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Wayfinding Behavior and Spatial Knowledge Acquisition: Are They the Same in Virtual Reality and in Real-World Environments?

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Finding one's way is a fundamental daily activity and has been widely studied in the field of geospatial cognition. Immersive virtual reality (iVR) techniques provide new approaches for investigating wayfinding behavior and spatial knowledge acquisition. It is currently unclear, however, how wayfinding behavior and spatial knowledge acquisition in iVR differ from those in real-world environments (REs). We conducted an RE wayfinding experiment with twenty-five participants who performed a series of tasks. We then conducted an iVR experiment using the same experimental design with forty participants who completed the same tasks. Participants' eye movements were recorded in both experiments. In addition, verbal reports and postexperiment questionnaires were collected as supplementary data. The results revealed that individuals' wayfinding performance is largely the same between the two environments, whereas their visual attention exhibited significant differences. Participants processed visual information more efficiently in RE but searched visual information more efficiently in iVR. For spatial knowledge acquisition, participants' distance estimation was more accurate in iVR compared with RE. Participants' direction estimation and sketch map results were not significantly different, however. This empirical evidence regarding the ecological validity of iVR might encourage further studies of the benefits of VR techniques in geospatial cognition research. *Key Words: immersive virtual reality, indoor wayfinding, spatial knowledge acquisition, visual attention, wayfinding behavior.*

Wayfinding is a basic daily activity in indoor and outdoor environments. Elucidating human wayfinding behavior can improve our understanding of cognitive processes and spatial knowledge in an environment. The rapid development of virtual reality (VR) technologies, with a wide range of virtual environment setups from desktop to fully immersive, provides new experimental approaches for investigating wayfinding behavior and spatial knowledge acquisition (Darken, Allard, and Achille 1998; Gramann et al. 2005; Ehinger et al. 2014; Vilar, Rebelo, and Noriega 2014; Zhang, Zherdeva, and Ekstrom 2014; Coutrot et al. 2019). VR experimental designs provide controllable and convenient methods for elucidating the characteristics of human wayfinding behavior and spatial knowledge acquisition. Immersive VR (iVR) is particularly useful because it offers the possibility of conducting virtual experiments containing naturalistic sensory information, including visual, motor, proprioceptive, and vestibular changes from bodily movement, which are essential for spatial cognition (Grant and Magee 1998; Waller, Loomis, and Haun 2004; Riecke et al. 2010; Ruddle et al. 2011; Ruddle, Volkova, and Bülthoff 2011). Thus, iVR might reduce the gap between laboratory experiments and real-world environments (REs). However, because the ecological validity (Schmuckler 2001) of iVR in wayfinding remains poorly understood, it remains unclear whether people who navigate in iVR and RE settings exhibit the same wayfinding behavior and acquire equivalent spatial knowledge. Previous studies have shown that where and how we learn and explore spaces and environments influences our spatial knowledge acquisition (König et al. 2020). Therefore, revealing the similarities and

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differences of acquiring spatial knowledge after wayfinding in different environments could aid the application of iVR in the field of geospatial cognition.

In this study, we hypothesized that pedestrians in iVR would exhibit the same wayfinding behavior and obtain equivalent spatial knowledge compared with pedestrians in RE. To test this hypothesis, we conducted indoor wayfinding experiments in both RE and iVR setups. We used an eye-tracking approach to collect pedestrians' eye movement data during wayfinding. In addition, we conducted a retrospective verbal report protocol and postexperiment questionnaire to obtain supplementary information.

The remainder of this article is organized as follows. We first review previous wayfinding research in RE and iVR environments and mainstream research methods. We introduce the experimental design and data processing in RE and iVR environments following that. The results are then presented and comprehensively analyzed. We discuss wayfinding behavior and spatial knowledge and discuss possible explanations for our findings. Finally, we draw conclusions and outline future research possibilities.

Background and Related Work

Wayfinding Studies in iVR and RE

Wayfinding is an effective method for becoming familiar with a new environment. Throughout direct wayfinding, humans acquire spatial knowledge about the environment (Siegel and White 1975; Ishikawa and Montello 2006), developing a cognitive map of their surroundings (Wiener, Büchner, and Hölscher 2009). Numerous studies have revealed how people behave and what spatial knowledge they acquire during wayfinding processes in desktop virtual environments (DVEs; Meilinger, Knauff, and Bülthoff 2008; Weisberg et al. 2014; Weisberg and Newcombe 2016; Dong, Liao, et al. 2020), using the controllability of the experimental environment. In DVEs, however, users sense motion by perceiving visual information, but physical position movement is absent. As such, DVEs are considered to be inadequate for immersive wayfinding environments, and DVE users are often unable to clearly perceive temporal and spatial changes during wayfinding. Hence, wayfinding and navigation experiments in iVR, which enables greater immersion, have received substantial attention in recent years. The two main types of study in iVR are experiments revealing human wayfinding behavior (Török et al. 2018; H. Li et al. 2019) and experiments comparing the effects of different VR displays on wayfinding and spatial knowledge acquisition (Johnson and Stewart 1999; Ruddle, Payne, and Jones 1999; Ruddle, Volkova, and Bülthoff 2011; Egger 2016; Srivastava et al. 2019). No matter how realistic a virtual environment, however, differences between real-world and virtual environments are inevitable. In recent years, a substantial amount of wayfinding research has been conducted in RE settings (Liao et al. 2019; Bécu et al. 2020; Dong, Qin, et al. 2020; Stites, Matzen, and Gastelum 2020).

Overall, although wayfinding research has been conducted in both virtual environment setups (from desktop to fully immersive) and real-world setups, it remains unclear whether humans obtain equivalent spatial knowledge between iVR and RE. For virtual wayfinding research, there is no consensus regarding which types of setups enable participants to acquire more spatial knowledge (Zhao et al. 2020), although iVR setups can provide users with a 360° view of the environment, enabling them to obtain more sensory information. Many researchers have compared the cognitive processes and spatial knowledge acquisition between DVEs and RE. Ruddle, Payne, and Jones (1997) revealed that participants in DVEs ultimately developed near-perfect wayfinding abilities in a real building condition. Richardson, Montello, and Hegarty (1999) concluded that participants used similar cognitive mechanisms in spatial knowledge acquisition between RE and DVEs, although participants were more easily disoriented in DVEs. Conroy (2001) compared movement patterns and found that participants' movement through the DVE was analogous to their navigation in the RE. van der Ham et al. (2015) reported that participants in the RE performed better than those in DVEs in terms of route memory. In general, wayfinding in DVEs appears to be comparable to that in real-world settings but with reduced efficiency in some aspects (e.g., orientation and route memory). iVR settings provide a more authentic experimental environment, enabling more comprehensive investigation of wayfinding behavior and spatial knowledge acquisition. Few studies, however, have explored the ecological validity of iVR. In one study, Marín-Morales et al. (2019) reported that navigation in both environments involved significant differences only at the beginning of exploration. Therefore, to further investigate the ecological validity of iVR, this study sought to test the hypothesis that humans in iVR and RE exhibit the same wayfinding behavior and acquire equivalent spatial knowledge.

Wayfinding Behavior Research Methods

Traditional methods of exploring wayfinding behavior and spatial knowledge acquisition involve collecting behavioral data and testing hypotheses. Wayfinding behavior includes wayfinding efficiency (Zhou et al. 2020), wayfinding strategy (R. Li and Klippel 2016), working memory (Meilinger, Knauff, and Bülthoff 2008), visual attention (Dong, Liao, et al. 2020), user experiences (Kuliga et al. 2015), and other features (Conroy 2001). Spatial knowledge is often measured using distance and direction estimation and sketching maps of environments (Ishikawa and Montello 2006; König et al. 2019; Lokka and Çöltekin 2020). Behavioral tests, such as questionnaires and verbal protocols, are the most commonly used methods for examining pedestrians' behavior (Golledge et al. 1985; Hegarty et al. 2002; Ishikawa and Montello 2006). These methods have the advantage of easy data collection but are often conducted after, rather than during, the wayfinding process.

One potentially powerful methodological approach is to record brain activity during spatial navigation or wayfinding (Maguire, Nannery, and Spiers 2006; Spiers and Maguire 2007; Gramann et al. 2010; Zhang, Copara, and Ekstrom 2012; Epstein et al. 2017; Bellmund et al. 2018), which can reveal participants' internal representations of an environment. Because such methods are difficult to conduct in RE and iVR setups, however, little research has been conducted. Therefore, most previous studies using these methods in DVEs lack measures of visual, motor, proprioceptive, and vestibular changes related to bodily movement.

Eye tracking is also a useful method for examining human visual attention in studies of wayfinding, because the ways in which we perceive and understand the environment typically depend primarily on what we can see. High-quality eye movement data during wayfinding can be easily collected in virtual environments (Koletsis et al. 2017). To date, most wayfinding research using eye tracking has been conducted in DVEs (Andersen et al. 2012; Kiefer et al. 2017; Liao and Dong 2017). In recent years, the development of mobile eye trackers has enabled the collection of eye movement data in RE settings (Kiefer, Giannopoulos, and Raubal 2014; Wenczel, Hepperle, and von Stülpnagel 2017; Liao et al. 2019), more closely matching actual visual attention in wayfinding compared with laboratory settings. Eye-tracking technology has been widely used in the field of wayfinding but has rarely been applied to iVR or comparisons between RE and iVR. In addition, collecting eye movement data in two environment types under the same framework of analysis remains challenging.

In this study, we used eye-tracking technology in both environments to examine participants' visual attention while they found routes in the experimental area. At the same time, we recorded behavioral data (e.g., task performance and results, verbal report protocol, and postexperiment questionnaire) to comprehensively compare other types of wayfinding behavior and spatial knowledge acquisition, testing our hypothesis in more depth. This combination not only enabled examination of participants' spatial knowledge after wayfinding in the environment but also revealed their real-time spatial cognition and decision-making processes during the experiment.

Methods

Data Collection: Experiments in iVR and the RE

Participants. A total of sixty-five university students in two groups participated in the experiments. Of these, forty students participated in the wayfinding experiment in an iVR setting and twenty-five students participated in a wayfinding experiment in an RE setting. All participants were required to complete a questionnaire and several tasks to provide measures of basic information and spatial ability. Participants' background details are shown in Table 1. The two groups did not differ significantly in terms of basic characteristics (age, sex, discipline, and familiarity with the experimental area). All participants had normal or corrected-to-normal vision, and none of the participants had previous wayfinding experience in iVR. Spatial ability is a key factor affecting wayfinding behavior (Golledge 1999). To control for this factor, we assessed participants' spatial abilities using the Santa Barbara Sense of

Table 1. Participants' basic information

	Descriptive				Inferential	
	RE		iVR		t Test	
	M	SD	M	SD	t	p
Participants' age	22.04	1.457	22.55	1.358	1.432	0.157 (*ns*)
	Yes	No	Yes	No	Chi-square test	
					Value	p
Gender = male	4	21	10	30	0.737	0.391 (*ns*)
Discipline = geography	5	20	10	30	0.217	0.642 (*ns*)
Have visited the experimental area	6	19	9	31	0.020	0.889 (*ns*)
	M	SD	M	SD	t test	
					t	p
Santa Barbara Spatial Ability Scale	4.003	1.107	4.13	1.347	0.396	0.693 (*ns*)
Mental rotation	1.56	1.012	1.813	0.89	1.056	0.295 (*ns*)
Indoor spatial ability	4.04	1.351	3.906	1.343	0.390	0.698 (*ns*)

Note: RE = real-world environment; iVR = immersive virtual reality. *ns* = $p > 0.05$.

Direction Scale (Hegarty et al. 2002) and a test of mental rotation of three-dimensional objects (Shepard and Metzler 1971; see Figure S.1 in the supplemental materials). Because the Santa Barbara Spatial Ability Scale is mainly focused on large-scale outdoor environments, we created an indoor spatial ability questionnaire (see Table S.1) to further eliminate the effects of this factor. Questionnaire scores were not significantly different between the two groups. The university's institutional review board reviewed and approved the experiment. All participants provided written consent and were compensated 50 yuan (iVR) or 60 yuan (RE) for their participation.

Apparatus. In the iVR experiment, we employed an HTC Vive head-mounted display (HMD; HTC, Inc.; https://www.htc.com) with an embedded SMI VR Eye Tracker (Apple, Inc.; www.smivision.com) using a sampling rate of 90 Hz to record participants' eye movement. The Vive has 360° head tracking with a 110° field of view and a resolution of 2,160 × 1,200 pixels. A handheld joystick was used to move in the virtual environment. The HTC Vive HMD was connected to a laptop. The graphics card of the laptop was an NVIDIA GeForce GTX 1070 with 8 GB graphic memory. All equipment was placed in the laboratory to ensure constant light conditions and a noise-free environment. We used the Vizard engine (https://www.worldviz.com/vizard) to render, control, and record the virtual activity in the HMD. The specific movement mode and parameters were as follows: The ratio of physical space to virtual space was far less than 1. Therefore, we adopted a no-locomotion method (Zhao et al. 2020). Participants used joystick-based navigation to perform virtual activities. Physical body rotation controlled the wayfinding rotation in iVR; moving the joystick forward controlled forward movement, and moving the joystick left and right controlled slight shifts in position. The maximum speed for forward movement was 1.8 m per second, which is a little greater than a typical walking speed, to simulate pedestrians finding the destination as quickly as possible. These settings meant that the walking speed in the RE and iVR experiments was relatively consistent.

In the RE experiment, we used SMI eye-tracking glasses (ETGs; Apple, Inc.; https://www.smivision.com) with a sampling rate of 60 Hz to record participants' eye movement. The ETGs had typical tracking accuracies of 0.5° and 80° horizontal and 60° vertical tracking ranges. A forward-scene camera embedded in the ETG device recorded synchronous scene videos during wayfinding.

Experimental Areas and Materials. The experimental area was located in the main building of the university where the authors are affiliated. The main building was divided into two zones (Zone A and Zone B), connected via a footbridge on the fourth floor. We selected the third and fourth floors of the main building as the experimental area. Several administrative offices and conference rooms were located in this area. The floor plans of the third and fourth floors of the main building are shown in

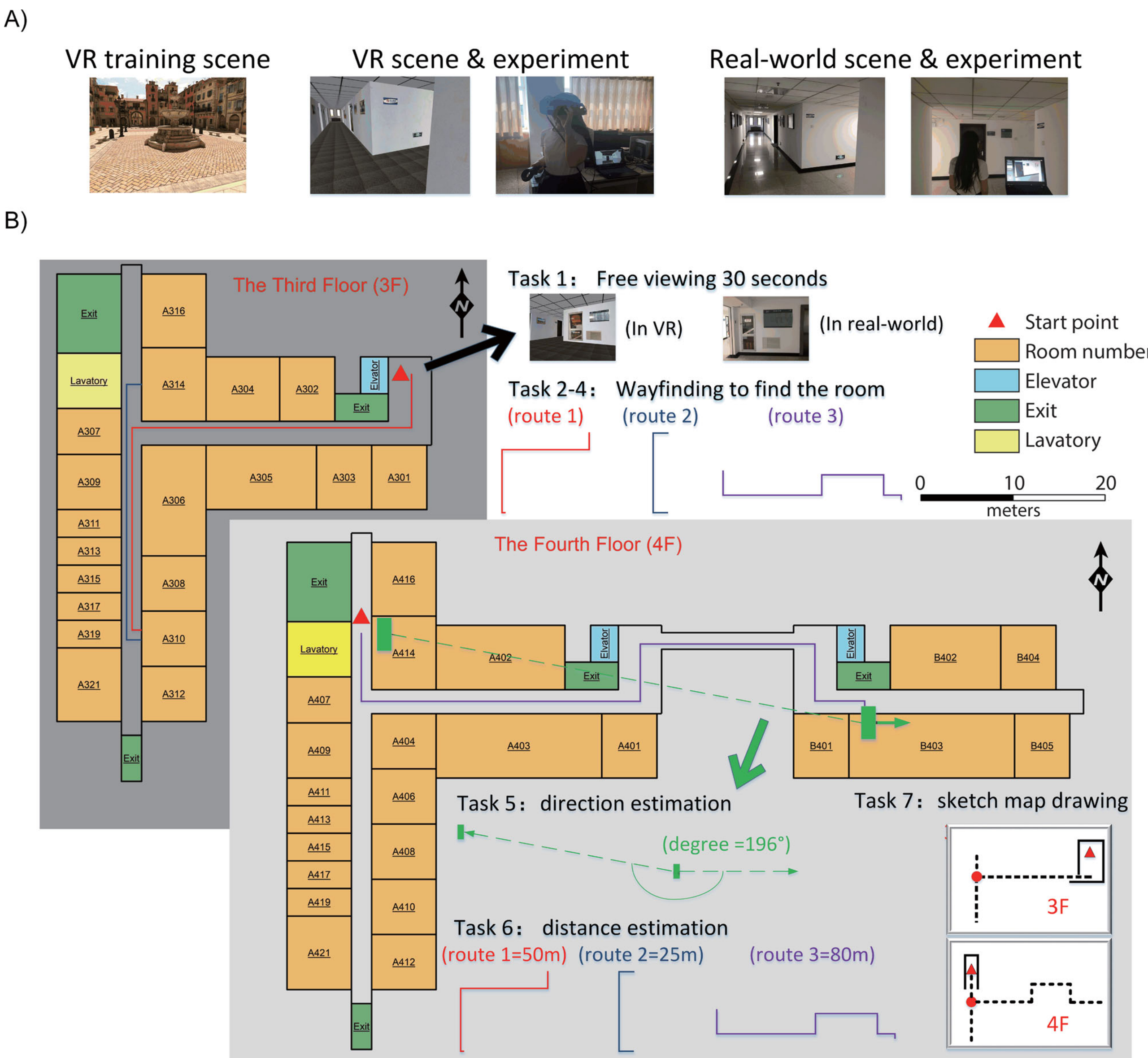

Figure 1. Floor map of the experimental area: (A) Experimental setup; (B) Experimental procedure. *Note:* VR = virtual reality.

Figure 1. For the iVR experiment, we built a three-dimensional model to simulate the real experimental area (with the same size) using Trimble Sketch Up (Trimble Inc. 2020) and pasted photographs onto the model.

Procedure. For the iVR experiment, after welcoming the participants and briefly introducing the experiment in the laboratory, we helped participants put on the VR helmet and conducted five-point calibration to ensure tracking accuracy. Participants were first brought into a virtual scene (Figure 1) to become familiar with the VR environment and movement operations. These steps took approximately five minutes. After this preparation, we presented the starting point on the third floor in the experimental scene to participants via the Vizard engine. Participants were required to complete the first set of tasks (Table 2) in the iVR environment, including one free viewing task and three wayfinding tasks. Subsequently, participants removed the VR equipment and finished the second set of tasks (Table 2) in the laboratory, including distance estimation, direction estimation, and sketch mapping tasks. The entire formal experiment took approximately thirty minutes.

The RE experiment was conducted inside a real building. We briefly introduced the experiment on the first floor and then helped participants put on

Table 2. Instructions for the tasks

Phases of the experiment	Task	Type
Wayfinding in the environment	Task 1	Free viewing of the environment
	Task 2	Wayfinding to Room A310 (Route 1)
	Task 3	Wayfinding to conference room 3 (Route 2)
	Task 4	Wayfinding to Room B403 (Route 3)
Spatial knowledge acquisition	Task 5	Direction estimation
	Task 6	Distance estimation
	Task 7	Draw a sketch map of the third and fourth floors' structure
	Task 8	Verbal report protocols about cognitive process
	Task 9	Postexperiment questionnaire

the ETGs and conducted a calibration procedure. After the preparation, we guided participants to the starting point on the third floor by taking the elevator. Participants were also required to finish two sets of tasks (Table 2) that were the same as in the iVR experiment. The specific tasks of the experiment were as follows:

1. *First set of tasks (wayfinding in the environment)*. The first set of tasks included free viewing and exploring novel destinations in the building (Allen 1999). We prepared a whiteboard with specific instructions for each task. At the beginning of each task, we presented the instructions to participants on the whiteboard. For example, the instructions for Task 2 were as follows: "Please start here and search for Room A310. Please tell me when you are ready, by saying 'start.' When you are sure of your destination, say 'I've found it.'" When the task began, participants did not receive any instructions or help. Participants in both environments were required to complete the following tasks in sequence. (1) Stand at the starting point to view the environment for thirty seconds. Participants were reminded to take note of information about conference room 3 (Task 1). (2) Explore from the starting point to find Room A310 on the third floor as quickly as possible (Task 2). (3) Explore from Room A310 to find conference room three on the third floor as quickly as possible (Task 3). (4) Explore from the starting point on the fourth floor to find Room B403 on the fourth floor as quickly as possible (Task 4). In the RE condition, we guided participants through the stairs to change the floors, whereas in the VR setup, we loaded different scenes to change floors. We informed participants that zones A and B were connected through an indoor overpass. It should be noted that the room number of conference room 3 (A314) was hidden in this task; however, this information could be found on the floor information board in Task 1. Participants did not know what the next task would be when they were performing the current task, and no external help or tips were provided.
2. *Second set of tasks (spatial knowledge acquisition)*. After completing the first part of the task, participants in the iVR setting removed the HTC Vive HMD and returned to the laboratory; participants in the RE setting removed ETGs and were guided to a meeting room on the first floor of the experimental building. Participants were asked to complete three tasks regarding spatial knowledge of the experimental environment in the laboratory (iVR) or meeting room (RE). We also prepared a whiteboard containing several questions for each task (Tasks 5–8) and a questionnaire (Task 9). Specifically, in the direction estimation measurement, we did not consider Routes 1 and 2 (the third floor) because the route directions are visible. For the fourth floor, we defined the east direction of the B403 corridor as the standard direction and required participants to estimate how many degrees (0°–360°) of clockwise rotation from that direction would be required to face the starting point on the fourth floor (Task 5); in distance estimation measurement, participants were required to estimate the shortest route path distance of the three sections (Section 1, from the starting point of the third floor to Room A310; Section 2, from Room A310 to conference room 3; Section 3, from the starting point on the fourth floor to Room B403; Task 6). Participants were asked to try their best to draw a sketch map of the third floor and fourth floor structures by hand, using the drawing panel provided (Task 7). In addition, participants were required to review the first part of the experiment (wayfinding videos) via a laptop and recall their visual attention during the wayfinding process. We conducted structural interviews and recorded participants' verbal reports with a mobile phone in MP3 format, to provide insight into participants' thoughts using a verbal report method (Task 8). Finally, all participants completed a postexperiment questionnaire about their experience of the experiment (Task 9).

Data Processing and Analysis

Data Quality Check. For the real-world condition, three data sets (one participant in Task 2 and two participants in Task 3) were excluded because of poor video recording quality (not suitable for drawing areas of interest [AOIs] to label landmarks for fixation). All other participants' data were valid and were included in the analysis. For the iVR experiment, three participants developed severe dizziness during Task 4 and requested to stop the experiment. Therefore, their direction and distance (route 3) data were missing. These three participants did not draw sketch maps of the environment. All other participants' data were valid. During preprocessing, outliers in the raw data were excluded empirically based on the following rule:

$$\text{Outliers} = \text{data} \;\; (\text{if } |\text{data} - \text{Mean}_{\text{data}}| \geq 2 \times \text{SD}_{\text{data}}). \quad (1)$$

Analysis Framework. To comprehensively compare human wayfinding behavior and spatial knowledge acquisition, we developed an analysis framework (as shown in Figure 2). For wayfinding behavior, we investigated wayfinding performance and user experiences via wayfinding tasks, eye-tracking experiments, structural interviews, and a postexperiment questionnaire in both environments. For spatial knowledge acquisition, Siegel and White (1975) proposed a spatial knowledge acquisition framework following a hierarchical structure: The first level is landmark knowledge, the second level is route knowledge, and the third level is survey knowledge. Montello (1998) challenged this framework, proposing that spatial knowledge acquisition is a continuous process. In this study, we used direction and distance estimation and sketch mapping results as measures of spatial knowledge acquisition. Regarding the method of comparative analysis, we conducted statistical tests between two environments. For numerical variable data, we used Wilcoxon rank sum tests (single factor [environment]) or Scheirer–Ray–Hare (SRH; Scheirer, Ray, and Hare 1976) tests (two factors [environment and route]), because the data were not normally distributed. For categorical variable data (verbal report results), we used chi-square tests. The specific metrics and analysis process of the two parts are described in the following sections.

Wayfinding Behavior. We recorded participants' behavioral performance in wayfinding tasks, using wayfinding time and the number of wrong decisions metrics. Wayfinding time (in seconds) provided a better reflection of participants' wayfinding efficiency when the two environments were the same size, and walking speed in iVR wayfinding was similar to that in the RE setting. Wrong decisions (when participants chose wrong routes or directions compared with the shortest route) were used to reflect wayfinding effectiveness.

In addition, we designed the questionnaire (Table S.2) to investigate users' experiences of the task. The first part of the questionnaire was about participants' evaluation of task difficulty and self-expression in the two environments. The second part was only conducted with participants in the iVR setting. They were asked to subjectively appraise their sense of authenticity and satisfaction of wayfinding in iVR. In addition, we conducted a structural interview for collecting each participant's verbal reports. Participants were required to review the first part of the experimental video and answered questions about wayfinding.

To investigate participants' visual attention to environments and landmarks, we exported all raw eye data (gaze point) for both the RE and iVR experiments. We then identified fixations using the I-VT algorithm (Salvucci and Goldberg 2000), and the velocity threshold was set to 30° per second. There are two types of metrics of visual attention to environments: information processing and information searching metrics. We used six quantitative eye movement metrics, which have been commonly used in visual behavior research (Liao et al. 2019; Dong, Yang, et al. 2020).

1. Visual information processing metrics.

   - *Average fixation duration (AFD, in milliseconds):* Average duration of all fixations. Participants were driven by the cognitive task in wayfinding. Longer AFD reflects greater difficulty interpreting visual information (Antes, Chang, and Mullis 1985).
   - *Fixation frequency (FF; fixations per second):* The number of fixations per second. Because visual information processing occurs during fixation, a higher FF implies greater efficiency of visual information processing.

2. Visual information searching metrics.

   - *Average saccade duration (ASD, in milliseconds):* Average time period of movement of eyes from

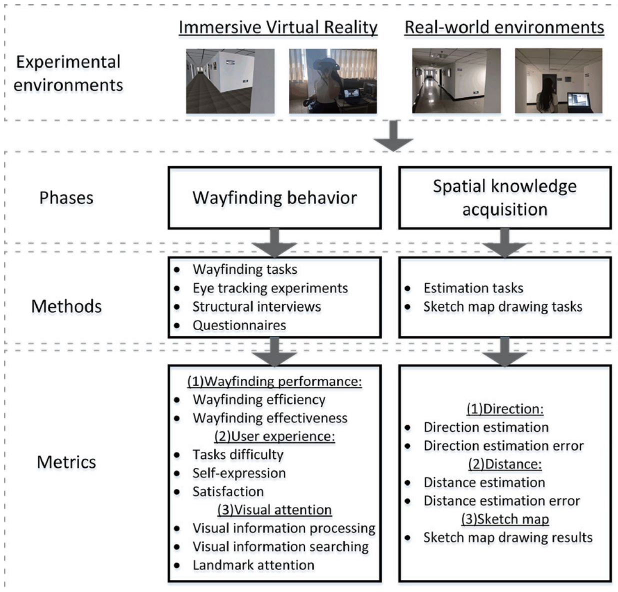

Figure 2. Analysis framework.

one fixation to another; a longer ASD indicates a longer time for visual search.

- *Saccade frequency (SF; saccades per second):* The number of saccades per second. A higher SF implies greater efficiency of visual information search (Garlandini and Fabrikant 2009).
- *Average saccade amplitude (ASA; degrees):* Average length of saccade in degrees; a greater ASA indicates a wider range of visual search.
- *Average saccade velocity (ASV; degrees per second):* Average velocity of current saccade in degrees per second, which was affected by the intrinsic value of visual information (Xu-Wilson, Zee, and Shadmehr 2009).

Landmarks are objects that stand out in the surrounding environment. They are frequently used as aids or guides for route planning, particularly in indoor wayfinding, considering that Global Positioning System and electronic maps are unavailable in most indoor environments. In this study, we used the room numbers and signs on the wall as landmarks because they contained rich semantic information and directly helped participants complete the wayfinding task.

Labeling semantic information to a fixation point can be challenging. Common methods include manually drawing AOIs or conducting semantic video segmentation (Dong, Liao, et al. 2020). The former method can provide better accuracy but is time-consuming; the latter method improves efficiency through deep learning, but the accuracy is lower than that of manual processing. In our study, for the iVR experiment, we recorded the landmarks corresponding to the gaze points by calculating the intersection of the gaze point and the environment model (each landmark in the VR model had a unique ID), which ensured the accuracy of gaze point labeling. To ensure comparability between the two environments, we manually drew the AOI in the RE setting to label the fixation point. After labeling, we used three metrics to represent visual attention to landmarks.

- *Number of participants who fixated on the landmark (NPFL; participants who fixated on the landmark/all participants):* The higher the NPFL, the more participants paid attention to this landmark.
- *Average fixation count on the landmark (AFCL; total number of fixations on the landmark/total participants):* The higher the AFCL, the more attention participants paid to this landmark.
- *Average fixation duration on the landmark (AFDL; total fixation duration on the landmark/total fixation count on the landmark):* This metric reflects the difficulty of interpreting landmark information. The higher the AFDL, the more difficult it was for participants to interpret the information.

Spatial Knowledge Acquisition. Cognitive maps represent the most advanced level of spatial representation and integrated knowledge about the environment. Direction and distance estimation, as an important metric in cognitive maps, reflect a person's survey knowledge of the environment. In this study, we used four metrics to represent participants' direction and distance estimation performance.

- *Absolute value of direction estimation (degrees):* Estimation of degrees, ranging from 0° to 360°. The truth value (azimuth angle between B403 office and the fourth floor start point) was 193°.
- *Direction estimation error (degrees):* Absolute value of the difference between the true value and the estimated value.
- *Absolute value of distance estimation (m):* The estimation of the shortest routes in Tasks 2 through 4. The truth values were 50 m, 25 m, and 80 m, respectively.
- *Distance estimation error (m):* Absolute value of the difference between the true value and the estimated value.

In addition, sketch mapping has been confirmed as a valid measure of internal cognitive maps (Billinghurst and Weghorst 1995). We prepared a sketching panel (Figure 3A) for participants. Participants were instructed to draw the indoor layout (i.e., the routes and corridors in indoor environment) as completely as possible, and route direction was used as the only criterion for judging whether the drawing routes were correct. The distance and length of the routes were not considered. The third-floor structure consisted of three sections and the fourth-floor structure consisted of seven sections (Figure 3B). Three drawing examples are shown in Figures 3C, 3D, and 3E. The black dotted line indicates the correct sections, and the red dotted line indicates the incorrect sections.

Results

Our experimental results are presented next, organized in accord with our analysis framework.

Wayfinding Efficiency and Effectiveness

Wayfinding performance results are shown in Figure 4 (see also Table S.3). The SRH test results revealed that wayfinding performance was influenced by the route, which indicates that three routes in our experiment were distinct and had validity. Participants in the iVR condition spent more time during Routes 1 through 3 compared with those in the RE setting ($p = 0.004$). This finding indicated that participants in RE exhibited greater wayfinding efficiency than in iVR. It should be noted, however, that participants in both groups took a similar average time in route 3. The results indicated that indoor wayfinding efficiency might be closer between two environments with increasing experimental time in iVR. Regarding the number of wrong decisions metrics, however, there were no environmental effects. This finding suggests that wayfinding effectiveness in the two environments showed no significant differences.

User Experience

The postexperiment questionnaire results are summarized in Tables S.5 and S.6. We found that iVR participants reported feeling more positive about the sketch map task and found it easier to perform compared with participants in the RE condition. Their performance, however, was no better than that of participants in the RE condition. This finding indicates that drawing sketch maps might involve different user experiences in different environments. In addition, 97.5 percent of iVR participants believed that the iVR experimental setting was very similar to a real-world situation, and 90 percent of iVR participants felt that the effects of the experiment in the two environments were similar. Only 37.5 percent of iVR participants preferred performing wayfinding experiments in iVR, though. The results revealed that the user experience of iVR wayfinding was relatively realistic but satisfaction was poor. Unfamiliarity and dizziness in the VR setting were reported as the main reasons for this preference.

In addition, we used a verbal report measure (Figure 5 and Table S.4) to examine participants' subjective experiences of wayfinding in the two environments. The answers to Questions 1 and 2 revealed that, in the free-viewing task (Task 1), participants tended to focus on the surrounding environment in the RE task, whereas participants in the iVR task attended to signs ($\chi^2 = 5.724$, $p = 0.057$). This led more participants in the iVR condition to find the room number corresponding to conference room 3 compared with participants in the RE condition. Questions 3 through 8 corresponded to Tasks 2 through 4, and participants' responses were generally similar in both environments. Specifically, participants paid attention to landmarks during wayfinding, making decisions according to the information signs at the T-shaped decision points on the third and fourth floors. Participants concentrated on finding the footbridge and roads to Zone B instead of the landmarks of Zone A. Interestingly, more participants in the RE condition looked at the mural hanging on the wall compared with iVR participants ($\chi^2 = 4.364$, $p = 0.037$), which was irrelevant to the wayfinding process.

Visual Attention to the Environments and Landmarks

Figure 6 and Tables S.7 and S.8 show participants' visual attention to the environments, analyzed using the SRH test. Surprisingly, we found that participants exhibited higher AFD and lower FF in iVR (AFF = 231.84 ms [iVR], 224.49 ms [RE]; FF = 2.57 fixations/second [iVR], 3.11 fixations/second [RE]), which indicates that it was more difficult and less efficient to process visual information in the iVR condition compared with the RE condition in wayfinding. Conversely, participants in the iVR setting performed better in visual information search than participants in the RE setting. iVR participants

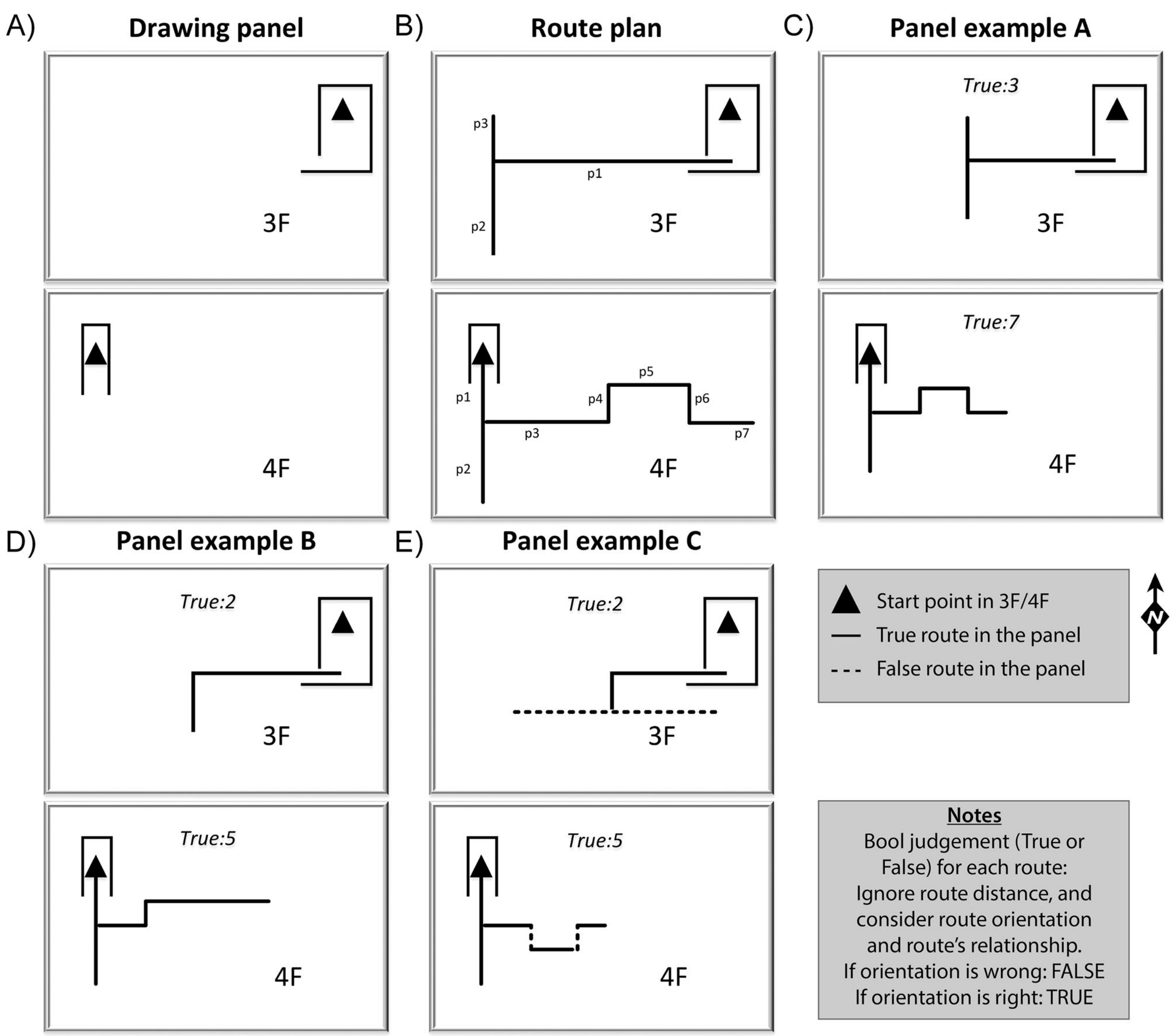

Figure 3. Sketching panel: (A) The drawing panel for participants; (B) the standard answers used to judge performance; and (C), (D), and (E) three examples explaining how the sketch mapping results were judged. *Note:* 3F = third floor; 4F = fourth floor.

searched information more efficiently (ASD = 46.77 ms [iVR], 29.74 ms [RE]; SF = 5.83 saccades/second [iVR], 5.19 saccades/second [RE]) and in a wider range (ASA = 9.12 [iVR], 6.55 [RE]). This finding indicated that participants in the two environments exhibited different visual behaviors, potentially affecting their route search and learning processes.

Furthermore, a total of twenty-two landmarks on the third floor were used for analysis. The results are shown in Figure 7 (Table S.9). Three metrics of visual attention to landmarks exhibited no significant difference in Wilcoxon rank sum tests (for NPFL $p = 0.424$ [Task 2], $p = 0.161$ [Task 3]; for AFCL $p = 0.062$ [Task 2], $p = 0.975$ [Task 3]; for AFDL $p = 0.280$ [Task 2], $p = 0.294$ [Task 3]). Furthermore, in both environments, participants paid less attention to landmarks as they became more familiar with the environment. All eye movement metrics in Task 3 (Figure 7B) were lower than those in Task 2 (Figure 7A). This finding indicates that participants acquired most landmark knowledge when they toured the environment for the first time.

Figure 7 shows the spatial distribution of the landmark fixation results. We found that, at the beginning of Task 2, participants in the iVR condition paid attention to landmarks on both sides of the corridor. More participants paid attention to landmarks on the right side after passing the decision point, possibly because the right-side landmarks had the

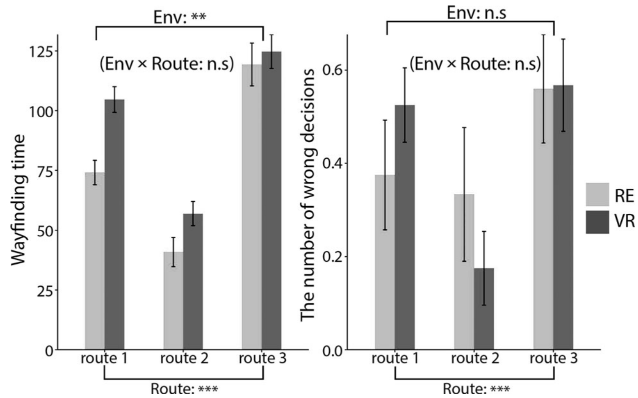

Figure 4. Wayfinding performance in two environments. All metrics were subjected to a two-factor (environment × route) significance test. The metric was the presence of a significant difference ($^{+}p < 0.1$. $^{*}p < 0.05$. $^{**}p < 0.01$. $^{***}p < 0.001$) or absence of a significant difference (ns = $p > 0.1$). *Note:* RE = real-world environment; VR = virtual reality.

same type of room number as room A310 (i.e., an even number). More participants in the RE focused on landmarks on the left side at the beginning, however. It is possible that this occurred because participants first looked at the landmarks on the left side and the beginning room numbers were far from the destination, leading them to ignore the information on the right side. Conversely, participants in the iVR condition might have searched for more information because the wayfinding setting was more unfamiliar. The landmarks that attracted most attention in both environments were the information signs at T-shaped decision points. After making their decisions, participants in both environments paid more attention to landmarks on the left side of the corridor. For landmarks on the right side of the corridor, participants glanced at a few landmarks closer to them and then their interest waned.

Spatial Knowledge Acquisition

Table S.10 shows participants' spatial knowledge acquisition results. Figure 8A shows the distribution of direction and distance estimates by participants in different environments; the red dotted line represents the true value. For direction estimation, we found no significant differences of estimated values and errors between the RE and iVR settings. A one-sample t test showed that participants' estimated directions in two environments have no significant differences with the true direction: iVR, $t(37) = 1.30$, $p = 0.20$, 95% confidence interval (CI) [188.52, 230.02]; RE, $t(25) = -0.23$, $p = 0.82$, 95% CI [163.89, 221.71]. For the distance estimation, however, participants in the iVR condition estimated the distance as shorter ($p = 0.02$) compared with participants in the RE condition. Specifically, the one-sample t test confirmed that participants in RE estimated distances were significantly not equal to 50 m (Route 1), $t(25) = 2.17$, $p < 0.05$, 95% CI [50.91, 87.65]. Their estimated distances were not significantly equal to 25 m (Route 2), $t(25) = 1.86$, $p = 0.075$, 95% CI [23.55, 52.29]. Their estimated distances were not significantly equal to 80 m (Route 3), $t(25) = 2.71$, $p = 0.01$, 95% CI [94.41, 186.38]. The one-sample t test did not show a significant difference between iVR participants' results and true distance, however: for Route 1, $t(40) = -0.76$, $p = 0.45$, 95% CI [35.25, 56.70]; for Route 2, $t(37) = 1.23$, $p = 0.23$, 95% CI [21.54, 39.21]; for Route 3, $t(37) = 1.36$, $p = 0.18$, 95% CI [70.23, 129.61]. Therefore, the results showed participants in the iVR condition estimated distance more closely to the true value than participants in RE. Interestingly, most participants substantially overestimated the route distance in the RE, but participants estimated the distance more conservatively in iVR. In conclusion, iVR participants estimate distances more accurately than those in the RE.

For the sketch mapping task, the only significant difference was that participants drew an average of 2.32 correct sections ($SD = 1.03$) in the RE condition and an average of 1.59 correct sections ($SD = 1.48$) in the iVR condition (third floor sketch map, $p = 0.02$). There were no significant differences between the drawing results for the fourth floor or the two floors together. Figure 8B shows the distribution of correct sections in participants' sketch maps in different environments. Performance in the iVR condition was relatively moderate; many participants produced good, medium, and poor drawing results, and the overall density curve was flat. Most participants in the RE condition, however, produced results that were biased toward the median value; relatively few participants exhibited good and poor results, and the density curve fluctuated more compared with the iVR group.

Participants in the iVR condition performed better than those in the RE condition in distance estimation, and there were no significant differences between direction estimation and sketch mapping. We conducted Pearson's correlation analysis to

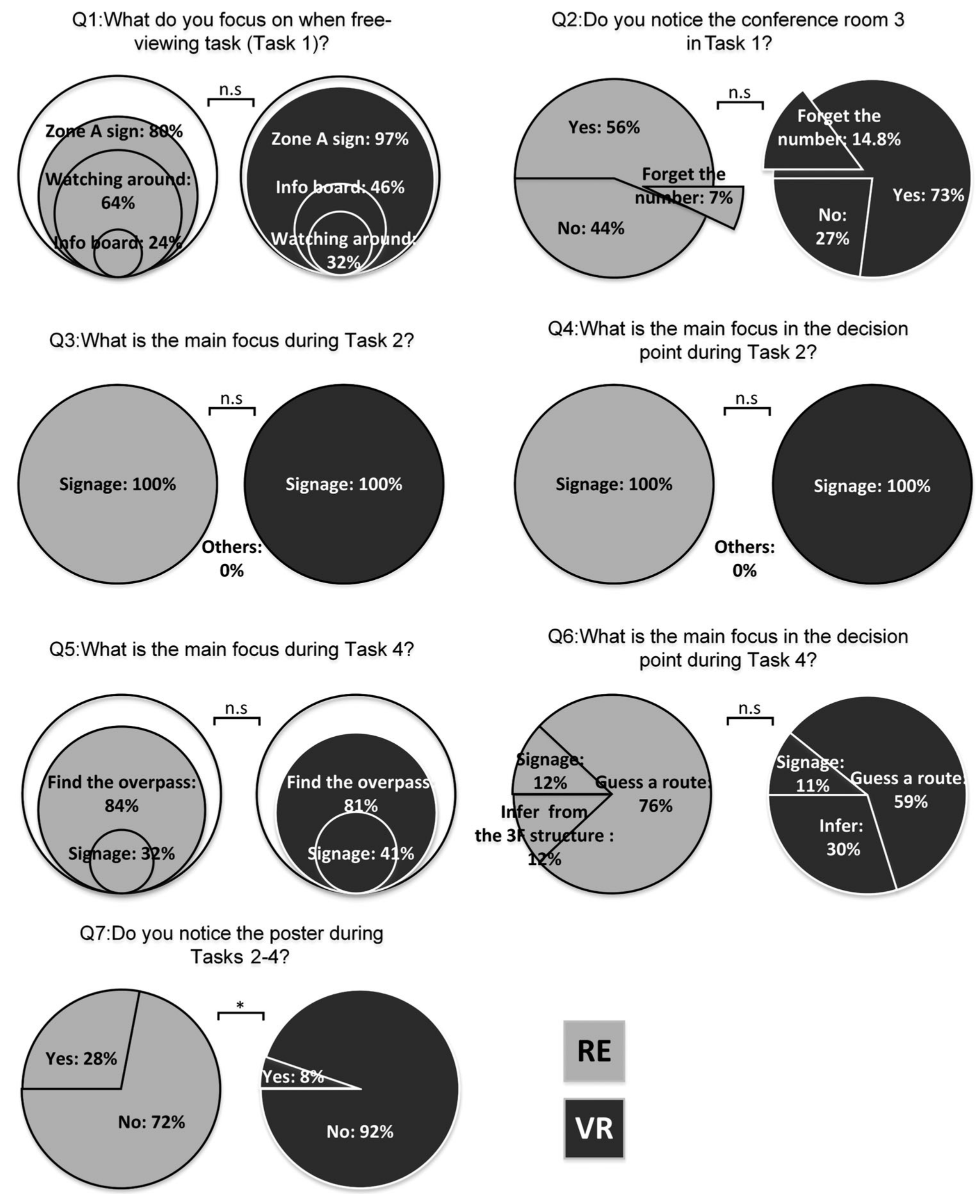

Figure 5. Verbal report protocol results. Seven question-and-answer results were quantified via pie charts. Results were subjected to a chi-square test. The result of interest was the presence of a significant difference ($*p < 0.05$) or absence of a significant difference ($ns = p > 0.05$). *Note:* RE = real-world environment; VR = virtual reality.

explore correlations in participants' spatial knowledge. Specifically, we used direction and distance estimation error to represent participants' direction and distance knowledge. The correlation coefficient results (Figure 8C) revealed that distance and direction were weakly negatively correlated with sketch map performance. This finding was in line with our expectations; the worse the estimated performance in the distance or direction (higher values), the worse the sketch map performance (lower values). The distance estimation and sketch map performance for different routes were strongly positively correlated, which shows that participants acquired similar spatial knowledge on different routes. Distance and direction estimation performance did not appear to be correlated, however.

Discussion

Differences between Two Environments

Participants Exhibit Different Visual Attention during Route Learning. During the route learning and wayfinding process, we found that participants

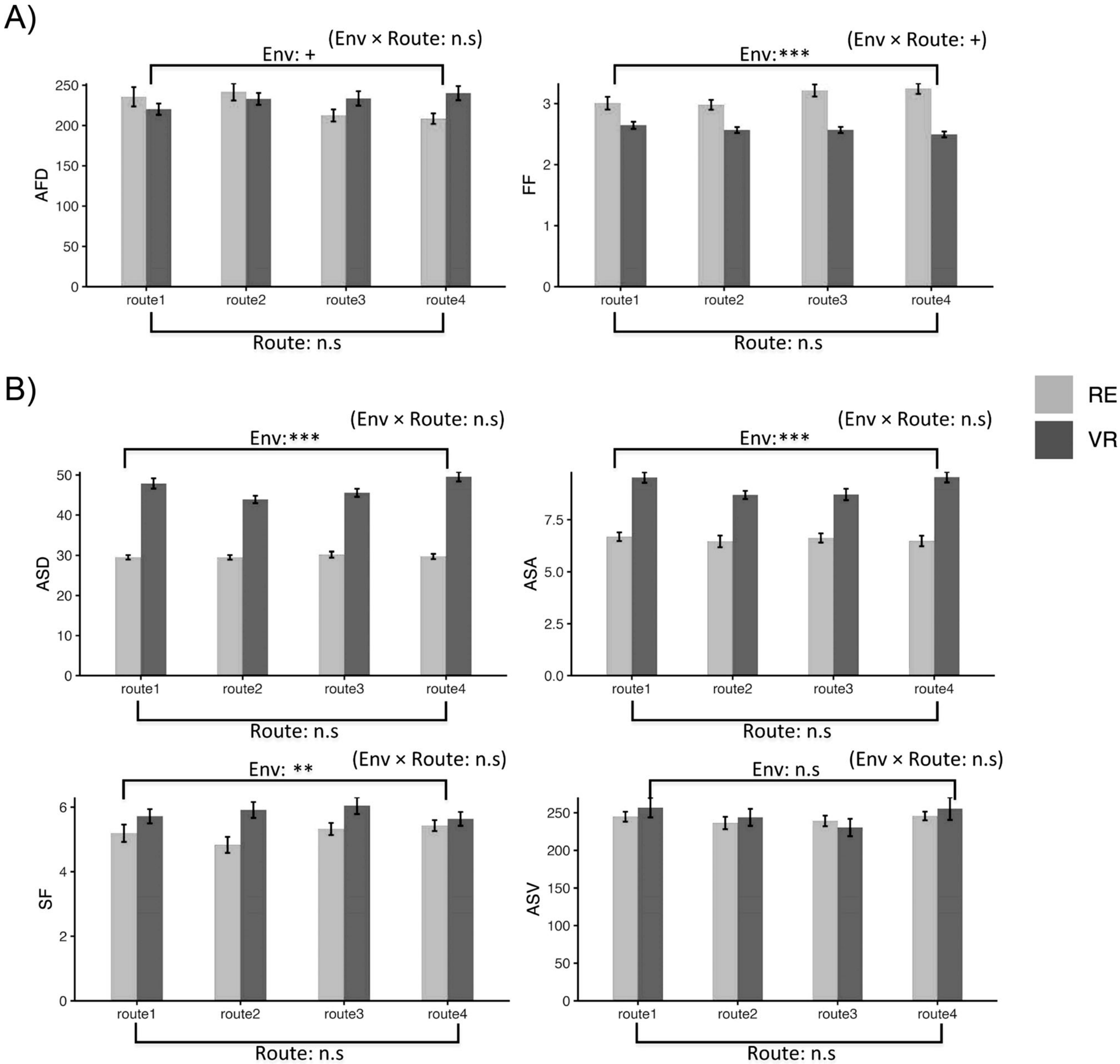

Figure 6. Visual attention in two environments: (A) Participants' visual information processing and (B) participants' visual information searching. All metrics were subjected to a two-factor (environment × tasks) significance test. The metric of interest was the presence of a significant difference ($^{+}p<0.1$. $^{*}p<0.05$. $^{**}p<0.01$. $^{***}p<0.001$) or the absence of a significant difference ($ns = p>0.1$). *Note:* RE = real-world environment; VR = virtual reality.

in the iVR condition performed better in visual information search, whereas participants in the RE condition performed better in visual information processing. In iVR, participants were able to search for targets more quickly and extensively (e.g., landmarks), but in the processing of visual information, efficiency was lower than in the RE condition. This might be because information in VR environments is less realistic compared with RE and therefore requires more time and effort to extract useful information. In addition, Lessels and Ruddle (2005) found that participants who were restricted to forward movement visited fewer objects than those with more flexible movement, which could partially explain these results. Participants' movements in the RE were restricted in our experiment, because the mobile eye tracker was physically connected to a laptop. Participants in the RE condition were focused on forward movement and exhibited greater efficiency in processing visual information.

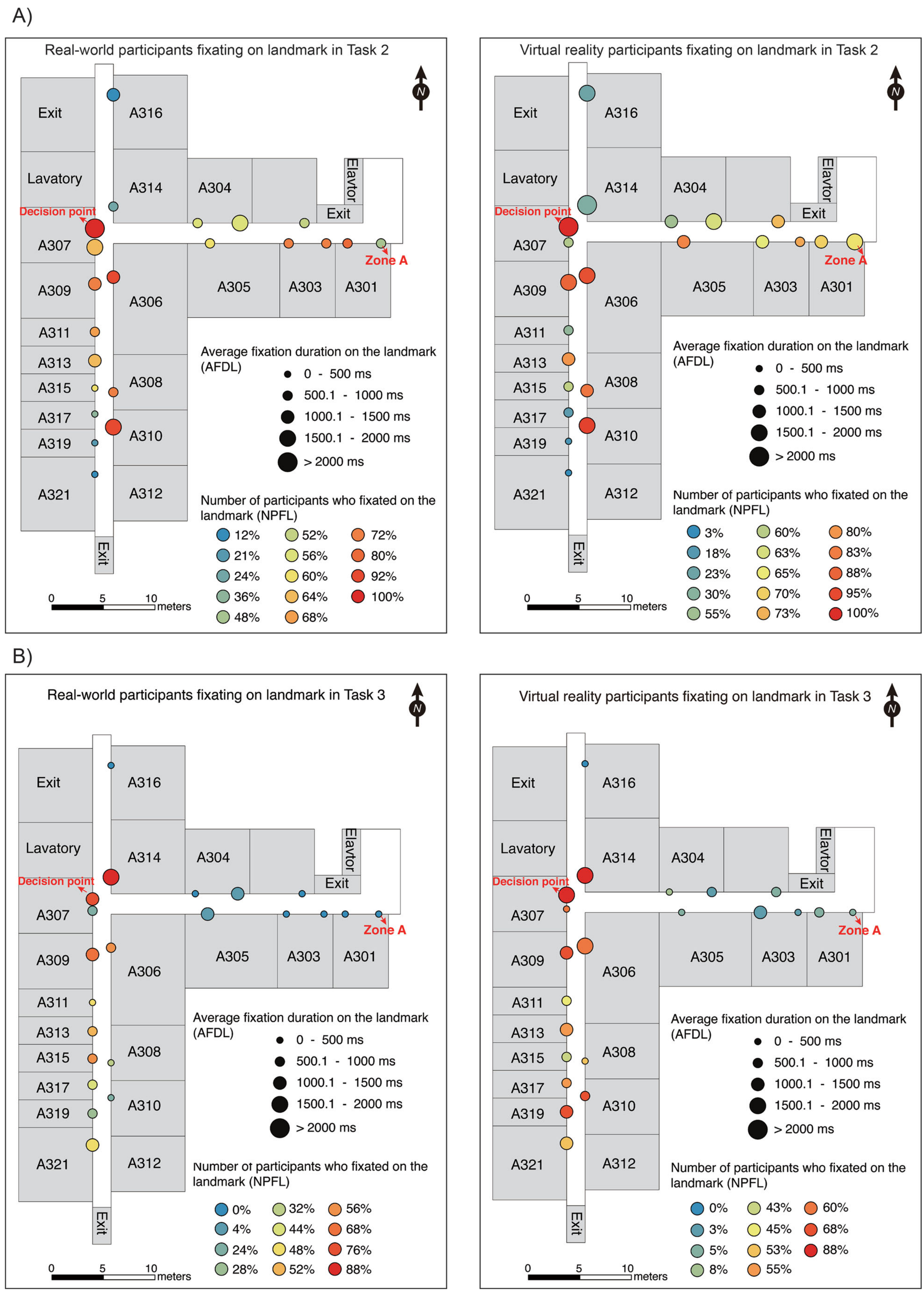

Figure 7. Landmark analysis in two setups: (A) wayfinding in Task 2; (B) wayfinding in Task 3.

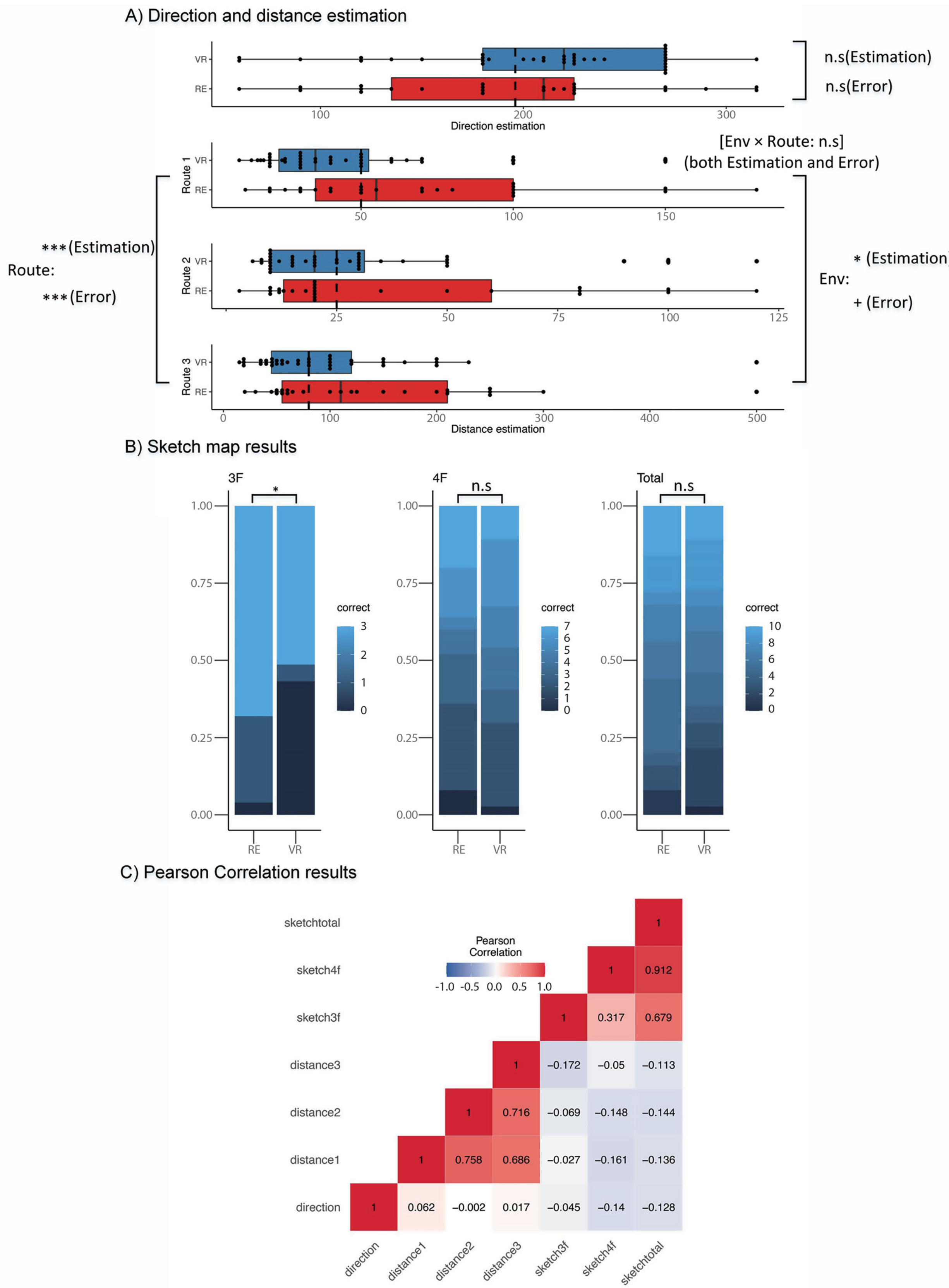

Figure 8. Spatial knowledge acquisition results in two setups: (A) Direction estimation and distance estimation distribution. The dotted line represents the truth value in each task. (B) Sketch mapping distribution. All metrics were subjected to a two-factor (environment × route) or one-factor (route) significance test. The metric of interest was the presence of a significant difference ($^{+}p < 0.1$. $^{*}p < 0.05$. $^{**}p < 0.01$. $^{***}p < 0.001$) or the absence of a significant difference ($ns = p > 0.1$). (C) Pearson's correlation coefficients for three types of spatial knowledge. *Note:* RE = real-world environment; VR = virtual reality; 3F = third floor; 4F = fourth floor.

Conversely, participants in the iVR condition moved more freely and easily, resulting in greater efficiency in visual information search.

According to the verbal report results, participants in the iVR condition searched for landmarks in the free viewing task (Task 1) and during wayfinding (Tasks 2 and 3), ignoring other objects in the environment. Conversely, participants in the RE setting were distracted by other objects in the environment, such as wall murals (irrelevant information). This finding implies that participants in the iVR were more purpose-driven. The iVR is substantially simplified compared with a real environment and might allow participants to focus more on searching for landmarks. Moreover, there are many uncertain factors in the RE, which could cause participants to be distracted by other objects. According to visual guiding roles of landmarks in indoor wayfinding (Dong, Qin, et al. 2020), this result might have arisen from differences of landmark salience in the two environments.

Participants in iVR Estimate Distance More Accurately. Estimating distance based on wayfinding time and speed in a virtual environment appears to be difficult, particularly when handheld joysticks are used to replace walking. Previous studies have reported that, in a VR environment, egocentric distance is generally underestimated, reported as being less than the distance in the model (Renner, Velichkovsky, and Helmert 2013). Interrante, Ries, and Anderson (2006) reported that distance perception was similar in iVR and RE. Interestingly, in this study, participants in both environments were prone to overestimating distance. Participants in the iVR condition, however, estimated distance more accurately, exhibiting a smaller estimation discrepancy for route distance compared with participants in the RE condition. There are at least two potential explanations for this finding. First, the usual process of distance perception involves the estimation of the time spent on wayfinding and the wayfinding speed. We initially asked participants to estimate the shortest route path distance. Many participants made incorrect decisions during wayfinding, however, causing their actual route path distance to be longer. Participants were inclined to overestimate the distance because of the increasing amount of time spent wayfinding. Second, we set a maximum speed (1.8 m per second, which was slightly higher than normal walking speed) in the iVR condition. Participants in the iVR condition easily reached the maximum speed (holding the joystick in the forward position, without loosening it) and were likely to have maintained this speed to finish the tasks, aiming to perform wayfinding as quickly as possible. Not every participant in the RE condition reached a similar maximum speed as those in the iVR condition, however. The participants in the RE condition wore the mobile eye tracker and were physically connected to the experimenter's laptop. Hence, the movement conditions in the two experiments cannot be guaranteed to be totally identical, which is limited by both the apparatus in RE and the movement mode in iVR. These factors could have caused differences in the results and affected their distance cognition. Overall, there are substantial individual differences in distance cognition, particularly for indoor route distance. The development of methods for presenting similar movement and speed perception in RE and iVR would enable further exploration of distance cognition.

Similarity between the Two Environments

Participants in the iVR Condition Exhibited Similar Overall Wayfinding Performance. Although the efficiency of wayfinding (wayfinding time) in the RE was higher than that in iVR, examining Task 4 alone revealed little difference in wayfinding time or efficiency between the two environments (wayfinding time = 124.76 s [iVR], 119.31 s [RE]). In addition, participants' wayfinding effectiveness (wrong decision times) was similar in both environments. This finding indicates that wayfinding performance in iVR might be related to familiarity with the iVR environment. Because daily life takes place in an RE setting, people might be more familiar with real-world experimental settings, adapting more quickly and easily. Importantly, because our participants had never experienced wayfinding in an iVR setting before, they might be expected to exhibit lower wayfinding efficiency than participants in the RE condition. The results indicated, however, that they were able to perform wayfinding with similar efficiency and effectiveness to that of participants in the RE as they became familiar with the iVR setup. In addition, our findings suggest that the results of previous studies of wayfinding in virtual environments might be time dependent (Ruddle, Payne, and Jones 1997; Marín-Morales et al. 2019). Future studies might benefit from more realistic simulation of real-world movement and elucidating the relationships between movement and wayfinding performance in iVR.

Participants Acquired Similar Direction Knowledge and Sketch Maps. Participants' spatial direction estimation revealed no differences between the two environments. This finding is in line with the results of Larrue et al. (2014), who reported that participants' direction estimation exhibited no significant differences between an RE condition and various VR conditions (full body-based information, translational component only, and without body-based information). In a simple single-floor environment, Richardson, Montello, and Hegarty (1999) reported that virtual environment and real-walking learners exhibited similar performance (less than 5° difference in error) when pointing between landmarks. Furthermore, this study was conducted in an immersive virtual environment and the rotation method was consistent with that in an RE setting. Therefore, we concluded that individuals are able to acquire as much direction information from learning in iVR as in an RE setting. The sketch map results, which reveal the mental representation of a spatial environmental structure, were also similar between the two environmental settings. These results indicate that participants processed direction and structural information in a similar way between the iVR and RE conditions, whereas, as we discussed, distance knowledge acquisition between the two conditions needs further investigation. Confirming this possibility will require further research into the detailed mechanisms of spatial coding at the level of brain activation and response. These findings provide preliminary evidence that spatial knowledge and cognitive maps developed in iVR might be transferred and used in RE settings.

Limitations

A major limitation of this study is that the number of participants differed between the two experimental conditions because the RE experiments were more difficult to conduct than the iVR experiments. In addition, participants' background characteristics (sex and familiarity with the experimental area) were not balanced between the experimental conditions. The aim of the study, however, was to investigate the ecological validity of iVR in indoor wayfinding. Thus, individual differences were not the main subject of our investigation. To eliminate the possible effects of these variables, we controlled for these variables in the composition of the two groups, revealing no significant differences. Future research should be conducted to elucidate how individual differences affect wayfinding behavior and spatial knowledge acquisition in different environments.

This study did not use a locomotion method to simulate movement in iVR. Participants rotated in the iVR by physically rotating their bodies and walked in the iVR environment using joystick-based navigation. It is unclear what effect the absence of movement simulation has on wayfinding behavior and spatial knowledge acquisition. Distance cognition is likely to be related to movement because of the path distance estimation method. We could not precisely set equivalent parameters and movement mode to simulate a real wayfinding experience. Therefore, the results reported here regarding distance perception should be interpreted with caution. Further investigation of distance knowledge in future empirical studies might yield interesting results.

A continuous development framework of spatial knowledge acquisition in new environments was reported by Montello (1998), proposing that metric knowledge develops continuously rather than discretely. In this study, the wayfinding task was participants' first direct experience in a new environment. The results might be useful for future studies to conduct longitudinal investigations (Ishikawa and Montello 2006; Weisberg and Newcombe 2016) of spatial knowledge acquisition in RE and iVR conditions, which could enable more comprehensive investigation of whether people learn as much about spatial knowledge in iVR settings as they do in RE settings. Furthermore, iVR experiments in larger outdoor areas and complex indoor environments will be needed to test the ecological validity.

Conclusions and Future Work

To comprehensively compare human wayfinding behavior in iVR and RE settings, we conducted wayfinding experiments in both iVR and RE conditions, exploring the impact of environmental factors on wayfinding behavior and spatial knowledge acquisition. The results revealed that the clearest difference in wayfinding behavior between the two environments was visual attention, which affected the efficiency of spatial knowledge acquisition. Regarding spatial knowledge acquisition, participants in the iVR condition acquired the same level of direction knowledge and drew similar sketch maps to those in the RE condition. Participants in the iVR condition, however, estimated distance closer to the true value, compared with participants in the RE. More empirical research will be needed to verify this result. These findings suggest the potential of iVR as a substitute for RE in research in wayfinding and the acquisition of spatial knowledge. This study provided two main contributions to this research area.

1. First, we comprehensively compared pedestrians' wayfinding behavior and spatial knowledge acquisition between RE and iVR settings. The findings reported here provide evidence for the ecological validity of iVR in wayfinding research.
2. Second, we conducted eye-tracking experiments in two environments to reveal pedestrian visual attention and explore its guiding role for spatial knowledge acquisition.

Conducting brain imaging experiments using functional magnetic resonance imaging in wayfinding research in iVR and RE settings remains an important challenge for future research and could help to elucidate spatial coding and response modes in the human brain in real time. In addition, longitudinal tracking, wayfinding training, and continuous learning of spatial knowledge to build cognitive maps in iVR are important issues and should be investigated more extensively in future studies.

The data that support the findings of this study are available on request from the corresponding author. The data are not publicly available because they contain participants' eye movement information that could compromise the privacy of the research participants.

Supplemental Material

Supplemental material for this article, which includes ten tables that provide additional experimental information and data and one figure that shows the test of mental rotation of three-dimensional objects, is available on the publisher's Web site at https://dx.doi.org/10.1080/24694452.2021.1894088.

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