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Evaluation of Wayfinding Aids in Virtual Environment

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It is difficult for a navigator to find directions to a given target in an unfamiliar environment, especially a virtual environment. The commonly used overview maps can show survey knowledge only on one particular scale but cannot provide spatial knowledge at other scales. In this study, three wayfinding aids (a view-in-view map, animation guide, and human system collaboration) were compared experimentally in terms of effectiveness, efficiency, and users' satisfaction. Results show that although these three aids all can effectively help participants find targets quicker and easier, their usefulness is different, with the view-in-view map being the best and human system collaboration the worst. Their usefulness also appears to be different for people with different spatial abilities. The results indicate that the design of wayfinding tools in virtual environments should consider the type and the presentation style of spatial information based on wayfinding tasks and users' spatial ability.

1. INTRODUCTION

Research on wayfinding in virtual environments (VE) is numerous and has highly diversified purposes. When a navigation destination is known, tools often focus on how to get a navigator to the destination quickly and accurately. For example, teleportation tools can bring the navigator to the destination instantly, and some tools, such as logarithmic movement (Mackinlay, Card, & Robertson, 1990), let systems execute viewpoint movement after the destination is specified. Although these tools are efficient in movement, they deprive the navigator of the opportunity to actively explore the VE.

Actually, exploration is critical to some navigation tasks. In situations such as training spatial knowledge of rare, remote, or dangerous places (Bliss, 1997), geographical information visualization, and scientific data visualization (Bartram,

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1997; Bjork, 2000), a navigator needs to understand spatial relationships among objects in virtual environments to construct a comprehensive cognitive map. Being able to explore the space is as important as being able to reach the destination quickly in these situations.

This article studies wayfinding aids to support exploration-oriented navigation with a known destination. We conducted an experimental study to examine the effects of three different aids on people with different spatial abilities and on tasks with different degrees of difficulty. The article reviews relevant research in Section 2 and proceeds to the introduction of our considered wayfinding aids in Section 3. Section 4 describes the experimental study, and results are presented in Section 5. After the discussion of the results, their implications for design, and limitations in Section 6, we conclude the article with future work.

2. RELATED WORK

2.1. Spatial Knowledge and Navigation

Wayfinding is defined as spatial problem solving (Passini, 1980). Before studying wayfinding issues, human spatial ability should be addressed, as it has been considered as a crucial factor that determines the success of navigation in both real-world and virtual environment (Downs & Stea, 1973; Sjolinder, 1996). According to Lohman (1979), spatial ability can be defined from three dimensions: spatial orientation, spatial visualization, and spatial relations. They can be measured by standard psychometrics tests, such as paperfolding test (Ekstrom, French, & Prince, 1963) and Purdue Visualization of Rotations Test (ROT; Bodner & Guay, 1997).

Although spatial ability varies among individuals, common principles of human navigation behaviors in the real world were found. Three levels of spatial knowledge in navigation were identified (Downs & Stea, 1973; Siegel & Herman, 1975), known as the Landmark-Route-Survey model: (a) landmark knowledge is the memory of salient objects for their particular shapes or individuals' preference, (b) route knowledge (or procedural knowledge) is formed by integration of these landmarks into a path or a sensorimotor sequence as the navigator travels, and (c) survey knowledge is a spatial model of the space formed from many sequential navigational experiences or abstraction from map-learning integration. Spatial learning was also described as a process in which participants move from an egocentric (referring to the body) to a fixed (referring to fixed external landmarks) and then to an abstract or exocentric (referring to the space coordinates) reference. People gather spatial knowledge and encode it in a hierarchical structure with information at different levels (Hommel, Gehrke, & Knuf, 2000).

Similarities between spatial knowledge in virtual and real environments (Goerger, Darken, Boyd, & Gagnon, 1998; May, Peruch, & Savoyant, 1995; Ruddle, Payne, & Jones, 1997; Witmer, Bailey, Knerr, & Parsons, 1996) link studies in these two worlds. It has been found that spatial knowledge gained from VE can be successfully transferred into physical reality (Peruch, Vercher, & Gauthier, 1995; Waller, Hunt, & Knapp, 1998). Thus, sufficient exposure to the virtual training environment can facilitate the acquisition of spatial knowledge of the real world.

However, research results also show that wayfinding in VE is not a simple replica of the real environment. Some studies indicated that participants have more difficulties in VE wayfinding (Goerger et al., 1998; Witmer et al., 1996), with more navigation errors and more inaccurate distance estimation.

It should be pointed out that environmental models used in many navigation research studies were abstract or simplified and lack rich spatial information about three-dimensional (3D) objects (e.g., realistic appearances of landmarks). Such an abstraction could be less efficient to help users remember the successive locations in navigation. Although creating more realistic and detailed VE models is time and labor consuming, it ensures the model fidelity, which is crucial to the generalization of research results (Darken, Allard, & Achille, 1998). Therefore, it is necessary to study navigation behaviors in environments with feeling of presence and more detailed spatial information, such as rich textures and realistic objects for wayfinding guidance (e.g., a virtual sun or architecture shades).

2.2. Wayfinding Aids for Navigation

Aimed at different activities, many wayfinding aids have been proposed. Chen and Stanney (1999) indicated that for different navigation purposes, an efficient supportive tool for one situation may not be helpful in another. Thus, there is a need to understand which kind of navigation activities certain wayfinding aids might support more effectively. In navigation, the destination may be either known or unknown, and the navigator can move to the destination by either passively relying on system-driven movement or actively exploring the space. Therefore, we can identify four different kinds of navigation activities based on where to go and how to get there: (a) reaching a known destination by self-exploration, (b) reaching a known destination with a system tool, (c) reaching an unknown destination by self-exploration, and (c) reaching an unknown destination with a system tool. The fourth case is not meaningful, because without knowing the destination, system tools cannot work.

Sometimes a navigator wants to get to a known place quickly and does not need self-exploration. In such situations, tools like teleportation are very useful. Such system tools can simply take the navigator from one place to another, which is preferable when efficiency is a concern. Nevertheless, the navigator is passive in obtaining the spatial knowledge between the origin and destination. Teleportation does not show users where they came from and how they got there in the traveling process. In some situations, to have route knowledge and survey knowledge is indispensable. Constraining user movement to a certain degree is a way to balance the navigation awareness and execution efficiency. For example, system-constrained navigation is designed to restrict the navigator's degree of freedom to avoid meaningless movement, but it usually brings extra confusion in large virtual environment (Ahmed & Eades, 2005; Hanson, Wernert, & Hughes, 1997). In the meantime, such constraints and provisions also curb users' activity and deprive them of their freedom to access interests.

If the destination is unknown and the navigator needs to explore the space to find the destination, navigational aids usually focus on providing visual information about the environment so that the navigator can find the destination. Visual information could be the overview of the environment or significant landmarks (May et al., 1995). An overview can be in two-dimensional (2D) maps, such as in Darken and Sibert's study (1993), or 3D, such as in Stoakley, Conway, and Pausch's study (1995). These two styles have both been tested and found to be useful in assisting wayfinding activities in VE (Chittaro & Venkataraman, 2006; Darken & Sibert, 1993). These tools are usually presented in another window besides the main window or nested in the window to provide an overview of the environment. Map-based aids can also be used to show the user's real-time position relative to the origin and/or the destination. A you-are-here map (Levinew, Marchon, & Hanley, 1984) combines a map with a you-are-here marker and dynamically updates position and orientation, which helps to keep the user's spatial awareness. If a separated overview window is not preferred when screen estate is limited (Buering, Gerken, & Reiterer, 2006), zooming techniques can be applied. Google Earth is an application that allows users to view selected satellite images by zooming in on different levels of overviews. It still requires people to establish a connection between the 2D overview satellite images with the 3D real architectural images, which many people find difficult to do.

Sometimes, even when the system knows the target location, it is still necessary for a navigator to get to the destination in person. For example, in spatial knowledge training, firefighters and military soldiers need to transfer their spatial knowledge into the real world and thus exploration becomes important; in games like Second Life, gamers need to go back to a location quickly, but route knowledge is still important because fortune or risk may occur in the path. Moreover, collaborative navigation is ubiquitous for searching in a large-scale structure (Zhang, 2005; Zhang & Furnas, 2005) and the actor needs to find the target even though his or her collaborator with an overview can tell where the destination is. Such exploration is not naive search because destination is unknown for the navigator and thus needs different tools to solve such a problem.

To summarize, wayfinding aids are needed in two situations. In the first situation, neither the navigator nor the system knows where the destination is. In the second situation, only the system knows the destination. In both cases, navigator's self-exploration is important. However, Situation 2 is the focus of our study because the system generated aids could potentially improve navigation activity substantially. In this work, we focus on the evaluation of several wayfinding aids for such navigation in terms of effectiveness, efficiency, and users' satisfaction.

3. THE CONSIDERED WAYFINDING AIDS

Our interest is in three wayfinding aids: human–system collaboration (HSC), animation guide (AG), and view-in-view map (VVM). HSC represents the practical collaboration problem between a high-standing overview guide (Person A) and a local navigator (Person B). An AG interface is designed to provide a dynamic connection between the overview and local information from origin to destination. A VVM shows the situation that one user can acquire real-time relative position information both for overview and local all the time. Their detailed explanations follow.

3.1. HSC

Our HSC interface established collaboration between the navigator and the System: direction information is calculated automatically by the system based on the location of the target and the user, and the user decides when to ask for such information. Rather than clustering all the information at one time, designs by Ballegooij and Eliens (2001) and by Chittaro and Burigat (2004) allow users to find their interest when they want. These query-based designs simplify the interaction and limit the caused visual obstruction to adequately aid the user's visual access to VE. We followed such design criteria and applied them in our design. Directions were given in an egocentric way, showing the target in avatar's "left/right" or "front/back." However, such a design may be problematic in the real world because collaborators may not know what direction each is facing when working in separate worlds. Although powerful tools like global positioning systems can provide orientation information based on action history, the accuracy on exact orientation at a particular time is questionable. Communication difficulty urges that a public language that can be mutually understood should be provided. For wayfinding issues, we found that geographical exocentric direction can be shared as a common context.

Therefore, in our study, we extend this kind of query design by providing exocentric directional hints, such as "Now your target is to the north (or south, west, east, northeast, northwest, southeast southwest)" (see Figure 1). Because the navigator changes his or her orientation all the time, he or she cannot follow the guidance directly but must translate it into his egocentric direction of "front, back, left or right" based on the local environmental clues, such as building shade directions. The shades play a similar role as that of a compass but are more realistic to the wayfinding situation in the real world. In our experiment, participants were told that it was sunset time and all shades in this virtual city were pointing to exact east. The user could acquire directional hints of the target from the system whenever they want by pressing the predefined button.

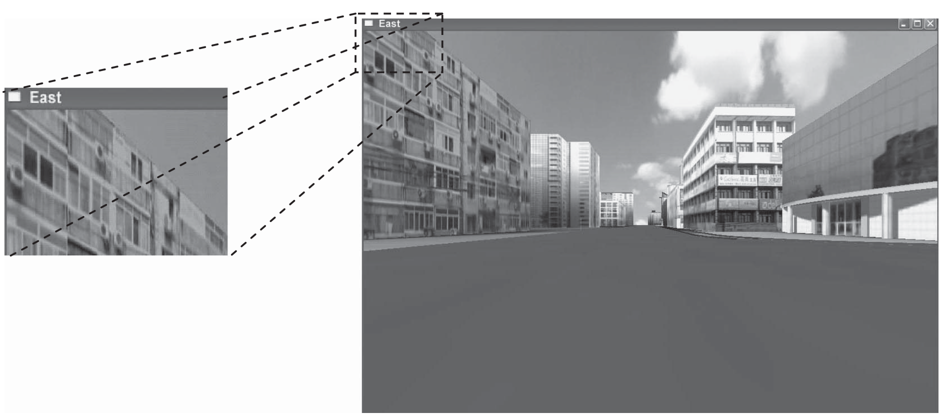

FIGURE 1 Human–system collaboration aid interface. *Note.* Perspective lines added to show direction information. "East" tells the user that the target is on the east at that moment.

3.2. AG

AG aid means that users are guided by watching a short animation before they begin to search for the target. Zhang (2005) proposed a special animation form, "space-scale animation," to provide users with the information about the connection of both space and scale. Based on this idea, we designed an AG by lifting up the viewpoint from a starting point and then lowering it down on the way toward the destination (see Figure 2). In the 35-sec animation, users can acquire the landmark information of the target when landing and survey knowledge from a high-standing view.

3.3. VVM

VVM adds an additional channel (map channel) in the right bottom of the screen. It shows the target representation (dot) and navigator's current position (triangle; see Figure 3). Using this interface, users can get the spatial information about the target in the map channel and perceives the local 3D entity in the main window. This VVM interface can be regarded as an overview map without detailed information, such as buildings and streets. Such information is omitted because we focus on the guidance of the relative direction to the target rather than detailed survey knowledge.

As seen, these three aids all give users more spatial information that may be necessary for wayfinding but differ in the extent to which they can help spatial information integration. The HSC aid provides local orientation information but requires the users to mentally incorporate the global context, the VVM aid provides the global context, but only at the highest level, and the AG condition shows spatial information at all necessary scale levels. Such difference may affect the outcome of cognitive map construction in wayfinding and consequently the performance of wayfinding activities.

4. EXPERIMENTAL STUDY

Successful wayfinding aids help people travel without getting lost, wasting time, or feeling stressed. In this experiment, 31 participants evaluated the usability of the three considered wayfinding aids. Success rate (effectiveness), performance time (efficiency), and satisfaction data were measured. We are mainly interested in two questions: What is the different effect of the three aids interface in wayfinding tasks with different difficulties, and is there any preference for individuals with different spatial abilities?

4.1. Experiment Design and Hypotheses

As introduced in Section 3, the three aids provide additional spatial information for navigation, compared to the control condition (self-navigation [SN]). Thus, it is reasonable for us to make our first hypothesis:

H1: Additional spatial information provided by the HSC, AG, and VVM aids can improve wayfinding performance.

(a)

(b)

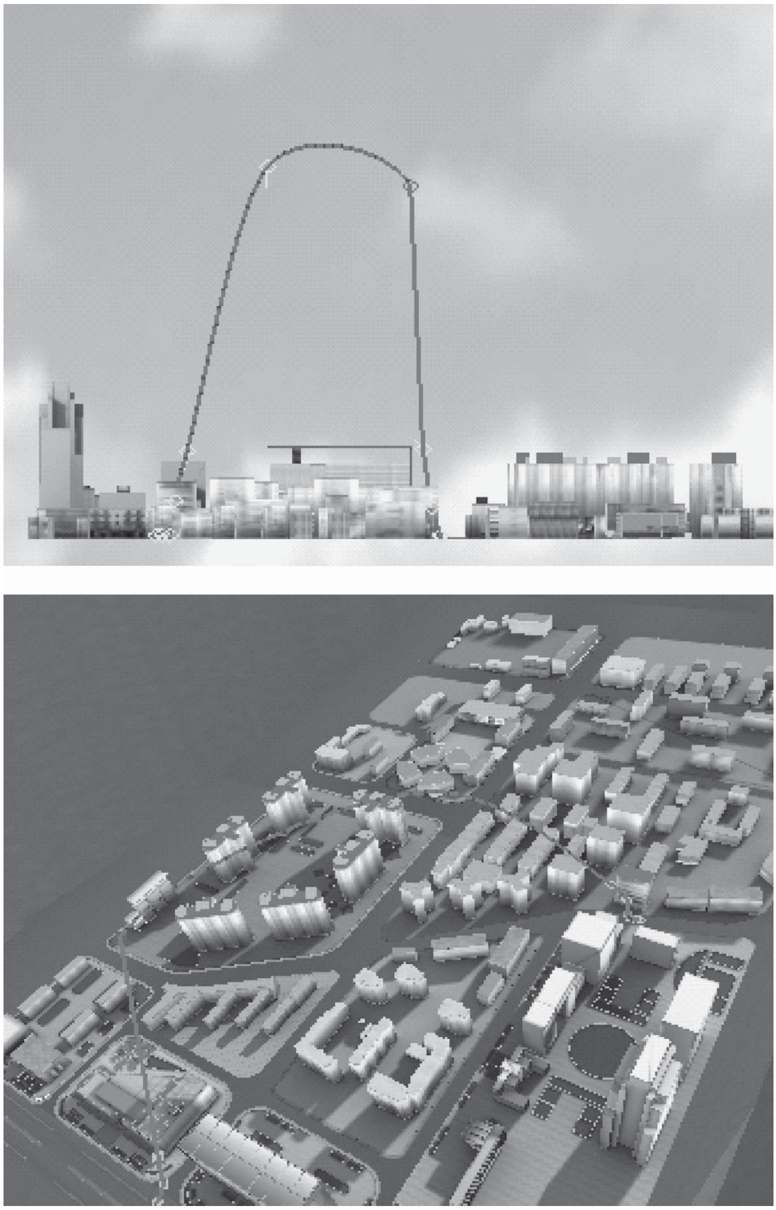

FIGURE 2 Animation guide aid interface. *Note.* (a) Front view of animation guide trajectory (zooming out, translation/rotation, and zooming in). (b) Three-dimensional view of animation guide trajectory.

Without any aid, a navigator has to collect all necessary spatial information through self-exploration. Any tool that can feed the navigator with useful spatial information could improve wayfinding performances. Presumably, each of the three proposed wayfinding aids has a unique strength, which makes it predictable

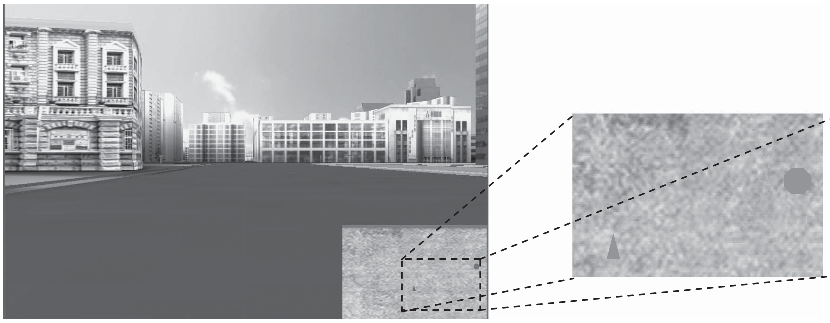

FIGURE 3 View-in-view map aid interface. *Note.* Perspective lines added to show relative direction to the target.

that they should have different impact on users' performance because they provide different degree of spatial information integration. Both the VVM and AG provide the user with overview spatial information and local details. The difference between them is that VVM simultaneously presents the overview plus details, whereas AG only dynamically shows the connection of the two by animation. The "overview plus detail" is a mature visualization technique used to display multiscale information (Card, Mackinlay, & Shneiderman, 1999) and has been used in many applications for more efficient navigation (e.g., Beard & Walker, 1990). However, as some literature has already pointed out, establishing connection between the 2D representations on maps with the 3D entities in the real world needs much cognitive effort (Oulasvirta, Nurminen, & Nivala, 2007; Thorndyke & Hayes-Roth, 1982). As explained in Section 3.2, AG was proposed to solve this problem by continuously changing the viewpoint within the 3D scenes. Nevertheless, Gonzalez (1996) pointed out that only carefully designed animation interfaces can counter the side effects of this change (e.g., extra memory workload, too complex or too fast). HSC needs users themselves to cognitively integrate the spatial information across scale by interpreting directional hints with the 3D scene. Moreover, the wayfinding tasks in this experiment ask avatars to find the target by first-view navigation. Some studies have shown that users need to spend more time on exocentric spatial tasks than egocentric ones (Carpenter & Proffitt, 2001; Tlauka, 2002).

With required spatial information, a navigator also needs to put different kinds of spatial information together. The way in which spatial information is presented may affect this integration and consequently wayfinding performances. Our second hypothesis concerns this integration factor:

H2: Tools like the AG and VVM that require less cognitive effort may lead to better wayfinding performances than tools like the HSC that require more.

Aid tools are an external support in wayfinding activities, whereas navigators' spatial ability is the internal capacity to interpret and utilize the information provided. Thus, besides wayfinding aids, participants' spatial ability is another dimension we need to take into consideration. Although some studies failed to find strong correlation between the scores of spatial ability tests and participants' wayfinding performance (e.g., Rovine & Weisman, 1989), some literature repeatedly reported the connection (Allen, Kirasic, Dobson, Long, & Beck, 1996; Blajenkova, Motes, & Kozhevnikov, 2005; Thorndyke & Goldin, 1981). Solving this dispute within the spatial cognition area is not the aim of this study. This experiment first tested whether there is a correlation. If there is, then we further expect there will be individual preference differences in wayfinding aids because of their different characteristics. As previously described, HSC requires more cognitive effort in establishing the correspondence between the global directional hint and human perceived direction in the 3D scene, so it may be difficult to use for an individual with lower spatial abilities.

Research has shown that animation can improve users' performance and satisfaction in spatial information learning, especially for individuals with lower spatial abilities (Hays, 1996). Our third hypothesis focuses on the impact of these tools on people with different spatial capabilities:

H3: The usefulness of a wayfinding aid may be affected by a user's spatial capability.

Users may prefer different kinds of tools in spatial information integration because of their different spatial abilities. To test these hypotheses, our study employed a mixed-design involving two within-subjects factors (interface type and wayfinding difficulty levels) and one between-subjects factor (spatial ability level). By varying the level of difficulty for the tasks, we defined the problem within each level and hoped that this factor might magnify the differences between the interfaces.

The interface type factor has four treatments: the HSC tool, the AG tool, the VVM tool, and an environment without any wayfinding aid where only SN is allowed to serve as a baseline condition.

The wayfinding task used in the experiment had three levels of difficulty: low, medium, and high. The difficulty of the task was measured by the required traveling distance and number of turns. For example, Figure 4 shows a wayfinding task, which starts from the triangle and ends at the dot. In our experiment, the definition of the three levels of difficulty is low (200 m with no turn), medium (400 m with one turn), and high (800 m with two turns). The line in Figure 4 illustrates that the required travel distance is 400 m and requires at least one turn. So it is considered as medium difficulty level.

To analyze the effect of individuals' spatial ability differences, participants had to take two psychometric tests before the formal experiments. The two psychometric tests are paperfolding test (Ekstrom et al., 1963) and ROT (Bodner & Guay, 1997), with 20 questions each. According to the sum of the two test scores (maximum 20 + 20 = 40 scores), participants were divided into three categories: high spatial ability category ([36, 40] points, above 90% accuracy), medium spatial ability category ([24, 36], between 60% and 90% accuracy), and low spatial ability category ([0, 24], below 60% accuracy). The results of the tests showed that the number of participants belonging to these three levels was 8, 14, and 9, respectively.

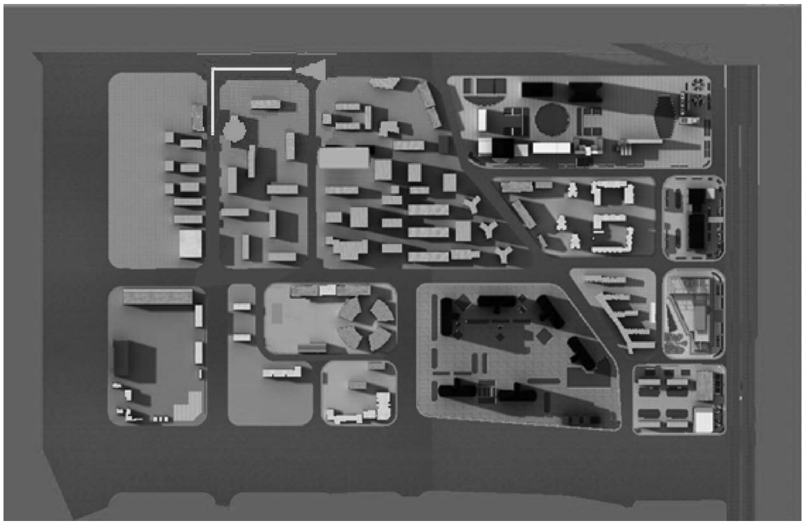

FIGURE 4 Wayfinding task difficulty level illustration (a medium difficulty task).

4.2. Participants

Thirty-one college students (16 male and 15 female) were recruited through a local online community. They volunteered for the experiment and were paid an honorarium for their participation. The average age of the participants was 23, ranging from 21 to 27. The majority of participants, 20 of 31, were engineering majors. Only 1 student reported being ambidextrous; all the rest were right-handed. A background survey questionnaire suggested that all the participants were familiar with computers with standard input devices (a regular keyboard and a mouse) that were used in our experiments, and more than 90% reported that they use computers on the average of several hours daily. In our experiment, all the selected participants performed 12 wayfinding tasks (four interfaces including SN with three difficulty levels in each).

4.3. Apparatus

The experiment was performed on a regular personal computer (Pentium IV CPU 2.8 GHz, 2 GB memory). The machine had a NVIDIA Quadro FX1100 graphics card and a 19″ ViewSonic Professional Series P95f monitor with 1024 × 768 resolution. The participants interacted with the virtual environment through a three-button mouse and a standard keyboard. All keys needed in the test were labeled with action names on white tapes so that subjects could locate needed keys quickly.

4.4. Test Scenes

As mentioned earlier, constructing an environment as real as possible can reduce navigation difficulty in virtual world and has been considered as an important fidelity measurement when using VE to study spatial behavior. Therefore, four virtual city models with rich texture of visual image were created (e.g., Figure 1 shows the 3D images that participants could perceive in the experiment, and Figure 4 is a bird's-eye view of one virtual city model). Each model corresponded to test an aided interface or SN nonaided interface. All models share certain common features, such as the street layout and most of the background buildings. The area size of each model is about 1.5 km × 1 km. However, these four models also differ from each other by their unique part: one model with three different restaurants, one with three different student association buildings, one with three different banks, and one with three different bookstores. The four models were treated such that they have the same complexity in terms of city structure. The target buildings in one city model do not appear in the others so that participants would not meet the same target building in any other model.

4.5. Procedure

Participants were required to fill out a background survey questionnaire with detailed instructions and then subsequently complete the standard spatial ability test, paperfolding test, and ROT. We allowed as much time as possible for participants in the training practice so that they could get familiar with the VE and were able to use each interface adeptly. Participants could start to perform formal tasks only after they could show that they had practiced enough by successfully passing our two pretests. For each task in the formal experiment, participants were asked to find a target building in the virtual city by using one of the aids interface. The name of the target was given to participants, and the name sign became visible when participants were close enough to the building. Each participant had 5 min to perform a task. If a participant could not find the target within this maximum time, 5 min was recorded as his or her performance time (PT) for the task, and one failure was noted. All participants took 12 tasks: 3 for each interface using one of the four city models at three different difficulty levels. Their success rate (SR) and PT for each task were recorded. We applied four-level Latin Square experiment design to counterbalance the interface types and asked participants to carry out the experiment randomly within each interface at different difficulty levels. Participants could take a break before starting the next task, but no participant did so.

Participants were asked to answer a nine-question satisfaction questionnaire after using each interface. An adaptive satisfaction questionnaire (Cook, 1991) was used to measure the difficulty to perform the tasks, confidence after the tasks, spatial awareness, and memory workload. The scale ranged from 1 (*strongly disagree*, *negative comment*) to 5 (*strongly agree*, *positive comment*). After all the interface tests had been completed, an overall preference rating was given for the four interfaces. The preference rating for the four interfaces ranged from 1 (*I don't like it at all*) to 10 (*I like it best*). For each participant the whole procedure took approximately 1½ hr.

5. RESULTS

Data collected in the experiment included SR, PT, and user satisfaction (SAT). Both parametric and nonparametric techniques were employed in data analysis. SR value is either 1 (*success*) or 0 (*failure*). It is impossible to satisfy the "normality assumption," so only nonparametric techniques can be used, such as McNemar test and Cochran's Q test. SAT has evaluation value from 1 to 5 and cannot satisfy normality assumption either, so also nonparametric techniques were used, such as Wilcoxon rank test. However, PT value is the time, measured in seconds, and could potentially satisfy the assumption, so it becomes possible to use parametric analysis techniques, such as a two-way analysis of variance.

5.1. Effectiveness—SR

For every task, one failure (0) is recorded when the participant could not find the target within a maximum time of 5 min. McNemar Test (with aids vs. without) was used to test H1 (if the use of aids interface can significantly improve success rate). The results show that all the three aids were significant (SN & HSC, $\chi^2(1, 93) = 7.314$, $p = .007$; SN & AG, $\chi^2(1, 93) = 18.581$, $p < .001$; SN & VVM, $\chi^2(1, 93) = 28.003$, $p < .001$).

Figure 5 shows the average SR in the four conditions. The Cochran's Q test showed significant difference among the three aids interfaces, $Q(2, 93) = 17.200$, $p < .001$. However, the post hoc McNemar Test showed no statistical differences of SR between AG and VVM ($p = .063$). Thus, AG and VVM outperformed HSC in terms of task completion.

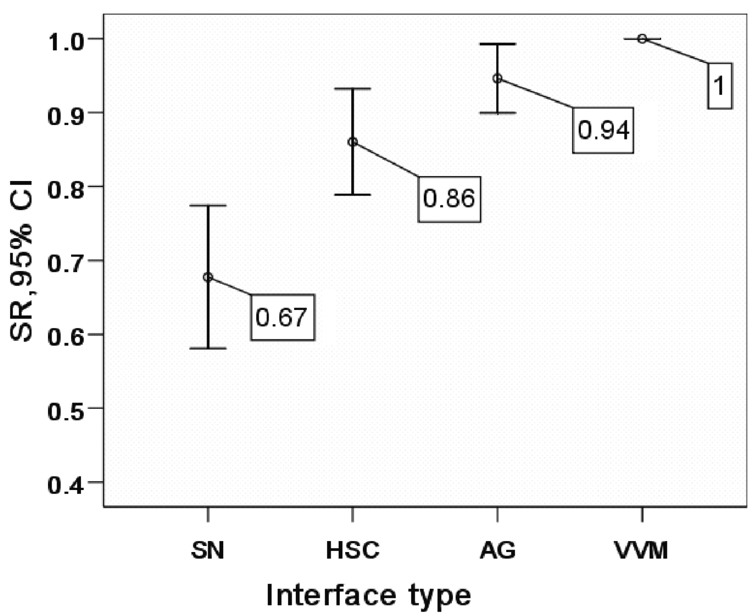

FIGURE 5 Success rate for different interface types. *Note*. SN = self-navigation; HSC = human-system collaboration; AG = animation guide; VVM = view-in-view map.

5.2. Efficiency—PT

The VVM performed best, with an average PT of 58 sec. Including 35 sec animation time, the AG was the next, with an average PT of 77.1 sec, whereas HSC was the slowest, with an average PT of 132.5 sec, compared to SN with an average PT of 142.3 sec. A two-way within-subjects analysis of variance test of PT suggested significant main effect of wayfinding aids type, $F_{0.05}(2, 270) = 29.473$, $p < .001$. A subsequent Tukey's test showed that the difference between VVM and AG was not significant ($p = .168$); however, the differences between HSC and AG, HSC and VVM were both significant ($p < .001$). Figure 6 illustrates the average PT results with respect to wayfinding aids type and task difficulty level. The task difficulty level main effect was also found to be significant, $F_{0.05}(2, 270) = 12.412$, $p < .001$. Interaction effect between wayfinding aids type and task difficulty level was not significant, $F_{0.05}(4, 270) = 1.279$, $p < .278$.

5.3. User Satisfaction-SAT

Figure 7 illustrates the overall preference of the four interfaces and specific evaluation questions including spatial awareness, ease of navigation, and less memory requirement for each interface. Friedman's test was employed to compare the differences. Overall satisfaction difference was found significant among the three aids, $\chi^2(2, 31) = 40.75$, $p < .001$, whereas a Wilcoxon rank test was employed to see the one-by-one difference (HSC & AG, $Z = -4.733$, $p < .001$; AG & VVM, $Z = -3.590$, $p < 0.001$).

For specific evaluation questions, significant differences were also found. Participants commented that AG was much better than HSC in helping them to be clearly aware of where they were ($Z = -3.320$, $p = .001$), but no noticeable difference

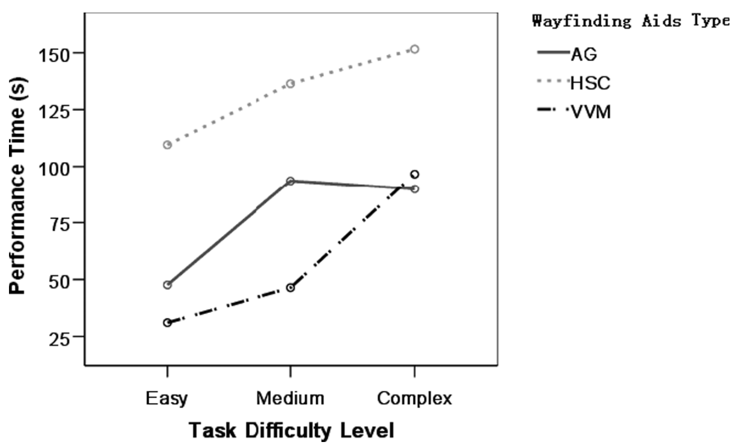

FIGURE 6 Mean performance time in target searching with different task difficulty levels. *Note.* AG = animation guide; HSC = human–system collaboration; VVM = view-in-view map.

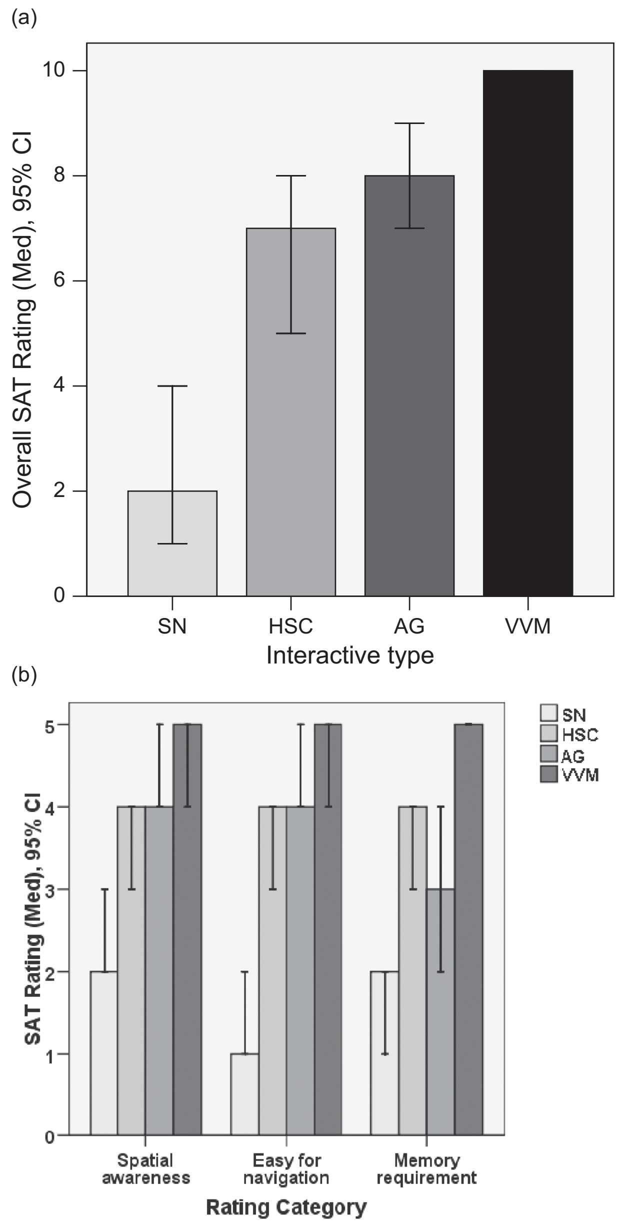

FIGURE 7 Satisfaction ratings (higher point is better). (a) Overall preference rating. (b) Specific rating. *Note.* SN = self-navigation; HSC = human–system collaboration; AG = animation guide; VVM = view-in-view map; SAT = Spatial Ability Test; CI = confidence interval.

was found between AG and VVM ($Z = -0.132$, $p = .895$). Satisfaction data also suggested there was a clear rank of "easy to find the target." VVM was considered to be the easiest and HSC was the most difficult (HSC & AG, $Z = -2.652$, $p = .008$; AG & VVM, $Z = -2.555$, $p = .011$). Participants' comments on memory requirement showed significant difference among the three wayfinding aids (AG & HSC, $Z = -2.023$, $p = .043$; HSC & VVM, $Z = -4.008$, $p < .001$). This subjective rating result was consistent with the objective performance data.

5.4. Spatial Ability Effect

The Pearson test showed that the paperfolding test and ROT test had a good correlation ($r = .71$, $p < .001$). The Spearman test suggested that participants' average PT has a negative correlation with the sum score of the two tests ($r = -.59$, $p = .001$). Among the four interactive types, the Spearman correlation test results suggested a strong correlation when using HSC ($r = -.751$, $p < .001$) and medium correlation when using AG ($r = -.387$, $p = .032$), but no satisfactory relationship in the SN ($r \leq .001$, $p = .998$) or VVM ($r = -.290$, $p = .114$).

Figure 8 shows PTs of the three groups with different spatial ability test scores when they used AG and HSC. Participants with a high spatial ability score could achieve nearly the same efficiency with AG as with HSC. Participants with a medium spatial ability score spent significantly less time with AG than with HSC. Participants with a low spatial ability score spent significantly longer time with

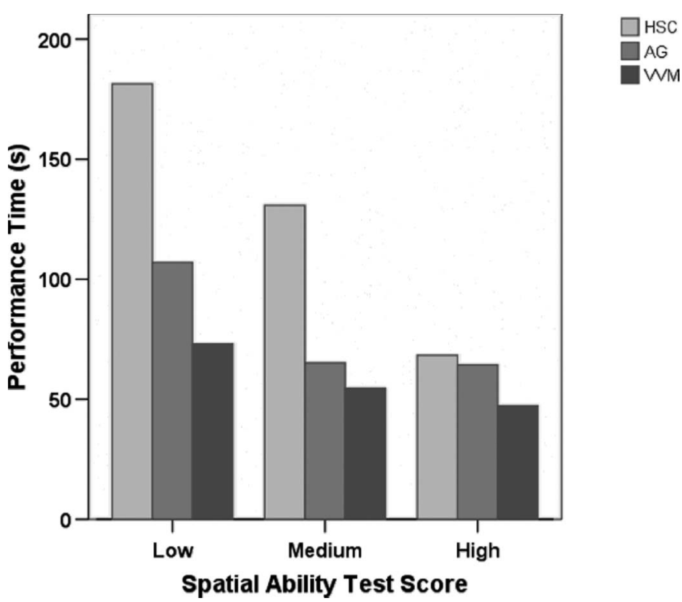

FIGURE 8 Performance time comparison considering individual's spatial ability. *Note.* HSC = human–system collaboration; AG = animation guide; VVM = view-in-view map.

both aids interface than the other two groups, but longer for HSC. As for AG, users with medium spatial ability score have similar PT to those with a high spatial ability score, whereas HSC depends greatly on the individuals' spatial ability.

6. DISCUSSION

6.1. Effectiveness of Wayfinding Aids

Our wayfinding aids interfaces have been found useful in helping a navigator find a target in a virtual city. For the SN condition with no aids, participants wandered aimlessly in the virtual city and could not relocate the buildings they had just visited. The average SR with no aids was 67%, lower than the SR of those aids by at least 19 percentage points aids (VVM = 100%, AG = 94%, HSC = 86%). The differences between the treatment without aid and those with an aid are significant. Considering the longer PT for SN condition, if task maximum allowed time is shortened from 5 min to 2 min which is adequate for the other three conditions with aids on average. The SR of SN will be significantly reduced, which means wayfinding aids do increase the effectiveness of searching process. This result confirms H1.

The significant differences in the SR between the HSC and other two aids confirm H2. These differences might be caused by their different requirements for cognitive resources in spatial information integration. By using VVM, participants can always see their momentary relative position to the target, marked by two signs in the overview, and adjust their movement until they meet the target. This mechanism makes the SR of VVM to be nearly 100%. AG provides a guide for participants to know where the target is and how to get there before navigation, but users are still exposed to the risk of forgetting what they have seen in the animation. Most of this kind of memory failures happened when participants could remember what the target looked like but not the exact route. Then the "lost" users had to navigate by themselves, almost like in SN, and thus could not complete the task within the given time. This result is consistent with the Landmark-Route-Survey (LRS) model that landmark knowledge is easier to form than route knowledge. Nevertheless, users becoming "lost" were rare, and results indicated no significant difference of success rate between AG and VVM. HSC needs users' spatial ability to interpret the help information from the system. By using HSC, users need to figure out which direction he or she is facing depending on the local shade first before asking for directional help to decide how to move. After choosing a street, the participant only needed to pay attention to the buildings on the street until the next crossing, and then he or she could repeat the same strategy thereafter. From our observation and participants' feedback, most participants seemed to find difficulty using HSC because they could not efficiently translate the exocentric expression, such as north, west, east, south, to their egocentric mental map direction, like front, back, left, right. Some participants also failed to ask for help at the proper time, for example, at a crossing. Participants became puzzled when they made a mistake and then got lost after several more mistakes. Calculating the direction and looking for a target at the same time needs much cognitive effort. These interesting phenomena might explain why HSC had the lowest success rate among the three wayfinding aids.

6.2. Efficiency of Wayfinding Aids

Figure 6 compares the PT among three aids across different task difficulty levels. As seen, both the VVM and AG aids are more helpful than the HSC does in all task difficulty levels. This may be because these two aids, by providing visual spatial information across scales, can help participants integrate spatial information better and then improve task completion time. With the VVM, participants had both local and global information during the whole wayfinding process. Our data shows that the average PTs in the three task levels are almost proportional to the travel distances. This may indicate that participants did not waste much time in non-travel-related actions, probably including spatial information integration. Using the AG, participants could see local buildings and overall routes. They knew “where I am” at the beginning of the animation and noticed “which road I should take, then at which intersection I should turn right/left” when they saw the city from the sky. Then in the later wayfinding, participants followed the route map formed in their minds during the guidance animation. For the HSC, participants had to translate spatial information between large and small scale and needed to reorient themselves more frequently. This may slow down the searching process.

One interesting pattern found in this figure is the interaction between the aid factor and the task difficulty factor. In particular, whereas the VVM is better than the AG in both the easy and medium tasks, these two tools led to similar performance for the complex task. One possible explanation is that although the VVM can provide participants with spatial information at both the local and global scale levels, the AG also gives participants other spatial information between these scale levels, and such additional spatial information can help the construction of cognitive maps and consequent navigation activities. This may indicate that the AG tool could outperform the VVM as the task complex increases, but we need further research on this issue, because based on the current data, the difference between these two tools in the complex task is not found significant, $t(30) = 0.558$, $p = .581$.

Overall, measured by SR, PT, and SAT, the VVM is the best wayfinding aid in exploration-based navigation with a known target, so we felt the need to find a design pivot. The VVM differs from traditional 2D bird’s-eye view map in that it does not need to give precise road and building information. It seems that the precise road and building information is less important compared with relative positions for the design. To verify this idea, we conducted a derived 8-participant experiment in a similar condition except that the 2D map had detailed information, as shown in Figure 9. No significant difference of demographic information and spatial ability was observed between these 8 participants and the 31 participants in our formal experiment. As we expected, neither SR (still 100%) nor PT, $t(115) = -0.053$, $p = .958$, outperformed the original. Thus, the pivot of the design was to show the relative position of the navigator and the target in a real-time way but it was not necessary to render all details in an additional channel. This information is extremely useful in mobile navigation aids where computing capacity is limited.

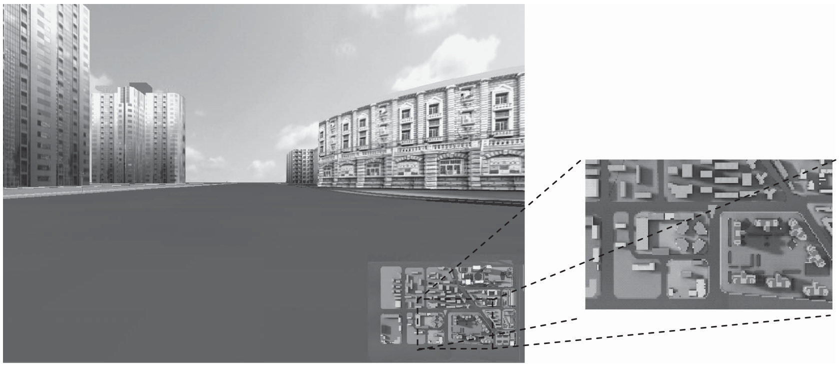

FIGURE 9 Modified view-in-view map aid interface in additional experiment.

6.3. Spatial Ability and the Usage of Wayfinding Aids

Results indicate that the impact of these aids varies with participants' spatial abilities. In the SN condition, no matter what kind of spatial ability scores participants have, they first had to make a random decision at interactions. Thus, the effect of spatial ability was not significant at all. However, VVM goes to the other extreme. It helps users who were not able to build up a mental model of the VE to recognize the results of their action: whether approaching or leaving the target, and then to be able to adjust their next step orientation. This kind of real-time feedback may eliminate the need for a mental model and thus reduce the performance difference among participants with different spatial abilities. In comparison, HSC demands more cognitive effort in solving wayfinding problems in our experiment. In our HSC, the translating process from exocentric direction guide into egocentric is expected to rely largely on a person's ability to form a mental representation of the environmental information. For those who have trouble effectively constructing such a mental map, they inevitably had to perform repetitive and time-consuming search. Figure 8 illustrates the different impacts of these tools on people with different spatial abilities. As seen, the VVM and AG aids helped participants with low or medium scores in spatial ability tests than those with high scores.

The implication of this finding is that wayfinding designs may need to adapt to a user's spatial ability. For people with lower spatial ability, advanced tools like animation would be welcomed. However, for those with higher spatial ability, the gain from such tools may not compensate the time consumed on them and constrain the freedom for active expression. Simple tools that can provide needed information might be better.

This study has two limitations. First, we only considered wayfinding tasks within a small-sized city model (1.5 km × 1.0 km). Although, in our results, there is no interaction effect between task difficulty level and interface type, it is perhaps because of the limited size and complexity of our city model, which constrains the range of task difficulty. Second, participants' homogeneity needs more investigation by subsequential experiments. Like most other empirical studies, our participants were all college students in engineering and science. Although we tried to balance such factors as video game experience, their education backgrounds are very close. Education training factors such as course work on Engineering Drawing may affect their spatial tasks. Thus, it could be a question whether the relationship between spatial abilities and the type of wayfinding aids from this study is representative enough and can be generalized to greater population.

7. CONCLUSIONS

This article presented a study on the design and evaluation of aids interfaces for wayfinding in virtual environments. The results show that in wayfinding, people can benefit from tools that provide more spatial information across different scale levels and tools that help spatial information integration. We also find that the impacts of tools on people's performance vary with their spatial abilities.

Our results can shed some light on the design of wayfinding tools, which become increasingly popular in recent years. In choosing different wayfinding tools, our result indicates that for people with weak spatial ability, dynamic tools, such as animated routes, can provide rich information and thus requires little cognitive resource will be helpful, whereas those with strong spatial ability may only need simple tools to provide lightweight directional information. Also, in designing overview tools, environment information can be simplified with less details (e.g., the building shapes and street grid). For situations where computation and rendering resources are limited (e.g. mobile navigation tools), this finding is beneficial.

Our future work will focus on two directions. First, we will study wayfinding in a larger and more complex environment and to see whether the complexity of tasks and the environment may affect the effectiveness of different wayfinding tools. For example, we notice that in our study, although the VVM tool performed the best in both easy and medium tasks, it was outperformed by the AG tool in the most difficult task by a small and nonsignificant margin. We will investigate whether more complex tasks may amplify this effect and in what situations the AG and VVM tools can benefit users differently. Second, we are interested in deepening our research on the relationship between wayfinding and spatial ability. We will expand our study by recruiting more diverse participants, such as students from other disciplines (e.g., social science, humanity, education, etc.), nonstudents, and so on. This will allow us to have a more comprehensive understanding about whether and how spatial ability may affect the use of wayfinding tools.

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