

## Full length article

# Assessing the influence of repeated exposures and mental stress on human wayfinding performance in indoor environments using virtual reality technology

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## ABSTRACT

This study aimed to examine the effect of repeated exposures to indoor environments on people's indoor wayfinding performance, both under normal condition and during fire emergency which could induce significant mental stress. Indoor wayfinding experiments were conducted in an immersive virtual museum developed using virtual reality technologies. Participants of the experiments were divided into three groups, who participated in one, two and three trials, respectively. Those who participated in more than one trial were given an interval of two weeks between two consecutive trials. Each trial of the experiment included a treasure hunting task and an egress task. Participants were presented with a virtual fire emergency during the egress task of their last trial. Data of wayfinding performance measures of the participants, as well as their physiological and emotional responses, sense of direction, wayfinding anxiety and simulator sickness were collected and analyzed. The results revealed significant positive impact of repeated exposure on participants' wayfinding performance, which resulted in a decrease in the time needed to complete the treasure hunting task. The results also revealed significant negative impact of mental stressed caused by the fire emergency on participants' wayfinding performance, which led to increased travel time and distance during egress. Such negative impact of stress, however, could be noticeably diminished by the repeated exposures, showing significant interaction effect between these two factors.

## 1. Introduction

Wayfinding involves complex cognitive processes that include goal setting, perception, acquisition, assessment and movement [1]. Wayfinding behavior has been extensively examined in existing literature [2–5]. Prior experience with a space has been identified in the literature as an important factor to influence people's wayfinding abilities [6–8]. Through experience with a space, people acquire and encode environmental cues as spatial knowledge in cognitive map that can be retrieved for improving wayfinding performance [9]. Cognitive map is the mental representation of spatial knowledge about environmental cues [10]. Cognitive map is first stored in working memory after it is developed based on perception, and is then stored in episodic memory for long-term use [11–14].

Enriching the experience, with repeated exposures to the same space, has the potential to enhance the quality of cognitive map, which could improve choice of wayfinding strategies and the overall wayfinding performance [14,15]. Several prior studies reported preliminary

evidence to this hypothesis [16,17]. In these studies, however, repeated exposures were performed all at once, with every successive exposure almost immediately following the preceding one. What has remained largely unknown and requires further investigation is how repeated exposures, when they are separated by certain time interval, would affect people's wayfinding performance. This is important to investigate because of two reasons. First of all, in theory, people perform episodic long-term memory tasks very differently than working memory tasks [18]. For wayfinding, in particular, Matheis et al. [19] contended that spatial knowledge acquired through prior experience and stored in the cognitive map could endure partial loss over time. In their study, a 24-h delay caused significantly worse spatial knowledge recall and recognition than a 30-min delay. This suggests the repeated exposures, when separated with time interval, may have different effects on wayfinding performance than otherwise. Secondly, in reality, separated repeated exposures are commonly observed in a wide variety of scenarios such as shopping malls and museums. Understanding their effect on human wayfinding performance in indoor environments would have significant

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empirical implications pertaining to building design (e.g. optimizing circulation in commercial buildings), building service (e.g. providing better indoor navigation service) and building emergency management (e.g. conducting more efficient emergency rescue operations).

Fire is the foremost life-threatening hazard in indoor environments. According to U.S. Fire Administration (USFA) statistics, building fires caused 2635 fatalities and 12,800 injuries in the United States in 2015 [20]. Recent apartment fires in London and New York that involved massive victims once again demonstrated the risks of building fires, and highlighted that successful evacuation of building occupants during fire emergencies was vital for their chances of survival. The efficiency of building fire evacuation is largely determined by the wayfinding abilities of the occupants under a stressful indoor environment [21]. Prior research has found that emergency condition could impact the perception of people about environmental cues and the retrieval of cognitive map, and hence decrease their wayfinding performance [22]. A recent study reported potential learning effect of repeated exposures on wayfinding performance in tunnel fire emergency [23], but such interaction effect of repeated exposure and fire emergency is still unclear and requires further investigation.

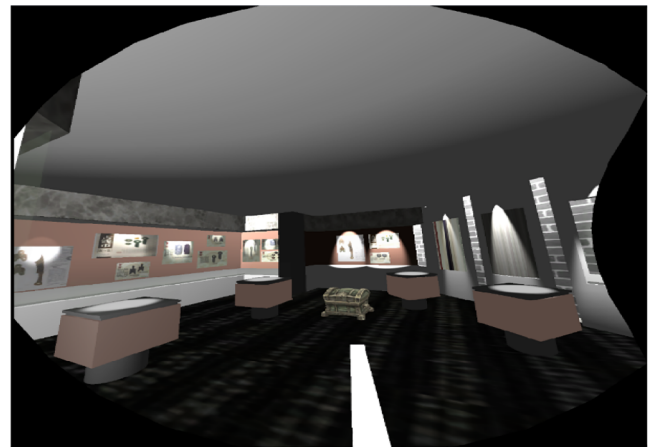
Conducting wayfinding behavior experiments at real building fire emergency scenes is challenging due to legal and moral reasons. Immersive Virtual Environments (IVEs), which are built on Virtual Reality (VR) technologies, provide a promising alternative approach [24]. With rapid advancement of VR technologies in recent years, a large number of studies has tested IVE in wayfinding-related experiments and repeatedly reported its effectiveness [14,22,25]. Previous studies have used IVEs to examine different aspects of people's wayfinding behaviors during their escape from building fire emergencies, including their route choice [23], waiting time [26], and adaptivity to emergency situations [27].

In the present study, the following two research questions are addressed. First, how do repeated exposures influence human wayfinding performance in exploring and egressing from indoor environments? Second, how does mental stress in fire evacuation interact with repeated exposures to influence human wayfinding performance during indoor fire emergency evacuation? To address these two questions, IVE-based wayfinding behavior experiments were conducted, and the results are reported and discussed in this paper.

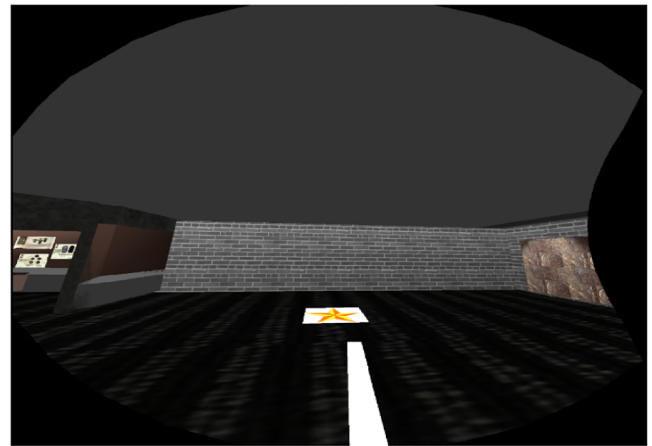
## 2. Methods

### 2.1. Participants

Sixty Chinese undergraduate and graduate students from a major university in Beijing, China, were recruited in this study. The recruitment was done by distributing a call-for-participant flyer through online social media. Interested students expressed their intent to participate by filling out an online questionnaire. Responses to the questionnaire were assessed to make sure that all participants had normal or corrected-to-normal vision, none of them had color blindness, and that there was an equal number of male and female participants. Participants who responded to the call were invited to the experiment on a first-come, first-served basis until the required number of participants was reached. Each of them received fifty CNY as monetary incentives for completing one trial which lasted around thirty minutes. Participants who were invited to come back for a second or third trial were given doubled or tripled incentives. This study was approved by the Ethics Committee of the Psychology Department of Tsinghua University. Of all sixty participants, twelve participants were not able to complete their experiment as scheduled. Excluding the above participants, a total of forty-eight participants ( $20.9 \pm 1.96$  years old on average, ranging from 18 to 25; 24 males and 24 females) were considered in this study.



a



b

Fig. 1. Illustrations of the virtual display used in this study from left eye: boxes within treasure keys (a) and the treasure point (b).

### 2.2. Apparatus and virtual displays

We used a HTC VIVE head-mounted-display (HMD) virtual reality system [28]. Fig. 1 shows the screenshots from the left eye of the HMD. The participants were instructed to use an Xbox Joystick to interact with the IVEs. This locomotion method was used because of its low tracking errors, low workload and high usability as well as its wide application in prior VR-based behavioral studies [24,29,30]. The IVEs were created using Unity3D game engine [31], which was also used to run the experiment.

A 38 m (length)  $\times$  15 m (width)  $\times$  3 m (height) virtual monetary museum (see Fig. 2 for the layout) was used for the present study. The layouts can be seen in Fig. 2. All of the display cabinets and showcases in the virtual museum were protected by crowd control queue station posts and barriers, so the participants were kept at least 50 cm away from them.

Under the condition of fire evacuation, the spreading of fire and smoke was based on numerical computation results generated with Fire Dynamics Simulator (FDS) software, and the fire and smoke were visualized and displayed (see Fig. 3a for an illustration) by particle system in Unity3D. The participants would hear standard fire alarm from headphone (default headphone in HTC VIVE set) with medium volume at the same time. To be more specific, virtual fire (subtending an area of 4.2 m  $\times$  6.6 m) was presented at two certain locations near the treasure point (see Fig. 3a for an illustration). The virtual smoke (subtending an area of 38 m  $\times$  15 m) spread from the ground up to as

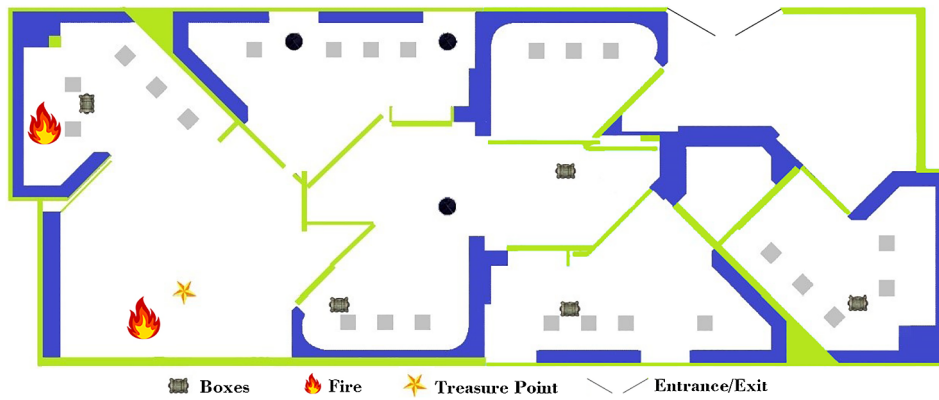
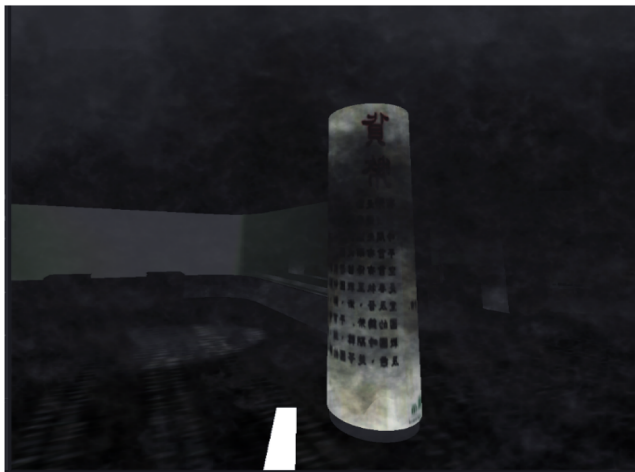


Fig. 2. Illustration of the layout of the virtual museum.



a



b

Fig. 3. An illustration of the virtual fire (a) and the virtual smoke over the walls (b).

high as 3 m, so it could be seen over the walls from every location within the museum (see Fig. 3b for an illustration).

During the experiment, the participants physically remained still, and manipulated the joystick to move forward or make turns at a constant speed of 1.5 m/s. Their travel distance, travel time and travel routes were monitored and recorded by the system.

### 2.3. Design

The experiment lasted approximately 3 months. Forty-eight participants were randomly divided into three groups (with the constraint of having equal numbers of males and females in each group). The first group consisted of 16 participants, who were invited to participate in one trial, during which they were asked to navigate through the IVE and then to find their way out when a fire emergency broke out in the IVE. We refer to this group as Fire1 group. The second group consisted of 16 participants, who were invited to participate in two trials. For the first trial, they were asked to navigate through the IVE and then to find their way out under normal circumstances. Approximately two weeks later, participants in this group came back to the laboratory to participate in a second trial, during which they navigated through the same IVE and then found their way out under a fire emergency. We refer to this group as Fire2 group. The third group, which we refer to as Fire3 group, consisted of 16 participants, who were invited to participate in three trials. During the first and second trials, which had approximately two weeks in between, the participants were asked to navigate through the same IVE and then to find their way out under normal circumstances. Approximately another two weeks later, participants in Fire3 Group were invited to a third trial, during which they navigated through the IVE and then found their way out during a fire emergency. In summary, participants in the Fire1, Fire2, and Fire3 groups encountered the virtual building fire emergency and performed way-finding under this emergency circumstances during their first, second, and third trial, respectively.

### 2.4. Procedure

When participants first signed up for this study, they were asked to answer a questionnaire that collected basic demographic information about the participants, including age, gender, and the sense of direction measured with the Chinese version of Santa Barbara Sense of Direction Scale (SBSOD) [32]. The questionnaire was hosted using an online survey tool [33].

An overview of the procedure in one trial is shown in Fig. 4. When the participants came to the laboratory and signed in to the experiment, they were asked to sign a consent form. The participants were then instructed to put on a skin conductivity sensor that was used to collect electrodermal activity (EDA) data, and complete a questionnaire that was composed of the Chinese revision of Positive Affect and Negative Affect Scale (PANAS) [34] and the Simulator Sickness Questionnaire (SSQ) [35]. PANAS is a standard scale of emotions designed by Watson et al. [36] and widely used in psychology studies. Considering the difference in culture and language, Qiu et al. [34] modified the original

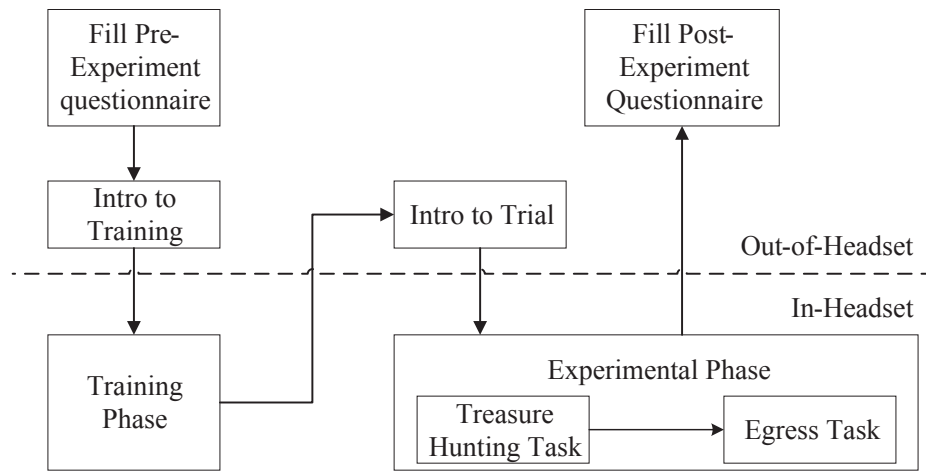


Fig. 4. Study procedure in each trial (events above the dashed line occurred outside of the VR headset, and events below the line took place while the participant was wearing the headset).

PANAS and developed a Chinese revision of PANAS, which has been widely used in studies that involve participants whose native language is Chinese [25,37]. The Chinese revision of PANAS includes nine items describing positive emotions (active, enthusiastic, inspired, elated, excited, proud, happy, invigorating and grateful), and nine items describing negative emotions (guilty, upset, scared, nervous, terrified, shamed, irritable, jittery and afraid). Participants need to subjectively evaluate their current status of each emotion and rate the corresponding item in 5-point scale. The items of positive emotions include active, enthusiastic, inspired, elated, excited, proud, happy, invigorating and grateful. The items of negative emotions include guilty, upset, scared, nervous, terrified, shamed, irritable, jittery and afraid. Next, the participants were instructed to finish two phases of the trial, including a training phase and an experimental phase. During the training phase, they needed to follow instructions to complete a treasure hunting task and an egress task in a simple demo IVE. The objective of having the participants go through this training phase was to help them become familiar with the tasks they needed to perform in the experimental phase, and the joystick-based operations to interact with the IVE. The participants were allowed to enter the experimental phase only after they had completed the training phase and were used to the sense of immersion and the joystick-based operations in the IVE.

When the experimental phase started, the participants first read an instruction about two tasks they needed to complete. A treasure hunting task asked them to first explore the space, by finding five boxes in the monetary museum IVE where they could retrieve five treasure keys (see Fig. 1a for an illustration of the boxes, and see Fig. 2 for locations of the boxes), which they could then use to retrieve a hidden treasure in a treasure point (see Fig. 1b for an illustration and Fig. 2 for its location). Then, an egress task asked participants to egress from the museum through the exit as fast as possible. When they were clear about these instructions, the participants put on the HMD. In the IVE, the participants found themselves initially positioned at the entrance of the museum, where they could enter the museum and start exploring the space. As soon as they collected all five treasure keys and arrived at the treasure point, a visual sign, “Treasure found, please exit the museum immediately”, popped up to instruct the participants to exit the museum. If the trial included a fire emergency, the participants would also see fire and smoke and hear fire alarm, until they reached the exit and completed the egress task.

The participants were informed that they could choose to quit the training phase or experimental phase at any time if they felt sick or uncomfortable in the virtual environment. After both phases were completed, the participants were required to answer the PANAS and SSQ once again, and complete a self-report questionnaire about their

wayfinding spatial anxiety [38].

### 2.5. Data recording and analysis

Four types of data were recorded in the experiment for analysis: (1) Wayfinding behavior measures. These included the travel distance (d1) and travel time (t1) of the participants when performing the treasure hunting task, and the travel distance (d2) and travel time (t2) of the participants when performing the egress task; (2) The participants’ subjective evaluation to simulator sickness, spatial anxiety, and sense of direction; (3) The participants’ emotional responses measured by PANAS; and (4) The participants’ physiological responses measured by EDA during the treasure hunting task and egress tasks. EDA reflects the sympathetic activation of the autonomic nervous system. It is widely used in prior VR-based studies to validate the emotional arousing and sense of presence of participants in virtual environments [39,40]. The specific EDA indicator used in this study was Skin Conductivity Response Amplitude (SCR amplitude) [41], which was reported based on raw segment EDA data processed using ErgoLAB platform [42].

## 3. Results and discussions

### 3.1. The first exposure

First of all, we focused on the results from the participants’ first trial. Participants in Fire1 group were compared to participants in Fire2 + Fire3 group (Comparison A; A nomenclature of all comparisons reported in this paper can be found in Table 1). Movies 1, 2, 3, are sample video recordings of three participants (ID#63 in Fire1 group, #37 in Fire2 group and #18 in Fire3 group) participating in the first

Table 1  
A nomenclature of all comparisons.

Comparison	Control variable	Independent variable	Study Groups	
A	Periodic repeated exposure	Emergency condition	Fire Normal	Fire1 Fire2 + Fire3
B	Periodic repeated exposure	Emergency condition	Fire Normal	Fire2 Fire3
C	Normal condition	Periodic repeated exposure	First Second	Fire3 Fire3
D	Fire emergency	Periodic repeated exposure	First Second	Fire1 Fire2
E	Fire emergency	Periodic repeated exposure	Second Third	Fire2 Fire3

**Table 2**  
Mean of four behavioral measures in Comparison A (standard deviation in parentheses).

Behavioral measures	t1	d1	t2**	d2***
Fire1 Group	135.31 (42.50)	97.91 (27.38)	57.13 (32.69)	53.76 (28.64)
Fire2 + Fire 3 Group	136.90 (59.30)	100.36 (27.64)	42.66 (37.35)	37.95 (14.98)

Note:

\*\*  $p < .05$ .

\*\*\*  $p < .01$ .

trial. The means of the four behavioral measures (d1, t1, d2, and t2) under the fire emergency and normal condition are shown in Table 2. Anderson Darling test [43] rejected that d1, t1, d2 and t2 in all two samples of Comparison A followed normal distribution (partly  $p < .10$ ). The Mann-Whitney  $U$  test, a nonparametric independent samples test, was therefore applied in Comparison A [44]. The test revealed a significant group differences in t2 ( $U = 139.50$ ,  $z = -2.55$ ,  $p = .011$ ,  $r = -0.37$ ) and d2 ( $U = 131.00$ ,  $z = -2.74$ ,  $p = .006$ ,  $r = -0.40$ ) and no significant group differences in t1 or d1 (all  $p \geq .646$ ).

The results revealed that participants who exited the museum under fire emergency spent more time and traveled a longer distance than those who exited the museum under normal condition. This is consistent with findings reported in prior studies that people's wayfinding performance would be adversely impacted by fire emergency [23,45,46]. There are two possible reasons. First, fire and smoke reduced the visibility of the environment. Prior studies found that difficulty in visual access of the environment could impact recognition of landmarks and position [47] which could in turn affect the assessment of wayfinding progress with cognitive map and consequently reduce the wayfinding performance [1]. Secondly, prior studies found that virtual fire emergency could cause stress on participants [45]. Stress could affect environmental perception of the participants, and make them inclined to rely on random route choices, instead of making reasonable wayfinding decisions based on the spatial knowledge in their cognitive maps [45,48].

### 3.2. The second exposure

Then, we focused on the results from the participants' second trial. Movies 4 and 5 are sample video recordings of two participants (ID#37 in Fire2 group and #18 in Fire3 group) participating in the second trial. The means of the four behavioral measures (d1, t1, d2, and t2) of all participants in Fire2 group who were under the fire emergency, and Fire3 group, who were under normal condition, respectively, are shown in Table 3 (Comparison B). Anderson Darling test rejected that d1, t1, d2 and t2 in Comparison B followed normal distribution (partly  $p < .10$ ), hence the Mann-Whitney  $U$  test was suitable to analyze d1, t1, d2 and t2 in Comparison B. The test revealed no significant group difference in any behavioral measure (all  $p \geq .160$ ).

The results showed that, to the contrast with the first exposure, participants who egressed under normal condition had comparable travel distance and time to those who egressed under fire emergency. A possible explanation of this distinction between the two exposures is related to the three types of spatial knowledge in cognitive map, namely landmark knowledge, procedural (route) knowledge and survey knowledge [49,50], and their different roles in facilitating wayfinding. Landmark knowledge can speed up perception of position and

environmental cues [12,13,51]; Procedural knowledge can be used to form a mental representation of the connections between landmarks and develop a plan for movement of the next step using an allocentric navigation strategy [22,50,52]; Survey knowledge, the acquisition of which usually requires long duration and/or multiple exposures [1,53], can be used to assess optimal routes from the current position to the wayfinding goal [50,54,55]. Werner et al. [56] pointed out that procedural knowledge is critical to wayfinding for a destination whereas landmark knowledge is critical to recognition and estimation of route distances. In the present study, considering the low visibility of landmarks and difficulty of perception under fire emergency, it is possible that the participants in the second exposure relied mostly on procedural knowledge that they acquired in the first exposure. Unlike landmark knowledge, the procedural knowledge was not subject to significant impact of environmental visibility and mental stress [57,58], hence the wayfinding performance of participants in fire emergency was not impacted in the second exposure. Adding to the evidence of this assumption was the fact that a number of participants in Fire2 group mentioned in an after-experiment informal interview that, although smoke caused difficulty in their environmental perception, they remembered the orientation to the exit and did not feel that they were affected by the fire emergency in finding their way out. This indicated that people's wayfinding abilities under indoor fire emergency circumstances could be improved with repeated exposures.

Next, we assessed the effect of repeated exposure on the wayfinding performance in normal condition. The treasure hunting task results in the first and second trials of participants in Fire3 group were compared, as shown in Table 4 (Comparison C). Anderson Darling test rejected that d1 and t1 in Comparison C followed normal distribution (partly  $p < .10$ ). The Wilcoxon Signed Rank Test, a nonparametric related samples test, was therefore applied [59]. The means of the two behavioral measures during treasure hunting task (d1 and t1) in the first and second trials of participants in Fire3 group are shown in Table 3. The Wilcoxon Signed Rank Test result indicated that t1 was statistically significantly higher in the first trial than the second trial ( $Z = -0.199$ ,  $p = .046$ ), while there was no significant difference in d1 between the two trials ( $p = .469$ ). Given the inconsistency between test results of t1 and d1, an additional test was done to compare the average speed (d1/t1) in Comparison C. Paired samples T test result revealed significant group difference in the average speed ( $t = -1.852$ ,  $p = .084$ ,  $df = 15$ ).

This result could be explained by different effects the repeated exposures may have on the acquisition of different types of spatial knowledge. Landmark knowledge is useful for understanding the configuration of an indoor space such as a room [60]. That the participants traveled comparable distances in two exposures but reduced their travel time in the second exposure meant that they reduced the non-movement time, the most of which was spent on seeking treasures in semi-closed spaces in the museum. A possible reason was that the

**Table 3**  
Mean of four behavioral measures in Comparison B (standard deviation in parentheses).

Behavioral measures	t1	d1	t2	d2
Fire2 Group	122.00 (42.92)	99.23 (34.98)	44.69 (28.13)	41.81 (21.12)
Fire3 Group	100.75 (32.24)	89.70 (32.62)	35.94 (11.94)	37.94 (12.99)

**Table 4**  
Mean of four behavioral measures in Comparison C (standard deviation in parentheses).

Behavioral measures	t1**	d1
First exposure	127.20 (46.90)	97.801 (30.30)
Second exposure	100.75 (32.24)	89.70 (32.62)

Note:

\*\*  $p < .05$ .

participants benefitted from landmark knowledge when performing the treasure hunting task for the second time, which enabled them to reduce the time they spent on configuration perception within each semi-closed space. On the other hand, procedural knowledge and survey knowledge are mainly responsible for representing the connections between rooms in an indoor space [56]. Considering that procedural knowledge cannot impact the travel distance, the comparable travel distance of participants in the two exposures indicated that participants were not able to use survey knowledge to find shorter routes in the second exposure. There are two possible reasons. One is that participants did not form a high-quality cognitive map with survey knowledge in the first exposure and did not know the relative positions of five treasure keys. Insufficient exposure duration might cause absence of survey knowledge in cognitive map [1,53]. Another possible reason is that participants acquired survey knowledge in the first exposure, which was stored in working memory but was lost in the following two weeks. Considering the passive forgetting process of memory system, forgetting of the survey knowledge in cognitive map in long-term memory was possible [9,19,61].

Moreover, to assess the effect of repeated exposure on the wayfinding performance under fire emergency, the egress task results of Fire1 group in the first trial and Fire2 group in the second trial were compared (Comparison D). The means of the two behavioral measures during egress task (d2 and t2) in Comparison D are shown in Table 5. Anderson Darling test rejected that d2 and t2 in Comparison D followed normal distribution (partly  $p < .10$ ), hence the Mann-Whitney *U* test was suitable to analyze d2 and t2 in Comparison D. The Mann-Whitney *U* test revealed a marginally significant group difference in d2 ( $U = 77.00$ ,  $z = -1.92$ ,  $p = .056$ ,  $r = -0.34$ ), and no significant group difference in t2 ( $p = .171$ ). Given the inconsistency between test results of t2 and d2, an additional test was done to compare the average speed (d2/t2) in Comparison D. Independent samples *T* test result revealed no significant group difference in the average speed ( $p = .104$ ).

The results showed that the travel distance in egress task under fire emergency was improved by repeated exposure. O'Neill [17] found that repeated exposure significantly improved wayfinding performance and overcame the negative effects of moderately complex indoor environment on wayfinding. Livingstone-Lee et al. [16] found that repeated exposure significantly impacted choice of wayfinding strategy, and contended that repeated exposure influenced cognitive map formation and subsequently influenced the selection of wayfinding strategies. The results in this study indicated the positive impact of repeated exposure on wayfinding performance also existed under fire emergency conditions. In addition, despite the discrepancy between travel distance which had marginally significant group difference and travel speed

**Table 5**  
Mean of four behavioral measures in Comparison D (standard deviation in parentheses).

Behavioral measures	t2	d2*
Fire1 Group	57.13 (32.69)	53.76 (28.64)
Fire2 Group	44.69 (28.13)	41.81 (21.12)

Note:

\*  $p < .10$ .

**Table 6**  
Mean of four behavioral measures in Comparison E (standard deviation in parentheses).

Behavioral measures	t2	d2
Fire2 Group	44.69 (28.13)	41.81 (21.12)
Fire3 Group	39.19 (13.83)	41.01 (14.88)

which had no significant group difference, the comparison of average speed showed no significant group difference. This suggested that the repeated exposure did not significant impact the non-movement time the participants spent on hesitation, environmental perception and decision making.

### 3.3. The third exposure

To further assess the effect of repeated exposure on the wayfinding performance under fire emergency, the egress task results of Fire2 group in the second exposure and Fire3 group in the third exposure were compared (Comparison E). A sample video recording of participant #18 in Fire3 group participating in the third trial is shown in Movie 6. The means of the two behavioral measures (d2, and t2) in Comparison E are shown in Table 6. Anderson Darling test rejected that d2 and t2 in Comparison E followed normal distribution (partly  $p < .10$ ), hence the Mann-Whitney *U* test was applied. The Mann-Whitney *U* test revealed no significant group difference in any behavioral measure (all  $p \geq .445$ ).

The comparable wayfinding performance indicated that a third exposure to the same environment did not lead to further improvement of the wayfinding performance. Prior studies have reported that there might be a threshold of number of repeated exposures, beyond which spatial memories and wayfinding performance could not be further improved [16,62]. A potential threshold is one or two repeated exposures, after which the stored spatial knowledge would become stable [16,51]. Evidence from research on spatial neural systems also suggested that the first and second exposures are critical to spatial memories [11]. The threshold appeared to have been reached by the third exposure in the present study. It is noteworthy that this threshold was observed under a particular time interval of two weeks between consecutive exposures. Whether the threshold would change or whether it even would still exist at all when the length of time interval changes would require further investigation in future research.

### 3.4. Physiological responses

To assess the effect of immersion in virtual emergency environment on the participants' autonomous nervous system, SCR amplitude data were analyzed. The SCR amplitude compares the EDA signal before and after an event defined by the experimenter. It is a widely used indicator to detect stimulation at the moment of the event [41]. In this study, the event was defined as the moment when the virtual sign showed up in the IVE instructing the participants to egress. Under fire emergency, this was also the moment when the fire and smoke broke out. Anderson Darling test rejected that SCR amplitude in Comparisons A, B, C, D and E followed normal distribution (all  $p < .05$ ). Thus, Mann-Whitney *U* test was applied for Comparison A, B, D and E, and Wilcoxon Signed Rank Test was applied for Comparison C. The Mann-Whitney *U* test result showed that SCR amplitude was marginally significantly different in Comparison A (0.47 vs 0.19,  $U = 156.00$ ,  $z = -1.85$ ,  $p = .065$ ,  $r = -0.27$ ), significantly different in Comparison B (0.85 vs 0.12,  $U = 49.00$ ,  $z = -2.63$ ,  $p = .014$ ,  $r = -0.49$ ) and Comparison E (0.74 vs 2.61,  $U = 56.00$ ,  $z = -2.49$ ,  $p = .019$ ,  $r = -0.45$ ), and not significantly different in Comparison D ( $p \geq .511$ ). Wilcoxon Signed Rank Test result showed that SCR amplitude was not significantly different in Comparison C ( $p = .612$ ).

Significantly higher SCR amplitude indicated that participants experienced stimulation at the beginning of the egress task. The results indicated that participants who egressed under fire emergency experienced significant stress when they started evacuation, whereas those who egressed under normal condition did not. The results also indicated that repeated exposures did not reduce the stress induced by the fire emergency circumstances.

### 3.5. Emotional responses

We collected the PANAS scores of all participants before and after each trial to assess the participants' emotional responses when they were immersed in the IVE. Anderson Darling test accepted that positive and negative emotions in Comparison A, B, C, D and E followed normal distribution (all  $p > .05$ ). Thus, Mann-Whitney  $U$  test was conducted for Comparison A for inequality of sample sizes, paired samples  $T$  test was conducted for Comparison C, and independent samples  $T$  test was conducted for Comparisons B, D and E [44,59]. The results showed that, the change of average score of positive emotions over the entire trial was not significantly different for any Comparison (all  $p \geq .177$ ). The change of the average score of negative emotions was significantly different in Comparison A (3.56 vs 0.25,  $U = 131.50$ ,  $z = -2.74$ ,  $p = .006$ ,  $r = 0.40$ ,  $df = 48$ ) and B (3.93 vs 1.00,  $ts = 0.380$ ,  $p = .006$ ,  $df = 30$ ), but not significant in Comparison C, D and E (all  $p \geq .210$ ). The above results indicated that fire emergency induced significant negative emotions on participants, and that participants experienced the same level of fire emergency-induced negative emotions in different exposures.

### 3.6. The participants' subjective evaluation

The results of subjective evaluation, including their simulator sickness, sense of direction and wayfinding anxiety, were analyzed.

Anderson Darling test accepted that the sense of direction, wayfinding anxiety and simulator sickness for Comparisons A, B, C, D and E followed normal distribution (all  $p > .05$ ). Thus, independent samples  $T$  test was conducted for sense of direction, wayfinding anxiety and dizziness in Comparisons B, D and E, paired samples  $T$  test was conducted for these variables in Comparison C, and Mann-Whitney  $U$  test was conducted for these variables in Comparison A due to unequal sample sizes. The results revealed that the confounding factors, sense of direction [63], wayfinding anxiety [64] and simulator sickness [35] were not significantly different in any comparison (all  $p \geq .10$ ). These results showed that the comparisons between groups would not be affected by simulator sickness, sense of direction and wayfinding anxiety.

### 3.7. Validity

This subsection discusses the validity of the present study and the reported results.

#### 3.7.1. Internal validity

Prior studies have found that sense of direction, gender and wayfinding anxiety could affect wayfinding performance [38,63,64]. In addition, VR technology could cause severe simulator sickness of participants and hence affect participants' decision making and behavior [65]. These factors could be confounding factors causing bias of the results. To avoid such bias, firstly, we randomly divided participants in three study groups with equal numbers of males and females, which controlled the impact of gender. Secondly, we asked participants to self-evaluate their sense of direction, wayfinding anxiety and simulator sickness using standard scales [32,35,38]. The results revealed that participants in three study groups had similar sense of direction, wayfinding anxiety and simulator sickness. Thirdly, Comparison C was a within-subject comparison, which controlled all possible confounding factors generated by individual differences. The above measures were

taken to ensure satisfactory internal validity of this study.

#### 3.7.2. Construct validity

Construct validity in the present study was mainly relied on whether the virtual environment accurately aroused wayfinding behavior and whether the virtual fire emergency could create a stressful wayfinding environment [66]. Prior studies suggested physiological and psychological responses of the participants were effective evaluation indicators for emotional arousing of participants and sense of presence in virtual environments [24,40]. According to both physiological and emotional assessment results in this study, the virtual fire emergency was successful in arousing mental stress on the participants. That being said, it is noteworthy that the degree of reality experienced by participants in the IVE could be further enhanced by introducing additional human senses and dynamic scenarios, such as real walking around, smelling the fire, feeling the heat of the fire, dynamic obstacles, and human group interaction. Realizing these attributes of IVEs requires the development of new modalities of human-computer interactions, which in turn relies on continuous advancement of VR technologies. Future research can consider enriching the IVEs with these attributes, tailoring them to the specific needs of particular experiments, to yield more realistic behavior data and hence deepen the understanding of human wayfinding behavior during indoor emergency situations.

#### 3.7.3. Statistical validity

To test the main effect of independent variables with considerations of the effect of co-variables, several statistical tools were applied in this study. Anderson Darling test was firstly used to examine the distribution of data due to its power with small sample size [67]. If the normal distribution was rejected in comparison between two groups, Mann-Whitney  $U$  test for between-group comparison and Wilcoxon Signed Rank Test for within-group comparison were used to analyze the data. ANOVA-based tools were not applied, as the experiment should not be considered as a  $2 \times 3$  design. The statistical significance level was set as 5% and marginal significance level was set as 10%.

Sufficient sample size is critical to yield statistically meaningful conclusions. Considering that typical sample size for each group is 16, 32 or 64 in experimental psychology studies [67], and that the sample size for each group ranged between 7 and 20 in most prior wayfinding and evacuation behavior studies [45,50,68], we decided to have 16 participants in each group. This sample size satisfied the sample size requirements of Anderson Darling test [69], Mann-Whitney  $U$  test [44] and Wilcoxon Signed Rank Test [59].

#### 3.7.4. External validity

Firstly, all participants in this study were university students in China. Considering possible age effect [12–14] and cultural effect [23,70], the external validity of the results on elders or children or people with different cultural backgrounds would require further investigation. Secondly, all participants had normal or corrected-to-normal vision and no color blindness, and each study group included equal numbers of males and females, which avoided bias in vision and gender. Thirdly, prior studies have found that cognitive map developed in VR can be used in reality, and that VR is suitable for studying wayfinding behavior [53,66,71]. The spatial knowledge in cognitive map formed in virtual environment could be retrieved for wayfinding tasks and improve wayfinding performance in both virtual environment and in reality [53,71,72]. Evidence from research on spatial neural systems also supports that the spatial memories acquired from virtual environment are stored and processed in the same brain area as those acquired from reality [12]. These findings suggested that the results of this study could be applied beyond a virtual environment and used to understand people's wayfinding behaviors in real-world environments.

#### 4. Conclusions

A wayfinding experiment was conducted in a virtual museum in the present study to analyze the influence of repeated exposures and fire emergency on people's indoor wayfinding behavior. Participants' wayfinding behavioral measures, physiological and emotional responses, sense of direction, wayfinding anxiety and simulator sickness were collected and analyzed. The results showed that repeated exposures significantly reduced the travel time of the participants in completing treasure hunting task, and that fire emergency significantly increased the travel time and distance of the participants in completing egress task. Interaction effect between repeated exposures and fire emergency was observed, indicating that repeated exposures may improve the egress performance of participants under virtual fire emergency. This study contributes to the existing body of knowledge by verifying the impact of mental stress on human wayfinding performance reported in prior research, discovering new findings about the impact of repeated exposures that are explained by cognitive map and learning effects, and revealing significant interaction effects between the above two factors. This study advances the understanding of human wayfinding behavior, and provides important practical implications regarding to human safety in buildings. Future research could be done to further explore the effect of length of time interval between consecutive repeated exposures on wayfinding performance. These findings can hopefully be used to support building evacuation training and building fire emergency management in practice.

#### 5. Declarations of interest

None.

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#### Appendix A. Supplementary material

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.aei.2018.11.007>.

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