquisition within virtual reality environments. *Future Generation Computer Systems*, 95:855–866, 2019. doi: 10.1016/j.future.2018.02.029

[38] H.-N. Liang, P. C. Parsons, H.-C. Wu, and K. Sedig. An Exploratory Study of Interactivity in Visualization Tools: 'Flow' of Interaction . *Journal of Interactive Learning Research*, 21(1):5–45, 2010.

[39] H.-N. Liang and K. Sedig. Characterizing navigation in interactive

learning environments. *Interactive Learning Environments*, 17(1):53–75, 2009. doi: 10.1080/10494820701610605
[40] M. Lütjens, T. P. Kersten, B. Dorschel, and F. Tschirschwitz. Virtual Reality in Cartography: Immersive 3D Visualization of the Arctic Clyde Inlet (Canada) Using Digital Elevation Models and Bathymetric Data. *Multimodal Technologies and Interaction*, 3(1), 2019. doi: 10.3390/mti3010009
[41] A. Matviienko, F. Müller, M. Schmitz, M. Fendrich, and M. Mühlhäuser. SkyPort: Investigating 3D Teleportation Methods in Virtual Environments. In *CHI '22*. ACM, New York, NY, USA, 2022. doi: 10.1145/3491102.3501983
[42] D. Medeiros, M. Sousa, A. Raposo, and J. Jorge. Magic Carpet: Interaction Fidelity for Flying in VR. *IEEE Transactions on Visualization and Computer Graphics*, 26(9):2793–2804, 2020. doi: 10.1109/TVCG.2019.2905200
[43] B. J. Mohler, W. B. Thompson, S. H. Creem-Regehr, H. L. Pick, and W. H. Warren. Visual flow influences gait transition speed and preferred walking speed. *Experimental brain research*, 181:221–228, 2007.
[44] D. Monteiro, H. Chen, H.-N. Liang, H. Tu, and H. Dub. Evaluating Performance and Gameplay of Virtual Reality Sickness Techniques in a First-Person Shooter Game. In *2021 IEEE Conference on Games (CoG)*, pp. 1–8, 2021. doi: 10.1109/CoG52621.2021.9619145
[45] D. Monteiro, H.-N. Liang, X. Tang, and P. Irani. Using Trajectory Compression Rate to Predict Changes in Cybersickness in Virtual Reality Games. In *2021 IEEE International Symposium on Mixed and Augmented Reality (ISMAR)*, pp. 138–146, 2021. doi: 10.1109/ISMAR52148.2021.00028
[46] Y. Moullec, M. Cogné, J. Saint-Aubert, and A. Lécuyer. Assisted walking-in-place: Introducing assisted motion to walking-by-cycling in embodied virtual reality. *IEEE Transactions on Visualization and Computer Graphics*, 29(5):2796–2805, 2023.
[47] J. W. Nam, K. McCullough, J. Tveite, M. M. Espinosa, C. H. Perry, B. T. Wilson, and D. F. Keefe. Worlds-in-wedges: Combining worlds-in-miniature and portals to support comparative immersive visualization of forestry data. In *2019 IEEE conference on virtual reality and 3D user interfaces (VR)*, pp. 747–755. IEEE, 2019.
[48] C. Niederauer, M. Houston, M. Agrawala, and G. Humphreys. Non-Invasive Interactive Visualization of Dynamic Architectural Environments. In *Proceedings of the 2003 Symposium on Interactive 3D Graphics*, I3D '03, p. 55–58. Association for Computing Machinery, New York, NY, USA, 2003. doi: 10.1145/641480.641493
[49] R. Pausch, T. Burnette, D. Brockway, and M. E. Weiblen. Navigation and locomotion in virtual worlds via flight into hand-held miniatures. In *Proceedings of the 22nd annual conference on Computer graphics and interactive techniques*, pp. 399–400, 1995.
[50] K. Rahimi, C. Banigan, and E. D. Ragan. Scene transitions and teleportation in virtual reality and the implications for spatial awareness and sickness. *IEEE transactions on visualization and computer graphics*, 26(6):2273–2287, 2018.
[51] J. Rasch, V. D. Rusakov, M. Schmitz, and F. Müller. Going, Going, Gone: Exploring Intention Communication for Multi-User Locomotion in Virtual Reality. In *Proceedings of the 2023 CHI Conference on Human Factors in Computing Systems*, pp. 1–13, 2023.
[52] J. Rounds. Strategies for the curiosity-driven museum visitor. *Curator: The Museum Journal*, 47(4):389–412, 2004.
[53] I. Rubino, J. Xhembulla, A. Martina, A. Bottino, and G. Malnati. MusA: Using Indoor Positioning and Navigation to Enhance Cultural Experiences in a Museum. *Sensors*, 13(12):17445–17471, 2013. doi: 10.3390/s131217445
[54] P. Schorch. The experience of a museum space. *Museum Management and Curatorship*, 28(2):193–208, 2013.
[55] M. Shehade and T. Stylianou-Lambert. Virtual Reality in Museums: Exploring the Experiences of Museum Professionals. *Applied Sciences*, 10(11), 2020. doi: 10.3390/app10114031
[56] M. Slater et al. Measuring presence: A response to the Witmer and Singer presence questionnaire. *Presence: teleoperators and virtual environments*, 8(5):560–565, 1999.
[57] F. Steinicke, G. Bruder, J. Jerald, H. Frenz, and M. Lappe. Estimation of Detection Thresholds for Redirected Walking Techniques. *IEEE Transactions on Visualization and Computer Graphics*, 16(1):17–27, 2010. doi: 10.1109/TVCG.2009.62
[58] R. Stoakley, M. J. Conway, and R. Pausch. Virtual reality on a WIM: interactive worlds in miniature. In *Proceedings of the SIGCHI conference on Human factors in computing systems*, pp. 265–272, 1995.
[59] R. Trueba, C. Andujar, and F. Argelaguet. Complexity and occlusion management for the world-in-miniature metaphor. In *International Symposium on Smart Graphics*, pp. 155–166. Springer, 2009.
[60] S. Truman and S. von Mammen. An integrated design of world-in-miniature navigation in virtual reality. In *Proceedings of the 15th International Conference on the Foundations of Digital Games*, pp. 1–9, 2020.
[61] J. Wang, H.-N. Liang, D. Monteiro, W. Xu, and J. Xiao. Real-Time Prediction of Simulator Sickness in Virtual Reality Games. *IEEE Transactions on Games*, 15(2):252–261, 2023. doi: 10.1109/TG.2022.3178539
[62] Y. Wang, Y. Li, and H.-N. Liang. Comparative Analysis of Artefact Interaction and Manipulation Techniques in VR Museums: A Study of Performance and User Experience. In *2023 IEEE International Symposium on Mixed and Augmented Reality (ISMAR)*, pp. 761–770, 2023. doi: 10.1109/ISMAR59233.2023.00091
[63] A. J. Wecker, J. Lanir, T. Kuflik, and O. Stock. Where to go and how to get there: guidelines for indoor landmark-based navigation in a museum context. In *Proceedings of the 17th International Conference on Human-Computer Interaction with Mobile Devices and Services Adjunct*, pp. 789–796, 2015.
[64] T. Weissker, P. Bimberg, A. S. Gokhale, T. Kuhlen, and B. Froehlich. Gaining the high ground: Teleportation to mid-air targets in immersive virtual environments. *IEEE Transactions on Visualization and Computer Graphics*, 29(5):2467–2477, 2023.
[65] T. Weissker, A. Kunert, B. Fröhlich, and A. Kulik. Spatial updating and simulator sickness during steering and jumping in immersive virtual environments. In *2018 IEEE conference on virtual reality and 3D user interfaces (VR)*, pp. 97–104. IEEE, 2018.
[66] C. A. Wingrave, Y. Haciahmetoglu, and D. A. Bowman. Overcoming world in miniature limitations by a scaled and scrolling wim. In *3D User Interfaces (3DUI'06)*, pp. 11–16. IEEE, 2006.
[67] L. Zhang, A. Agrawal, S. Oney, and A. Guo. VRGit: A Version Control System for Collaborative Content Creation in Virtual Reality. In *CHI '23*, pp. 1–14, 2023.
[68] Y. Zhang and T. Nakajima. Exploring the Design of a Mixed-Reality 3D Minimap to Enhance Pedestrian Satisfaction in Urban Exploratory Navigation. *Future Internet*, 14(11), 2022. doi: 10.3390/fi14110325
[69] Y. Zhao, J. Stefanucci, S. Creem-Regehr, and B. Bodenheimer. Evaluating Augmented Reality Landmark Cues and Frame of Reference Displays with Virtual Reality. *IEEE Transactions on Visualization and Computer Graphics*, 29(5):2710–2720, 2023. doi: 10.1109/TVCG.2023.3247078
[70] Z. Zhao, Y. Li, and H.-N. Liang. LeanOn: Simulating Balance Vehicle Locomotion in Virtual Reality. In *2023 IEEE International Symposium on Mixed and Augmented Reality (ISMAR)*, pp. 415–424, 2023. doi: 10.1109/ISMAR59233.2023.00056
[71] Z. Zhao, Y. Li, L. Yu, and H.-N. Liang. TeleSteer: Combining Discrete and Continuous Locomotion Techniques in Virtual Reality. *2023 IEEE Conference on Virtual Reality and 3D User Interfaces Abstracts and Workshops (VRW)*, 2023. doi: 10.1109/VRW58643.2023.00220