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A virtual reality based study of indoor fire evacuation after active or passive spatial exploration

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ABSTRACT

Here we report a study designed to examine the influence of spatial exploration mode on people's wayfinding performance during a building fire emergency. Using immersive virtual environments, we asked the participants to actively or passively explore a virtual museum to look for hidden treasure keys and then a treasure point. Half of the participants were asked to exit from a virtual museum during a virtual fire emergency after they had actively or passively explored the museum, whereas the other half of the participants were asked to complete the same task under the control condition without the virtual fire. Importantly, both the active and passive exploration conditions allowed the participants to control their own movement, whereas only those under the active exploration condition had the opportunity to make route decisions. Compared to those who explored the virtual museum passively, the participants did it actively traveled longer in completing the egress task. The results also revealed that participants under the fire emergency condition spent more time in finding their way to exit the museum than those under the control condition, and rated the evacuation task to be more difficult. The underlying mechanisms of these findings were discussed.

1. Introduction

Fire has always been the most significant hazard in buildings. The U.S. Fire Administration (USFA) statistics showed that building fires caused 2635 fatalities and 12,800 injuries in the United States in 2015 (USFA, 2017). Numerous incidents, including the most remarkable ones such as the Iroquois Theatre fire, the Coconut Grove fire and the Beverly Hills Supper Club fire, and most recent ones such as the London Grenfell Tower fire and the Bronx apartment fire, have repeatedly reminded people of the threat of building fires. When people evacuate from burning buildings, their wayfinding capabilities are critical in determining the efficiency of their evacuation and hence their chances of survival. Wayfinding is a cognitive process that involves the ability to learn a route and retrace it from memory to guide the move from one place to another, and judge the spatial information between people, objects, and surrounding environment (Allen & Golledge, 1999). Prior studies have pointed out that the wayfinding capabilities are largely impacted by people's cognition of an indoor environment (G Golledge, 1999; Maguire et al., 1998), which could be challenging, especially at spaces of public assembly where people may not necessarily be familiar with the environment.

Spatial knowledge, which is essential for spatial behavior, resides in cognitive maps (Downs & Stea, 1973; Tolman, 1948). The term cognitive map is used to describe mental representation of spatial information used for positioning (Papadopoulos, Koustriava, & Barouti, 2017; Tolman, 1948). Cognitive map is essential to the ability to recognize, save, remember and decode spatial information, as well as to the formation of an action chain of spatial information (Kitchin, 1994). Golledge (1999) emphasized that cognitive maps are the basis of wayfinding, as they provide a mental structure where environmental perceptions are stored to direct people in spatial decision making (Hong, 2007). Mackintosh (2002) also pointed out that developing and improving cognitive maps results in a more successful wayfinding and travel experience.

Cognitive maps can be developed through both primary experience and secondary media (e.g. maps) (Kitchin & Freundschuh, 2002). The primary experience is usually acquired through direct exploration of a space (Tolman, 1948), which can be done in two different ways, including active exploration and passive exploration (Chrastil & Warren, 2012). Active exploration is performed in such a way that people freely explore the environment and have both motor and cognitive control (Chrastil & Warren, 2013). By contrast, passive exploration is performed in such a way that people follow a given path to explore the environment and have none or limited cognition control during the process (Chrastil & Warren, 2013). These two types of spatial exploration differ in several ways. For instance, Chrastil and Warren (2012) reported that decision

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making during active learning was the primary component of the acquisition of known connectivity relations to the environment, whereas there was no decision making in passive learning. Afrooz (2016) contended that the difference between active and passive exploration not only can influence the cognitive configuration of the built environment, but also can influence the visual memory of way-finders. In another study, Attree et al. (1996) found that active exploration mainly enhanced spatial layout memory of the participants whereas passive exploration enhanced their object memory.

A number of prior studies have consensually reported that active exploration could lead to better spatial learning outcomes and consequently better wayfinding capabilities. For instance, Hazen and Nancy (1982) reported that young children who actively explored a playhouse were better at finding novel shortcuts and reversing routes than the children who were led or carried around by their parents. Peruch, Vercher, and Gauthier (1995) did an experiment in which the participants were asked to navigate through the environment to each of four landmarks by taking the shortest route possible, and they contended that active exploration led to significantly higher performance on the wayfinding task than the passive exploration. Chrastil and Warren (2013) also argued that the participants who had the chance to decide their own routes during spatial exploration had better performance in choosing the right routes to walk to a previously learned target than those who explored the space passively by watching a video.

Yet, such difference between active and passive exploration requires further investigation in the context of building emergency evacuation, mainly due to three reasons. First, in prior studies the effectiveness of active and passive exploration was mostly assessed by asking the participants to draw a map of the environment they have physically or virtually explored or to describe certain objects they saw in the environment. What was directly assessed by doing so was the impact of the spatial exploration on the formation of spatial memory of the participants, rather than on their actual wayfinding capabilities (Laird, 2012). There is apparent difference between the spatial memory and actual wayfinding behavior. During the wayfinding process, people would constantly monitor and correct their course of action and make adjustments to the original cognitive map (Russell & Ward, 1982). Second, when people evacuate from building emergency scenes, their primary wayfinding task is to find the exit, which does not always require complete and accurate spatial knowledge of the entire environment. Instead, this task could tolerate a certain level of incompletion or fuzziness in the cognitive map. The comparative impact of active and passive exploration on people's ability to perform this task has not been fully examined. Third, it remains unclear whether the difference between active and passive exploration still emerges when people are under stress, such as in a fire evacuation, which may influence how people perceive, process and act upon spatial information that relates to the environment that surrounds them, and may cause people to behave rather differently (Abu-Safieh, 2011).

To examine people's indoor wayfinding behaviors under fire emergency, several approaches have been adopted in prior research, including post-emergency investigation (Urbina & Wolshon, 2003; Zhao, Lo, Zhang, & Liu, 2009), fire evacuation drills (Kobes et al., 2010; Proulx, 1995), modelling and simulation (Lo, Huang, Wang, & Yuen, 2006), and animal experiments (Garcimartín, Zuriguel, Pastor, Martín-Gómez, & Parisi, 2014; Saloma, Perez, Tapang, Lim, & Palmes-Saloma, 2003). However, these approaches bear certain limitations (Zou, Li, & Cao, 2017), such as the scarcity and/or incompleteness of real behavioral data, high cost, difficulty in setting controlled experiment environment, and debatable similarity between human and animal subjects. Alternatively, Immersive Virtual Environments (IVEs) which are built on Virtual Reality (VR) technologies provide a promising alternative for conducting indoor wayfinding behavior studies. VR is a "real or simulated environment in which the perceiver experiences telepresence" (Steuer, 1992). Prior studies have showed that there are similarities in the spatial knowledge acquired in real and virtual environments (Jacobs, Thomas, Laurance, & Nadel, 1998; Ruddle, Payne, & Jones, 1997). A large number of studies, ranging in domains from cognitive psychology to neurosciences and psychophysiology, have tested IVE in wayfinding-related experiments and repeatedly reported its effectiveness (Bosco, Picucci, Caffò, Lancioni, & Gyselinck, 2008; Morganti, Carassa, & Geminiani, 2007).

The value of using IVEs in wayfinding behavior studies is further highlighted by its capability of creating stressful environment, such as building fire emergency scenarios, without any short- or long-term harm to the participants. These virtual stressful environments can be used to evoke certain mental and behavioral responses that are similar to those that people would experience in real stressful environments (Zou et al., 2017). Accordingly, a number of IVE-based evacuation systems have been developed in prior studies, such as interFIRE VR (Sullivan, 2000), SGEM (Lo, Fang, Lin, & Zhi, 2004) and Vegas (Xi & Smith, 2014), with a particular focus on indoor environments with high potential of accidents, such as mines (Tichon & Burgess-Limerick, 2011) and tunnels (Sharma, Jerripothula, Mackey, & Soumare, 2014). People's wayfinding behaviors, such as route choice (Kinateder et al., 2014), waiting time (Andrée, Nilsson, & Eriksson, 2016), helping behavior (Gamberini, Chittaro, Spagnolli, & Carlesso, 2015), adaptivity to emergency situations (Gamberini, Cottone, Spagnolli, Varotto, & Mantovani, 2003), during their escape from building fire emergencies, as well as the impact of gender factors (Castelli, Latini Corazzini, & Geminiani, 2008; Martens & Antonenko, 2012), personal characteristics factors (Shin, 2018), various social factors (Kinateder et al., 2014) and environmental factors (Duarte, Rebelo, Teles, & Wogalter, 2014; Vilar, Rebelo, Noriega, Teles, & Mayhorn, 2013) on these behaviors, have been examined in a number of recent studies that used IVEs.

Using an IVE-based approach, we aim to address two questions in the present study. First, how do the different ways of spatial exploration of indoor environment influence people's ability to find the exit? Second, how does the stress in fire evacuation interact with the spatial knowledge of the environment to influence people's ability to escape from a fire emergency?

2. Materials and methods

2.1. Participants

Sixty-four undergraduate or graduate students (mean = 21.6 ± 2.0 years, ranging from 18 to 27 years; 32 females and 32 males) from a major university in Beijing, China, took part in the present study. All of them have normal or corrected-to-normal vision, as well as normal color vision. Each participant received 50 CNY for their participation. The present study was approved by the Ethics Committee of the Psychology Department of Tsinghua University, and conformed to the ethical standards for conducting research established by the American Psychological Association.

2.2. Apparatus

The present study was conducted in the Virtual Reality Laboratory of the Department of Construction Management, Tsinghua University. We used a HTC VIVE head-mounted-display (HMD) VR system, which employed the SteamVR positioning technology to allow for 360-degree viewing of the displays (Niehorster, Li, & Lappe, 2017). The combined resolution of the displays shown for both eyes was 2160 (horizontal) × 1200 (vertical) pixels, whereas the display for each eye had a resolution of 1080 (horizontal) × 1200 (vertical) pixels (see Fig. 1 for an illustration of the screenshots for the left eye).

The experiment was run on a Dell Precision T7800 workstation with Intel Xeon E5-2603 processor and Gigabyte GTX1080 graphics card. We used the 3D Studio Max software to model and render the IVE (immersive virtual environment), and then imported it into the platform of the Unity3D game engine. We also used the particle system in Unity 3D

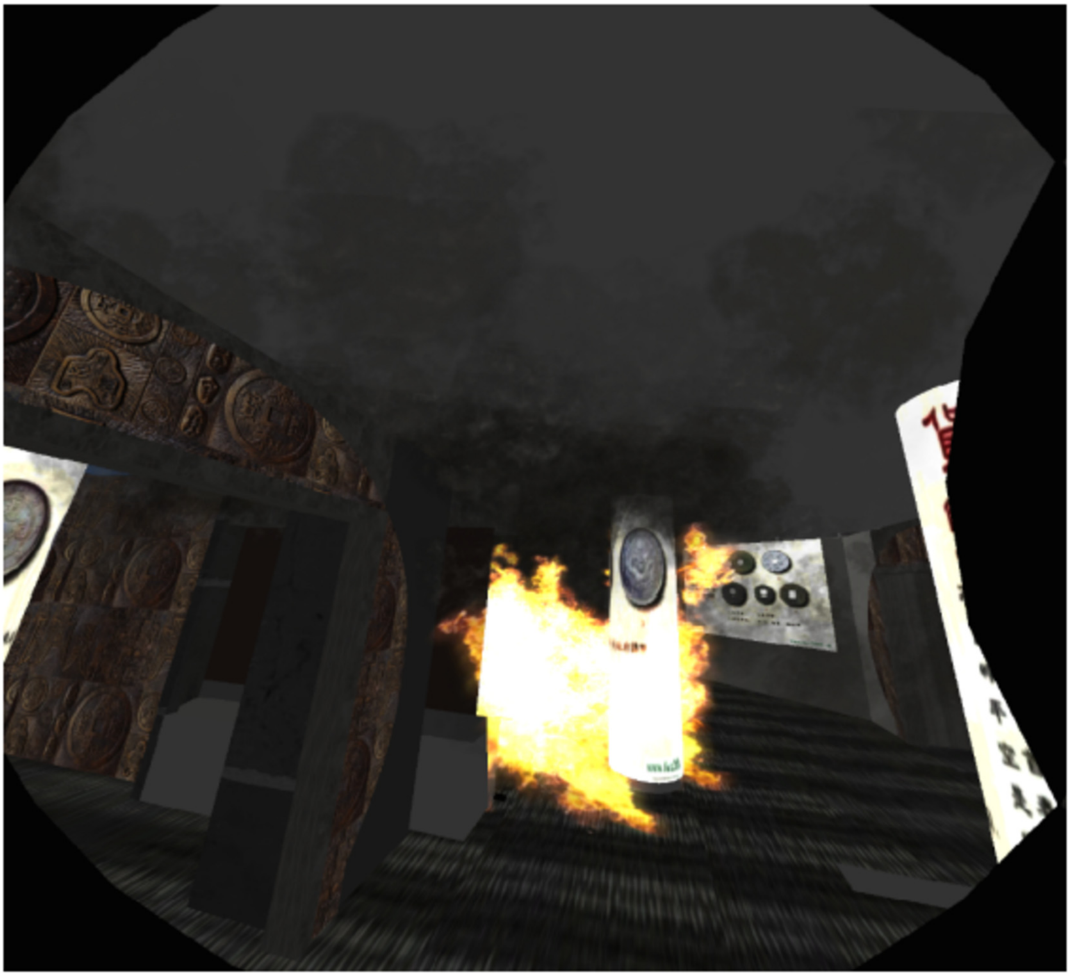


Fig. 1. An illustration of the screenshot for the display presented to the left eye inside the HTC helmet.

to visualize the spread of fire and smoke for the experimental condition of fire emergency.

During the experiment, the participants were instructed to sit in a chair and to use a Microsoft Xbox joystick to interact with the IVE. Specifically, they manipulated the joystick to virtually move in the IVE at a constant speed of 1.5 m per second, and to make virtual turns at their own speed while keeping their bodies physically still. Therefore, in the present study, the self-motion information regarding traveled distance and rotation was both provided purely via optic flow (Wan, Wang, & Crowell, 2010).

2.3. Virtual displays

The IVE used in the present study was a virtual museum which displayed various types of money used in different dynasties of China. The museum was 38 m long, 15 m wide, and 3 m high, decorated with grey bricks and black carpets. As can be seen in Fig. 2, there was only one door in the museum, which functioned as both the entrance and the

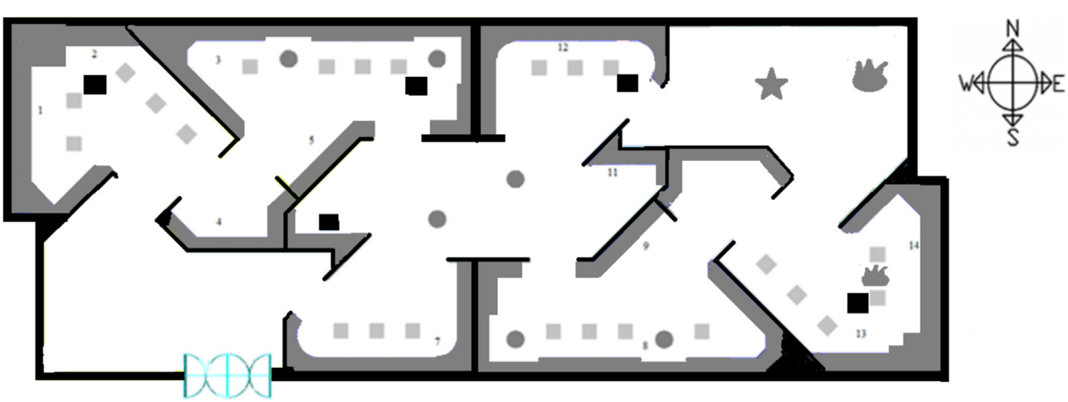


Fig. 2. An illustration of the museum layout. The glass-window display cabinets against the walls, display showcases, and display cylinders are denoted by the grey rectangles along the borders, grey squares, and grey circles, respectively. The five treasure keys, treasure point, and two fire points are denoted by the black squares, grey pentagram, and grey flame symbols, respectively.

Fig. 3. An illustration of the fire and smoke for the experimental condition of fire emergency.

exit. In this museum, there were a total of 16 glass-window display cabinets against the walls, 24 of display showcases, and 6 of display cylinders, all of which were protected by stanchion posts and barriers to keep the participants at least 0.5 m away. In addition, the participants were not allowed to walk through walls in this IVE.

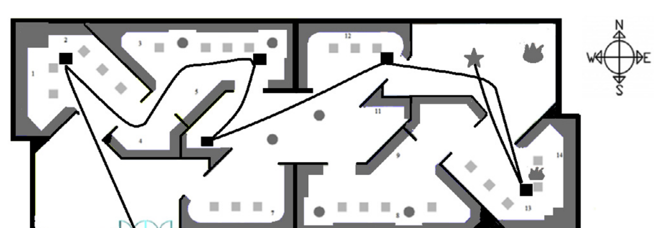
As shown by the two flame symbols in Fig. 2, there were two fires points in the museum for the experimental condition of fire emergency. Each fire spread in an area of 3 m × 3 m on the floor, while the smoke also spread to a much large range of areas and can be seen from everywhere in the museum (see Fig. 3 for an illustration).

2.4. Experimental design

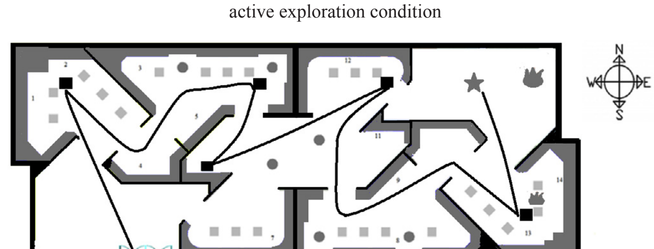
In the present study, the participants were asked to complete two tasks during the experiment, including a treasure hunting task and an egress task. The treasure hunting task was to explore the museum to find five hidden "treasure keys," and then to find a "treasure point" to retrieve the treasure with these keys. Upon arriving at the treasure point, the participants were asked to then conduct an egress task, for which they were asked to exit the museum as fast as possible.

We used a 2 (Exploration Mode: active or passive) × 2 (Experimental Condition: fire emergency or control) between-participants design. Prior to the experiment, the participants were randomly divided into four groups with the constraint of having equal numbers of males and females in each group. Two groups of the participants were instructed to freely explore the museum when trying to find the five treasure keys and the treasure point (i.e., the active exploration condition); whereas the other two groups were guided to travel along one of two pre-determined routes (see Fig. 4 for illustrations) to find the treasure keys and then the treasure point. Under the fire emergency condition, fire and smoke were presented in the IVE when the participants arrived at the treasure point; whereas no such stimuli were shown to the participants assigned to the control condition.

Here it should be noted that the participants assigned to the active exploration group were scheduled to take part in the study before the other two groups started, which allowed us to perform some preliminary data analysis on the routes they selected. To preview, we found two commonly chosen routes for the treasure hunting task, which were selected by 47% and 34% of all the participants under the active exploration condition, respectively. After we excluded some minor detours of these two routes taken by a few participants, we used the simplified version of these two routes to guide the participants under the passive exploration condition. Specifically, each participant under the passive exploration condition was randomly assigned to one of these two routes with the constraint of having equal size between the two groups and equal numbers of males and females within each group.



(A) This route (with minor revision) was taken by 47% of all participants under the active exploration condition



(B) This route (with minor revision) was taken by 34% of all participants under the active exploration condition

Fig. 4. The two routes for the treasure hunting task presented to the participants under the passive exploration condition.

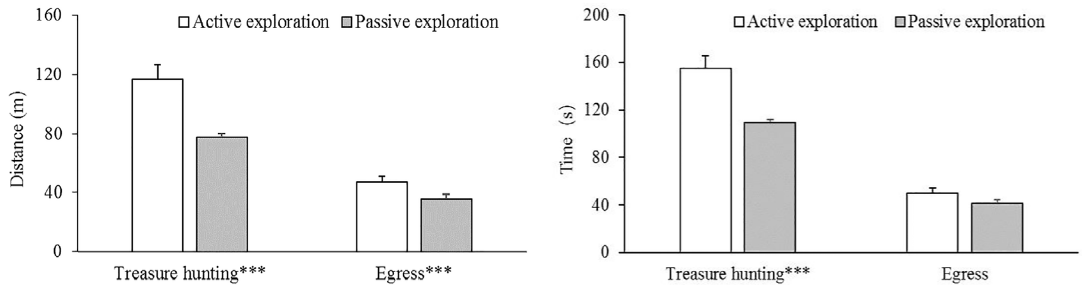


Fig. 5. The means of the travel distance and travel time of different exploration modes. The error bars indicate standard errors. ***p < 0.01.

Then each participant was required to explore the museum and to complete the treasure hunting task by following the route. All of the participants under the passive exploration condition followed these instructions and successfully completed the task.

2.5. Procedure

After arriving at the laboratory and signing a consent form, the participants were asked to rate the extent at which they felt nervous, scared and afraid, on 5-point Likert scale (Li, Chen, & Ni, 2013). Next, the participants were instructed to participate in a training session. They needed to complete a treasure hunting task and an egress task in a simple demo IVE that displayed a vacant room, in order to become familiar with the tasks and the joystick-based operations to interact with the IVE.

Then the main experiment started. As for the active exploration condition, the participants were instructed to freely explore the museum at their preferred direction to find the five treasure keys hidden in boxes (denoted by the red squares in Fig. 2), and then to find a "treasure point" (denoted by the yellow pentagram in Fig. 2) to retrieve the treasure using these keys. By contrast, the participants under the passive exploration condition were guided to follow pre-determined routes, demonstrated by some white arrows displayed on the floor, to pass by each treasure key location and then the treasure point. Importantly, the participants under both the active and passive exploration conditions were able to control their own movement in the IVE by using the joystick, whereas only those under the active exploration condition had the opportunity to make route decisions.

When the participants arrived at the treasure point, a sign saying "you have found the treasure, and please exist the museum as fast as you can" popped up in their sight. If under the fire emergency condition, virtual fire and smoke would also break out simultaneously; whereas no fire or smoke was presented for the control condition. The participants' view from the HMD was recorded over the entire main experiment with a video recording tool. The wayfinding behavior measures of the participants, including their travel distance and travel time for the treasure hunting task and the egress task, were also recorded during the entire main experiment.

After the main experiment ended, the participants were, once again, asked to rate the extent at which they felt nervous, scared and afraid, on 5-point scale, followed by a questions that asked them to estimate the time they spent in treasure hunting and evacuation, respectively. Then, they were asked to respond to the following questions on 5-point scales: (1) rating the level of difficulty of manipulating the joystick, finding the treasure, and evacuating from the museum; (2) indicating the extent at which they felt motion sickness during the main experiment, and their daily experience with playing video games; and (3) rating the vividness of the virtual museum presented in the main experiment phase, and their familiarity this IVE. Lastly, the participants were asked to respond to the Santa Barbara Sense of Direction Scale (Hegarty, Richardson, Montello, Lovelace, & Subbiah, 2002), and the wayfinding anxiety scale (Lawton, 1994).

3. Results

3.1. The wayfinding behavior measures

We used a total of four measures to assess the participants' wayfinding performance in the present study, including their travel distance (in meters) and travel time (in seconds) for the treasure hunting task and of the egress task. The means and standard errors of these four dependent variables are shown in Figs. 5 and 6.

Firstly, we performed 2 (Exploration Mode: active or passive) × 2 (Experimental Condition: fire emergency or control) between-participants ANOVAs on the travel distance and travel time for the treasure hunting task. The results revealed significant main effects of Exploration Mode on the travel distance, $F(1, 60) = 25.63$, $p < 0.001$, $\eta_p^2 = 0.30$, and on the travel time, $F(1, 60) = 18.42$, $p < 0.001$, $\eta_p^2 = 0.24$. These results revealed that the participants under the active exploration condition traveled for longer distance (116 m vs. 77 m) and spent more time (155 s vs. 109 s) than those under the passive exploration condition. None of other main or interaction effects was significant, all $Fs < 1.97$, $ps > 0.16$.

Similarly, the Exploration Mode × Experimental Condition ANOVAs on the travel distance and travel time for the egress task revealed a significant main effect of Exploration Mode on the travel distance, $F(1, 60) = 9.32$, $p < 0.01$, $\eta_p^2 = 0.13$. The results suggested that the participants under the active exploration condition traveled for longer distance (47 m vs. 36 m) than those under the passive exploration condition during the egress task. The results also revealed a

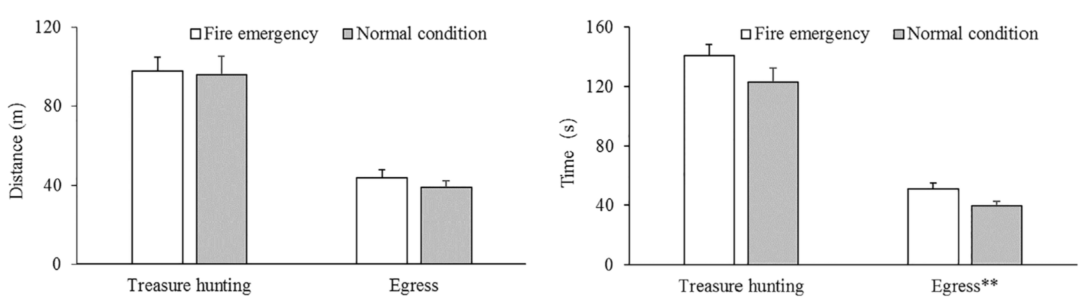


Fig. 6. The means of the travel distance and travel time under different environmental conditions. The error bars indicate standard errors. **p < 0.05.

Table 1
Mean scores of the subjective ratings in the present study (N = 64).

Subjective ratings (range of values)		Active Exploration		Passive Exploration	
		Fire (N = 16)	Control (N = 16)	Fire (N = 16)	Control (N = 16)
Feeling nervous (1–5)	Before	2.25 (0.93)	2.88 (1.09)	2.00 (0.97)	2.06 (0.77)
	After	2.88 (0.86)	2.94 (1.12)	2.13 (0.96)	2.06 (0.93)
Feeling scared (1–5)	Before	1.63 (0.72)	1.69 (0.87)	1.44 (0.89)	1.56 (0.73)
	After	2.31 (0.95)	1.81 (1.11)	1.63 (0.81)	1.31 (0.60)
Feeling afraid (1–5)	Before	1.63 (0.96)	1.69 (0.87)	1.44 (0.73)	1.25 (0.45)
	After	2.81 (1.28)	1.81 (1.22)	1.75 (0.93)	1.19 (0.40)
Estimated time in treasure hunting (in second)		322.50 (154.72)	286.88 (159.86)	253.13 (110.07)	187.50 (113.58)
Estimated time in evacuation (in second)		133.13 (118.98)	116.25 (70.89)	116.25 (78.90)	105.75 (89.23)
Difficulty of joystick manipulation (1–5)		2.63 (1.02)	2.88 (1.20)	2.88 (1.71)	2.19 (1.22)
Difficulty of treasure hunting (1–7)		2.88 (1.09)	2.94 (1.84)	1.81 (0.91)	1.25 (0.45)
Difficulty of evacuation (1–7)		3.56 (1.75)	3.19 (1.76)	4.63 (1.67)	3.13 (1.59)
Motion sickness (1–7)		3.93 (2.21)	3.94 (2.17)	3.00 (1.55)	3.56 (2.03)
Daily experience with playing video games (1–7)		3.19 (1.91)	2.63 (1.75)	3.00 (1.51)	3.00 (1.75)
Vividness of the IVE (1–7)		4.31 (1.26)	4.38 (1.45)	3.94 (1.44)	4.13 (1.41)
Familiarity with the IVE (1–7)		3.5 (1.26)	3.13 (1.31)	3.00 (1.32)	4.00 (1.41)
Sense of direction (15–105)		65.69 (16.12)	65.69 (14.73)	65.69 (15.68)	62.44 (19.87)
Wayfinding anxiety (8–40)		26.06 (6.38)	23.69 (4.82)	23.69 (5.93)	25.75 (5.81)

significant main effect of Experimental Condition on the travel time, $F (1, 60) = 5.67$, $p = 0.02$, $\eta_p^2 = 0.09$, suggesting that the participants under the fire emergency condition spent more time on exiting the museum than those under the control condition (51 s vs. 40 s). None of other main or interaction effects was significant, all $Fs < 2.74$, $ps > 0.16$.

In order to rule out any sex differences, we also performed Exploration Mode × Experimental Condition × Sex ANOVAs on the four measures. None of the main effect of Sex or interaction effects between Sex and other independent variable(s) was significant, all $Fs < 3.04$, $ps > 0.09$.

3.2. The subjective ratings of the participants

The mean scores of all subjective ratings from the participants are summarized in Table 1. First, we performed 2 (Session: before or after the main experiment) × 2 (Experimental Condition: fire emergency or control) mixed-design ANOVAs on the emotion ratings, with Session being a within-participants factor and Experimental Condition being a between-participants factor. The results revealed a significant main effect of Session on the ratings of feeling *afraid*, $F (1, 62) = 6.28$, $p = 0.01$, $\eta_p^2 = 0.05$, but it was qualified by a significant interaction term, $F (1, 62) = 5.38$, $p = 0.02$, $\eta_p^2 = 0.04$. To interpret this interaction term, we performed paired-samples t tests. The participants under the fire emergency condition felt more afraid after the main experiment than before it (2.28 vs. 1.53), $t(31) = 2.86$, $p < 0.01$, Cohen's $d = 0.33$; whereas no such effect was found for the participants under the control condition, $t(31) = 0.15$, $p = 0.88$. None of the main or interaction effects was significant on the ratings of feeling *nervous* or *scared*, all $Fs < 1.49$, $ps > 0.22$. These results suggested that, compared to the control condition, presenting the fire and smoke in the fire emergency condition did evoke *afraid* emotion among the participants.

We also performed 2 (Exploration Mode: active or passive) × 2 (Experimental Condition: fire emergency or control) between-participants ANOVAs on the self-estimation of the time spent on treasure hunting and egress. The results revealed a significant main effect of Exploration Mode on the estimation of treasure hunting time, $F (1, 60) = 6.12$, $p = 0.016$, $\eta_p^2 = 0.09$, suggesting that the participants under the active exploration estimated that they spent more time on searching for the treasure than those under the passive exploration (305 s vs. 220 s). None of other main or interaction effects was significant, all $Fs < 1.40$, $ps > 0.38$.

Next, the Exploration Mode × Experimental Condition ANOVAs on the ratings of task difficulty revealed a significant main effect of Exploration Mode on the rated difficulty of finding treasure, $F (1, 60) = 21.58$, $p < 0.001$, $\eta_p^2 = 0.26$. These results suggested that the participants under the active exploration condition considered the treasure hunting task to be more difficult than those under the passive exploration condition (2.91 vs. 1.53, out of 5 points). The results also revealed a significant main effect of Experimental Condition on the rated difficulty of egress, $F (1, 60) = 4.91$, $p = 0.31$, $\eta_p^2 = 0.08$, suggesting that the participants under the fire emergency condition considered the egress to be more difficult than those under the control condition (4.09 vs. 3.16, out of 5 points). None of other main or interaction effects was significant, all $Fs < 2.51$, $ps > 0.12$.

Last but by no means the least, analysis of covariance (ANCOVA) was conducted for each of the following confounding factors, including the participants' ratings of motion sickness, daily experience with playing video games, the vividness of the IVE, the participants' familiarity with the IVE, their Sense of Direction scores, and wayfinding anxiety scores. After effects of these covariates had been removed, the ANCOVA revealed no significant interaction on main effects.

4. Discussions and conclusions

The main findings and effects revealed in this study are summarized in Table 2. These findings are further discussed in detail in this section.

4.1. The influence of active or passive spatial learning on wayfinding

To sum up, the results of the present study revealed that the participants under the active exploration condition traveled for longer distance and time during the treasure hunting task. Intuitively, this makes sense, because the participants under the passive exploration condition, by following predetermined routes, needed much less spatial knowledge to complete the treasure hunting task. This further resulted in the fact that the participants under the active exploration condition rated the treasure hunting task to be more difficult, as they experienced more intensive acquisition and processing of spatial knowledge while performing the task. Moreover, the routes in passive exploration were free of circles or detours and were hence shorter than the average length of routes the participants took under the active exploration condition. This was evidenced by a review of video recordings of the experiment, which revealed that 53.1% (17 out of 32) of the participants who actively explored the space took circles or detours, leading to noticeable expansion of their routes and delays in completing the treasure hunting task.

The results also revealed that, compared to those under the passive exploration condition, the participants under the active exploration

Table 2
Summary of main findings.

Independent variable	Dependent variable	Averages and ANOVA results
Exploration mode (active vs. passive)	Travel time for treasure hunting task	155 s vs. 109 s; F (1, 60) = 18.42, $p < 0.001$, $\eta_p^2 = 0.24$
	Travel distance for treasure hunting task	116 m vs. 77 m; F (1, 60) = 25.63, $p < 0.001$, $\eta_p^2 = 0.30$
	Travel distance for egress task	47 m vs. 36 m; F (1, 60) = 9.32, $p < 0.01$, $\eta_p^2 = 0.13$
	Self-estimated travel time for treasure hunting task	305 s vs. 220 s; F (1, 60) = 6.12, $p = 0.016$, $\eta_p^2 = 0.09$
	Self-rating of difficulty of treasure hunting task	2.91 vs. 1.53, out of 5 points; F (1, 60) = 21.58, $p < 0.001$, $\eta_p^2 = 0.26$
Experimental condition (fire emergency vs. control)	Travel time for egress task	51 s vs. 40 s; F (1, 60) = 5.67, $p = 0.02$, $\eta_p^2 = 0.09$
	Self-rating of difficulty of egress task	4.09 vs. 3.16, out of 5 points; F (1, 60) = 4.91, $p = 0.031$, $\eta_p^2 = 0.08$
Session (before vs. after the main experiment)	Self-rating of feeling afraid	2.28 vs. 1.53, out of 5 points; F (1, 62) = 6.28, $p = 0.01$, ηp2 = 0.05

condition traveled for longer distance during the egress task and rated this task to be more difficult. This contradicted with Peruch et al. (1995), Hazen and Nancy (1982) and Chrastil and Warren’s (2013) studies, which all reported that active exploration resulted in better wayfinding performance than passive exploration.

One possible reason for this inconsistency may be related to the objective of the egress task, which was to find the exit of the space. To carry out this task may not require the entirety of the cognitive map. Rather, spatial knowledge that was related to the location of the exit played a more significant role. In this study, participants who followed predetermined paths and passively explored the space had the advantage of being less inclined to turn their heads and eyes to actively seek for the treasures. As a result, they were able to maintain a steady orientation of gaze relative to their body, and were less distracted by large volume of spatial information that was irrelevant to the location of the exit. These factors could have contributed to their ability to remember the direction of the exit as they egressed from the space.

Another possible reason for this inconsistency may lie in the fact that what was directly assessed in most prior studies was the impact of spatial exploration mode on spatial learning outcomes of the participants, rather than the impact on their actual wayfinding capabilities (Laird, 2012). There is apparent difference between the spatial memory and actual wayfinding behavior. Darken and Peterson (2001) argued that the cognitive map based on spatial memory is not a picture in the head. They believed that the cognitive map is not merely based on imagery but rather has a symbolic quality. It includes a variety of mental processes that people use to recall information, which shapes the way people travel in the built environment (Mondschein, Blumenberg, & Taylor, 2013). Among the few prior studies that tested the impact of spatial exploration mode on participants' actual wayfinding capabilities, Christou and Bülthoff (1999) reported results that also differed from the majority of prior studies. They found no difference between the active and passive groups in their experiments. The results observed in the present study added to the belief that there exists significant difference between capabilities of writing down or drawing the outline of a space by recalling spatial memory, and the capabilities of actually looking for certain target or location in the space by utilizing spatial memory.

4.2. The influence of fire emergency on evacuation

The results of the present study also revealed that the participants under the fire emergency condition spent more time in finding their way to exit the museum, and rated the evacuation task to be more difficult. These results were consistent with Meng and Zhang (2014) findings that the participants under the fire emergency condition had a longer escape time to find the exit than those under the control condition. These findings suggested that the fire emergency had a significant impact on the participants' wayfinding performance during egress, and there are several possible reasons.

Firstly, the virtual fire and smoke in the environment would have a direct impact on the participants' decision to start evacuation. A review of experiment videos revealed that when the fire broke out in the virtual environment, the participants were hesitant to follow the instruction to exit the museum immediately. Instead, they spent some time perceiving the environment and making their wayfinding decisions. A similar observation was reported in Gamberini et al.’s (2003) study. Drawing on the situated action theory (Suchman, 2007), which suggests that action is produced in strict interdependence with the local contingencies of the situation, Gamberini et al. (2003) argued that the breakout of fire forced participants to take time to re-organize their movement strategies in a way that they could be related to the specific circumstances of the environment.

Secondly, the virtual fire and smoke in the environment would impact the participants' abilities to use of spatial knowledge during the wayfinding process. Cognitive maps provide people with information relating to the destination and the route to get there from the current location (Tversky, 1993). In order to find the route to the exit, it was necessary for the participants to acquire sufficient knowledge about surrounding environment. The environmental knowledge acquisition, however, was made difficult by the presence of fire and smoke. Siegel and White (1975) proposed the Landmark, Route, and Survey (LRS) model, which was a knowledge-based model that described the components from which spatial knowledge could be acquired. Landmarks are critical components in the environment. Landmark knowledge is useful in establishing general directions, and it is an important part of the cognitive map (Woyciechowicz & Shliselberg, 2005). The virtual smoke in the museum blocked the sight of the participants who could not see landmarks in the distance. Consequently, they could not establish general directions immediately and needed more time to identify the direction and decide the next step to take (Sadeghian, Kantardzic, Lozitskiy, & Sheta, 2006).

Thirdly, the fire emergency could cause significant psychological responses on the participants. In this study, we found that the participants in the fire emergency condition felt more afraid after the main experiment than before it, whereas no such effect was found for the participants under the control condition. It is consistent with Proulx (1993) stress model, which suggests that people would feel fear or stress when they face a fire. In Ozel (2001) study, it was found that significant increase in stress could create a high tension state, which may limit the capacity of people to process environmental information effectively. For wayfinding, this limitation may significantly affect the efficiency of people to collect environmental cues and compare them with the cognitive map in their memory (Chorus & Timmermans, 2010), resulting in longer time that is required to complete a given wayfinding task.

At the meantime, it is noteworthy that the results revealed there was no significant difference in the distance the participants traveled during egress. This suggested that, although the presence of fire and smoke took the participants longer time to perceive and process the environmental information, it did not lower the quality of wayfinding decisions the participants made. The participants did not travel extra distance in the space under fire emergency, and were as successful as those under control condition in finding an efficient route to the exit.

It should also be noted that, as Walkowiak, Foulsham, and Eardley (2015) pointed out, navigation in virtual environments is effected not only by navigational strategy, but also an individual's personality, and other factors such as their level of experience with computers. We found that the participants assigned to the fire emergency and control conditions did not differ in their ratings of motion sickness, daily experience with playing video games, their perceived vividness of and familiarity with the IVE, their Sense of Direction scores, or wayfinding anxiety scores. The lack of between-groups differences ruled out the possibility that the difference in travel time observed in this study was due to individual differences.

4.3. Implications, limitations and future work

The findings of this study have several practical implications. First of all, based on the findings passive exploration model is recommended for indoor public spaces where setting predetermined routes for visitors is possible and public safety is a primary concern. Secondly, the findings suggested that setting up recognizable landmarks at critical locations and increasing their visibility could be an effective approach for facilitating people's egress in case of building fire emergencies. Lastly, the revealed impacts of exploration mode and experimental condition on the participants' behaviors could be used to improve existing engineering models that simulate indoor crowd evacuation, thus supporting performance-based fire safety design of buildings as well as building emergency management operations.

Admittedly, there are also several limitations in the present study, which can be addressed in future research. First of all, this study shares the same issue that all other VR-based behavior studies are faced with, namely the challenge to ecological validity of the results due to possible difference between the virtual environments and the reality. Ecological validity refers to the extent to which experiment subjects' perceptions and responses can be generalized to real-life settings (Brewer, Reis, & Judd, 2000). It highly relies on the sense of presence of the participants in the IVEs, which is determined by the level of realism of the IVEs (Zou et al., 2017). Future research is needed to further improve the IVEs, e.g. by enhancing the quality of model rendering, and integrating alarm sound and temperature stimuli.

Secondly, this study guided the participants to explore the virtual museum by asking them to complete a treasure hunting task, during which they had to find several locations scattered around the space. In reality, however, exploration of an indoor space could be done in a less purposeful manner, such as wandering in a shopping mall without particular wayfinding goals, or in a less thorough manner, such as moving between the entrance and platform of a subway station without exploring the entire space. We believe that whether the findings in this study are applicable when the spatial exploration is performed differently is an interesting question that warrants future research.

Thirdly, wayfinding is a complex cognitive process that includes goal setting, perception, acquisition, assessment and movement (Darken & Peterson, 2001). Each of these steps could be affected by spatial exploration mode and fire emergency. Future research can be done to examine these stepwise effects, which will deepen the understanding of people's wayfinding behavior, and enable the development of better wayfinding behavior interference methods and tools to support efficient evacuation during building fire emergencies.

Declarations of interest

None.

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