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How the completeness of spatial knowledge influences the evacuation behavior of passengers in metro stations: A VR-based experimental study

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ABSTRACT

Emergency evacuation in metro stations could be highly challenging due to complex underground environments, dynamic hazards and high-density crowds. There are different types of metro passengers, such as first-time visitors and daily commuters, who may possess different levels of prior spatial knowledge about the metro station. While spatial knowledge is known as an influential factor on people's indoor wayfinding behavior, it has largely remained unknown whether and how the level of completeness of prior spatial knowledge would affect people's wayfinding behavior during emergency evacuation in underground environments such as metro stations. Motivated by this gap, this study aimed to examine the effect of completeness of spatial knowledge on the evacuation behavior of passengers in metro stations, as they observed different patterns of crowd flow. An evacuation experiment was conducted in an immersive virtual environment, which was a virtual representation of a real metro station in Beijing. Participants were divided into six groups according to a 3 × 2 between-participants design. Participants could possess none, partial or complete spatial knowledge of the metro station, acquired from a spatial exploration task, prior to evacuation. Meanwhile, they could observe two patterns of crowd flow, modeled by having virtual avatars evacuating from the metro station evenly or unevenly split at every decision point (DP) along the evacuation routes. Five wayfinding performance measures, as well as the emotional responses, sense of direction, wayfinding anxiety, simulator sickness and sense of presence of all participants were collected and analyzed. The results showed that the completeness of spatial knowledge significantly impacted all measures of participants' evacuation performance, and that the pattern of crowd flow significantly impacted participants' evacuation speed, route choice, and directional choices at two DPs. Significant interaction effect between completeness of spatial knowledge and pattern of crowd flow was observed, which negatively impacted participants' evacuation time, distance and speed. The behavioral explanations underlying these findings, their practical implications and future work are also discussed in the paper.

1. Introduction

The world has witnessed rapid expansion of urban rail transportation in metropolitan regions in the past decades. The global annual ridership of metro systems reached 61 billion in 2017, which is going to be further boosted by an expected increase of metro lines by one third by 2022 [1]. As the volume of passengers continues to increase, metro stations are faced with an increasing amount of safety risks. In fact, incidents such as fires and explosions that may cause widespread panic in metro stations and lead to injuries and fatalities are not uncommon, and have happened in a number of cities, including Hong Kong [2], London [3] and Tokyo [4], in recent years.

When emergency incidents happen in metro stations, crowds of passengers need to evacuate to safe locations in a timely manner. The success of crowd evacuation is largely dependent on the efficiency of wayfinding of individual passengers [75], which in turn is influenced by a variety of factors, examples of which include signage systems [5], attributes of hazards [6], passengers' individual characteristics [7–9], and presence and behavior of surrounding crowds [7,10]. Among them, passengers' spatial knowledge about the indoor environment is a crucial factor [11], whose impact on people's indoor wayfinding behavior has been examined by a bulk of prior studies [12–14]. Despite these studies, however, one important question that remains unclear is whether the completeness of spatial knowledge would influence the evacuation behavior of people in an indoor space. This question is particularly pertinent and critical to metro passengers, whose spatial knowledge may significantly differ in terms of the level of completeness. Specifically, some passengers may be first-time visitors to a metro station, and

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have none prior spatial knowledge of the space; some other passengers may be daily commuters, who know nothing about the station but a routine path between a platform and an exit that they take on a daily basis; whereas a third type of passengers may have used different platforms and exits and hence have had a chance to explore the most part of the metro station. Passengers who possess none spatial knowledge may evacuate via the route with emergency signage or following surrounding passengers. Passengers with partial knowledge or complete prior spatial knowledge about the metro station may evacuate via the commuting route or the shortest route. However, such potential effect of the completeness of spatial knowledge on evacuation performance has not yet been studied. Understanding whether and how the evacuation behavior would differ among passengers who possess none, partial or complete prior spatial knowledge of the metro station may have important implications. This knowledge, for instance, could be used to improve crowd evacuation simulation, which essentially relies on fine-grained modeling of building space, dynamic hazards and the behavior of individual evacuees [15]. It could also be applied to facilitate metro authorities' emergency preparedness efforts, which would benefit from knowledge about how passengers may behave when caught in emergency situations [16]. Motivated by such need, the first research question this study aims to investigate is: how would the level of completeness of spatial knowledge (none, partial and complete) influence the evacuation behavior of passengers in metro station when emergencies occur?

There are a number of dynamic factors at possible emergency scenes in metro stations that may influence the wayfinding decision-making of the passengers. These factors include spreading fire and smoke [17], falling debris [18], moving attackers [19] and, notably, the crowds [20]. Passengers usually find themselves among large crowds in metro stations and, as prior research has pointed out, their wayfinding decisions may be significantly influenced by the crowds [7]. The crowd flow may exhibit diverse patterns, such as merging or splitting among different directions [21]. Meanwhile, passengers observing these patterns may respond differently by e.g. herding and avoiding the crowds [22,23], depending on their affiliation [19], social identity [24] and social influence [25]. Both spatial knowledge and observed crowd flow patterns are important factors that one could rely on as sources of information when making wayfinding decisions during evacuation. The information conveyed by these two factors, depending on their respective characteristics, could be either complementary or conflicting, hence reinforcing or weakening their respective influence on people's wayfinding decision-making. There could be important interactive effects of these two factors that may have complicated implications to the evacuation behavior of metro passengers, which have yet to be examined in the existing literature. Hence, the second research question this study aims to answer is: how would the pattern of crowd flow interact with the completeness of spatial knowledge to influence the evacuation behavior of passengers in metro stations during evacuation?

Recently, immersive virtual environments (IVEs) have been used increasingly in behavioral research related to building emergencies [26–28] and in psychological research about spatial knowledge and wayfinding [29–31]. IVEs are an effective tool in research to arouse realistic human emergency response behavior with reasonable ecological validity. They also provide researchers with an important approach to control and manipulate key variables according to experimental design, and to collect reliable qualitative and quantitative behavioral data [32,33]. Given the above advantages, the IVE-based experimental methodology is used in this study. IVEs were modeled after a real metro station in Beijing. A fire incident, the script of which was developed based on a similar incident that happened in Hong Kong in 2017 [34], was simulated in the IVEs. An IVE-based evacuation behavioral experiment was conducted, and multi-dimensional behavioral data were collected from the participants and analyzed to answer the aforementioned research questions. The experimental design and research findings are reported in the remainder of the paper. These findings of this study are expected to advance the existing knowledge about human evacuation behavior during indoor emergencies, and provide important practical implications for passengers' safety and emergency preparedness in metro stations.

2. Materials and methods

2.1. Recruitment

Participants were recruited by emails, flyers, personal solicitation and outlets on social media (e.g. WeChat) in Beijing, China. The requirement for participation in this study included normal or corrected normal vision, no color blindness, no heart-related illness, no wrist/hand injuries, and no uncomfortable VR experiences in the past. A total of 126 participants (22.9 ± 4.4 years old on average, ranging from 13 to 48; 65 males and 61 females) completed the experiment. While the participants were not specifically asked to disclose their occupation information, the vast majority of them appeared to be university students, and the rest were a few university staff and office workers. Each participant received 30 CNY for participation in this study. The study was approved by Ethics Committee of the Psychology Department of Tsinghua University.

2.2. Apparatus

The apparatus in this study consisted of two computer workstations and a set of HTC Vive head-mounted display (HMD) system [35]. One workstation was connected to the HTC Vive system as a client workstation, and the other as a server workstation. The two workstations were in the same local area network (LAN) and connected via Photon Server [36]. The headphone of the Vive system was used to provide audio stimuli (i.e., emergency broadcasting and fire sound) in the IVE. The structure of the apparatus used in this experiment is shown in Fig. 1.

During the experiment, the participants remained in a standing position and used the controller of the HTC Vive system to navigate in

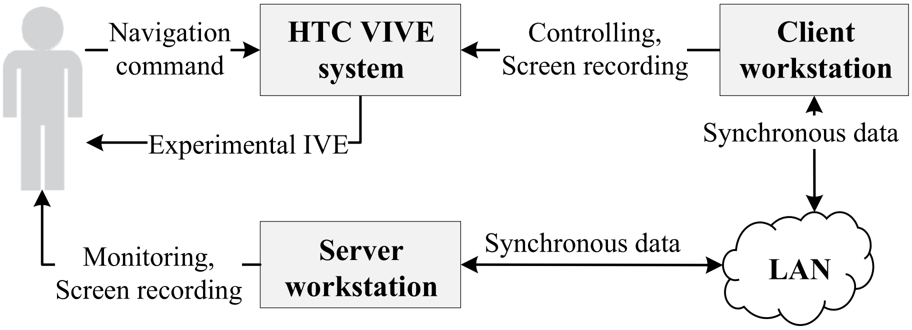

Fig. 1. The structure of the apparatus.

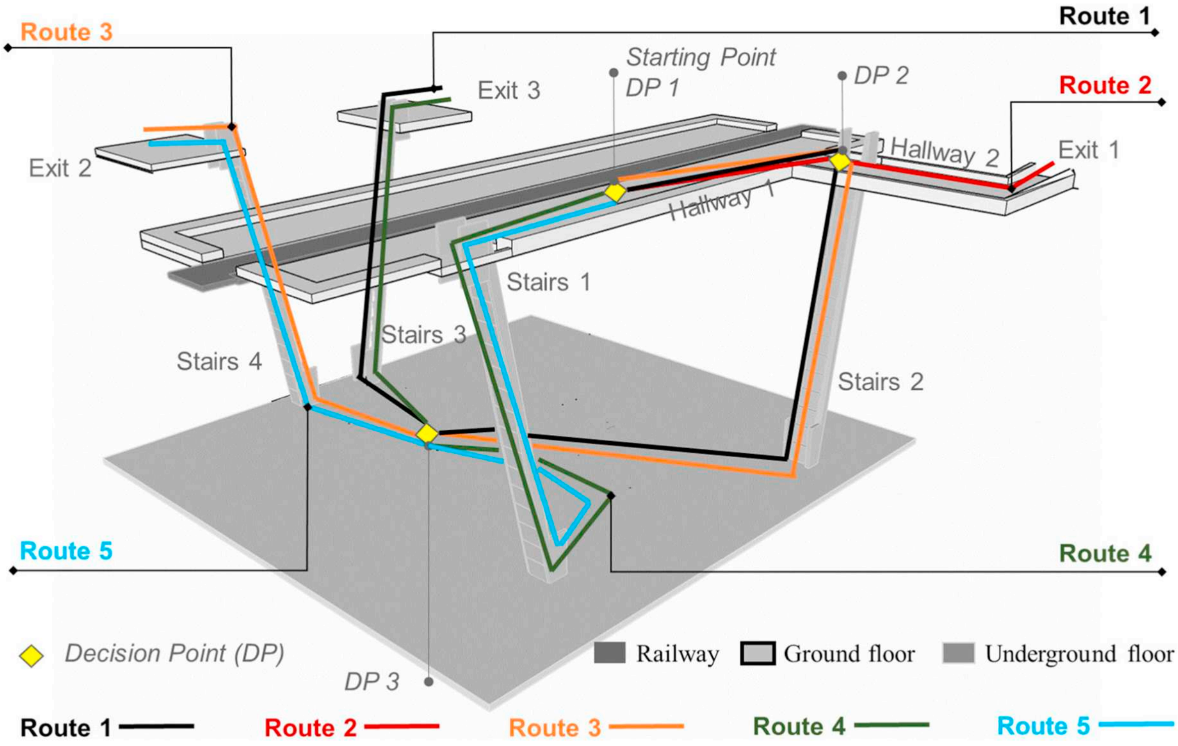

Fig. 2. Sketch map of the metro station marked with evacuation routes (not to scale).

the IVE. The orientation of navigation in the IVE was synchronized with the orientation of the HMD worn on participants' head. The resolution of the displays for both eyes was 1080 (horizontal) × 1200 (vertical) pixels. Participants could use the controller to move forward, backward, left or right at a constant movement speed of 2.4 m/s in the IVE. The speed, which was determined based on pilot experiments, was set to simulate running movement in the virtual station without causing VR sickness to participants.

2.3. Virtual displays

The IVE of this experiment was a virtual metro station modeled after a real metro station in Beijing. The virtual station model was developed based on 2D drawings of the station and rendered using 3D Studio Max. It had an area of approximately 6600 m^2, and was consisted of two floors, including a ground floor and an underground floor. A sketch map of the station is shown in Fig. 2.

At the beginning of the experiment, participants were initially positioned around the center of the platform (denoted as decision point 1, or DP 1) on the ground floor, when a metro train began to approach the platform. Fire broke out in one of the compartments of the train (Fig. 3) and began to spread. An emergency announcement began to be broadcasted repeatedly in both Chinese and English instructing passengers to evacuate. The script of this scenario was developed based on a similar incident that once happened in Hong Kong in 2017, in which a man carried out an arson attack onboard a metro train when it was approaching the Tsim Sha Tsui station. The incident triggered an emergency evacuation in the station and caused at least 17 injuries [34]. The storyline of this incident was reviewed and reconstructed based on related news articles. It was then modified, by removing the attacker and staff of the station and slightly scaling up the fire, and used as the script of the IVE. The participants could evacuate from the station through one of its three exits (denoted as Exits 1, 2 and 3) via five possible routes (denoted as Routes 1, 2, 3, 4 and 5). Depending on their route choices as well as their directional choices made at three DPs (denoted as DPs 1, 2 and 3), the participants may go through some of the staircases (denoted as Staircases 1, 2, 3 and 4) and hallways (denoted as Hallways 1 and 2) in the station. More specifically, at DP 1, the participants could choose to either go to Hallway 1 on the same floor, or go downstairs through Staircase 1. At DP 2, which was located at the end of Hallway 1, the participants could choose to either continue to go through Hallway 2 and evacuate from Exit 1, or go downstairs using Staircase 2. At DP 3, which was located between Staircases 3 and 4 on the underground floor, the participants could choose either staircase to reach Exits 2 or 3. At each DP, all alternative directions are shown by exit signs. Using the aforementioned virtual station model as input and based on the above script, the experimental IVE used in this study was developed with Unity 3D game engine [37]. The locations of the participants in the experimental IVE were automatically recorded every second, and the trajectories could be visualized in Unity 3D (Fig. 4).

A total of 53 avatars were modeled in the IVE. This number was relatively limited (with a crowd density of approximately 0.16 avatars/m^2 at the platform) to avoid overloading the graphical processor (GTX 1070), which would otherwise affect the smoothness of the display of the IVEs. Nevertheless, this crowd density was close to the actual crowd density in the station during off-peak hours (see a comparison in Fig. 5). The initial position of each avatar was fixed, either at the platform or inside the train, at the beginning of the experiment. Each avatar would run to a predetermined target location as soon as it perceived fire hazards within 15 m. Different patterns of crowd flow were created by setting the target locations of the avatars appropriately. The avatars were set to move at various fixed speeds ranging from 0.7 m/s to 2.8 m/s, depending on their age and gender, in accordance with the Chinese national standard of metro station evacuation [38].

2.4. Experimental design

The study used a 3 (completeness of spatial knowledge: none, partial or complete) × 2 (pattern of crowd flow: 50% vs 50% or 80% vs 20%) between-participants design. The completeness of spatial knowledge had three levels: 1) none, where participants had zero prior spatial knowledge about the station; 2) partial, where participants could

Fig. 3. Fire and smoke in the virtual metro train.

acquire partial knowledge about the station, by exploring a specific route in the station during an exploration task, before they performed the evacuation task; and 3) complete, where participants could acquire full spatial knowledge about the station, by exploring the entire station during an exploration task, before they performed the evacuation task. The pattern of crowd flow was represented in the IVEs by the way that avatars split at DPs along the evacuation routes. The pattern of crowd flow had two levels: 1) 50% vs 50%, where all avatars split evenly between two different directions at each DP; and 2) 80% vs 20%, where all avatars split unevenly at each DP, with 80% of them moving towards one direction and 20% moving towards the other direction. The paths taken by the avatars and their split at each DP are illustrated in Fig. 6.

Before the experiment, every participant was assigned to one of the six groups (Table 1) in such a way that in each group the total number of male participants and that of female participants were equal or nearly equal. The participants' initial location and the avatars' routes were selected such that the partial spatial knowledge (Route 5), complete spatial knowledge (Route 2, the shortest route), and unevenly split crowd flow (Route 1, the longest route) would indicate different evacuation routes to the participants, who would otherwise be expected to take a route randomly if they had none spatial knowledge and received no directional information from evenly split crowd flow. Such distinction was introduced in order to clearly demonstrate the influence of the independent variables in participants' wayfinding decision-making during evacuation.

Participants in Groups 3, 4, 5 and 6 needed to conduct an additional exploration task before the evacuation task, in order for them to acquire a certain level of prior spatial knowledge about the station. Specifically, participants in Groups 3 and 4 were instructed to explore the virtual metro station, which was under normal condition and free of avatars, by following marks on the ground, which led them to go through Route 5 back and forth, until they felt that they were familiar with this route. In contrast, participants in Groups 5 and 6 were instructed to explore the virtual metro station freely, until they felt that they were familiar with the entire space of the station. After the exploration, the participants were asked to select from nine sketch maps the one that matched

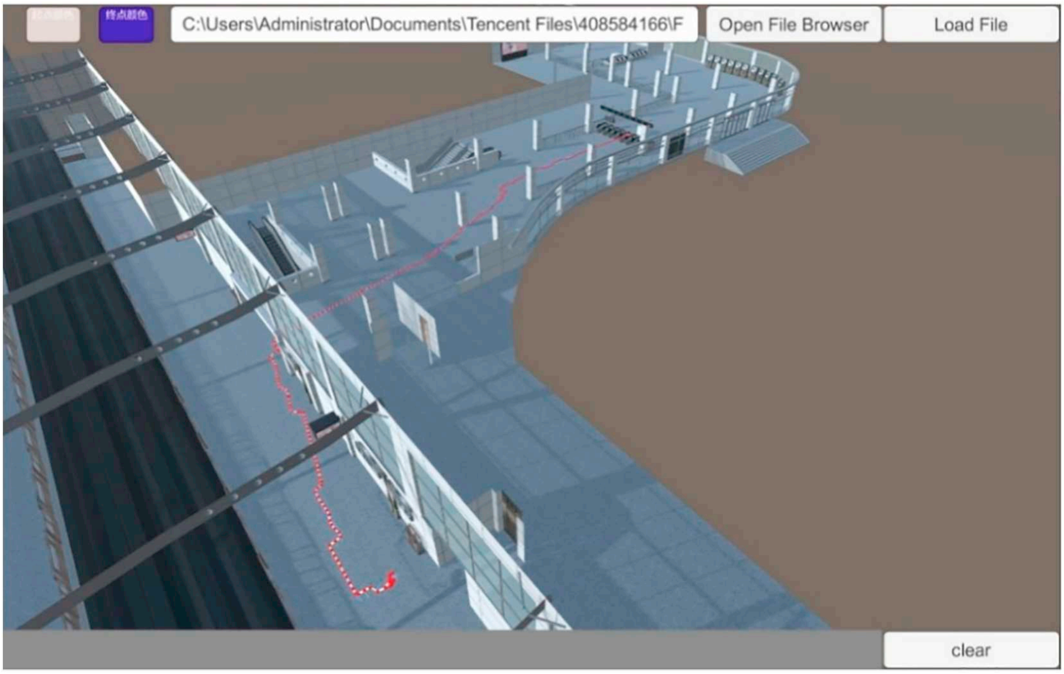

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Fig. 4. Display of the trajectory of a participant in Unity 3D.

Fig. 5. Comparison of the virtual station (model snapshot, left) and the real station (photo, right).

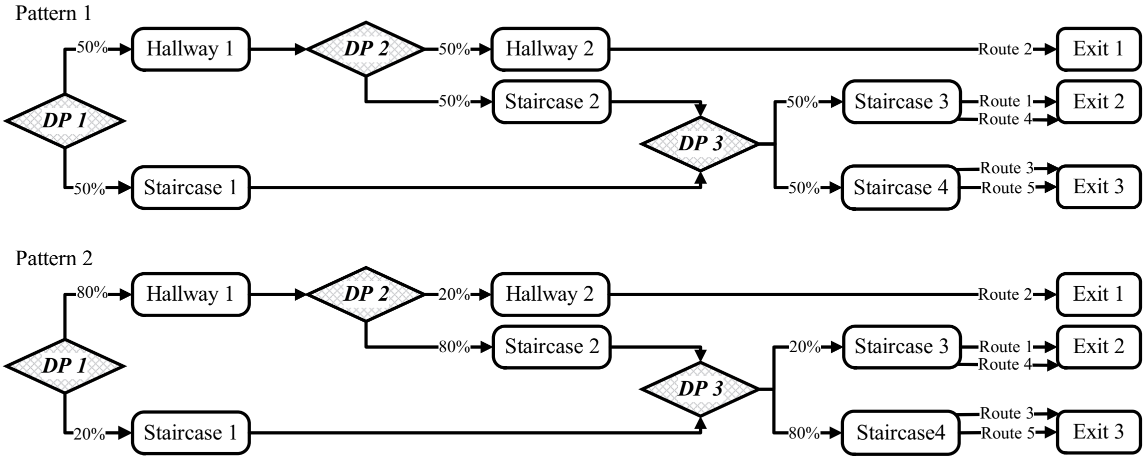

Fig. 6. Two patterns of crowd flow and associated routes taken by avatars (note: the percentage attached to each arrow indicates the proportion of avatars that chose this direction at the previous DP).

Table 1
Design of study groups.

Crowd flow	Spatial knowledge		
	None	Partial	Complete
Pattern 1 (50% vs 50%)	Group 1	Group 3	Group 5
Pattern 2 (80% vs 20%)	Group 2	Group 4	Group 6

exactly with the station. The purpose of this test was to examine the accuracy of prior spatial knowledge the participants acquired during the exploration. Sketch maps showed to participants in Groups 3 and 4 (Fig. 7) included only part of the station that was explored by the participants and hided the area and routes that they would not explore during the exploration task. The aim was to avoid disclosing any spatial information that they would not acquire during exploration. Sketch maps showed to participants in Groups 5 and 6 (Fig. 8) included the entire station. The distractors in Figs. 7 and 8 were developed from the correct sketch map, by adding or removing some architectural elements (e.g. exits and staircases) or changing existing architectural elements' locations.

After the exploration, the participants were then instructed to complete an evacuation task in the experimental IVE, with the presence of crowd flow and environmental cues of the fire emergency. The dependent variable in the experiment was participants' wayfinding performance in the evacuation task, which was measured by their evacuation time, distance, speed, route choice, and directional choices at three DPs. The evacuation time and evacuation distance referred to the time a participant spent and the distance a participant traveled, respectively, over the course of evacuation. These two measures were automatically recorded by the experimental apparatus, and their quotient was the participant's evacuation speed. Because participants may stop to observe the surroundings and hesitate in making wayfinding decisions, their evacuation speed was always lower than the constant movement speed defined in Section 2.2, and may differ between individual participants.

2.5. Procedure

After arriving at the laboratory, the participants were asked to sign a consent form before starting the experiment. After that, the participants were asked to complete a pre-experiment questionnaire, which included questions about their basic demographic information, the positive affect and negative affect scale (PANAS) [39,40], and the simulator sickness questionnaire (SSQ) [41]. Next, the participants were asked to read an instruction manual on how to navigate in the IVE using the Vive system. Then, they were asked to conduct a training task. They needed to put on the HMD and immerse themselves in a simple demo IVE of an empty open space, in order to familiarize themselves with the operation of VR equipment and sense of immersion in the virtual environment.

Next, participants in Groups 3, 4, 5 and 6 were asked to read instructions for the exploration task, and then conduct the task. Participants were not informed whether their selection of the sketch map at the end of the exploration task was correct, in order to avoid influencing their spatial cognition or their wayfinding decisions in the following evacuation task. However, only the evacuation performance

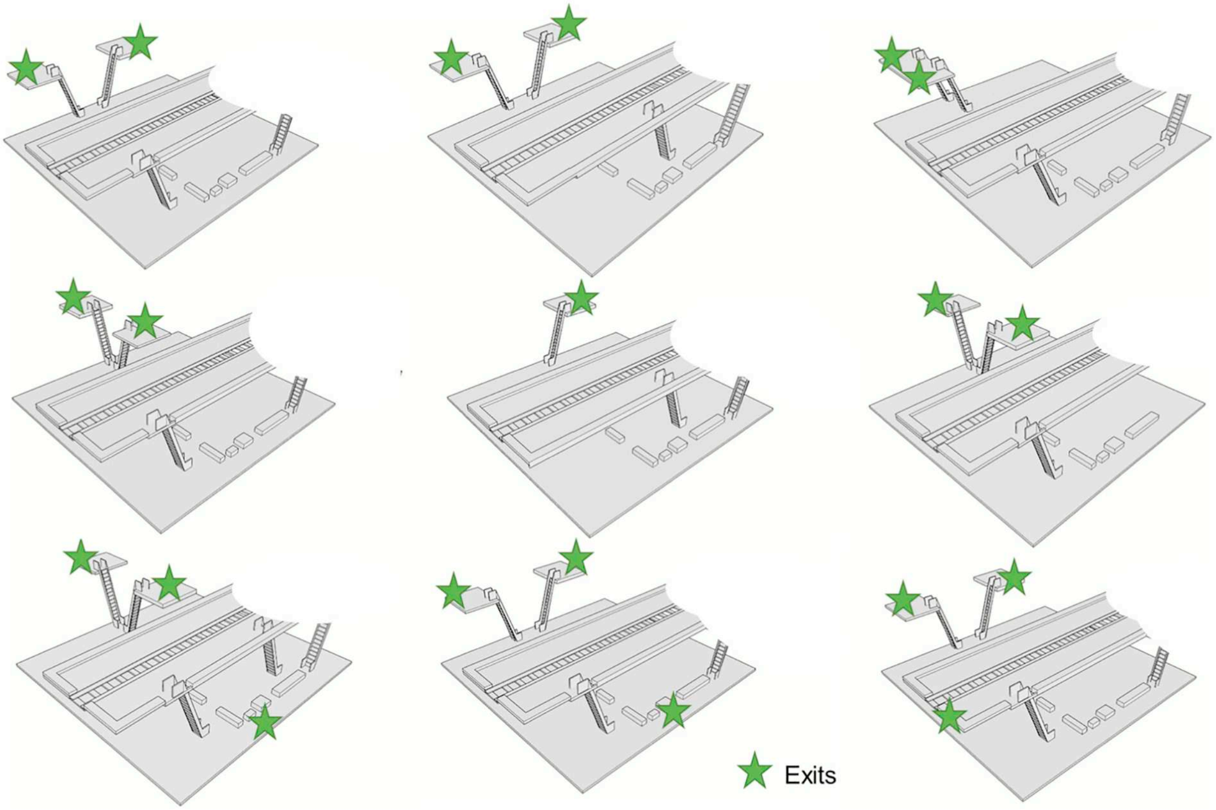

Fig. 7. Sketch maps showed to participants in Groups 3 and 4 after the exploration task (the upper-left sketch map was the correct one).

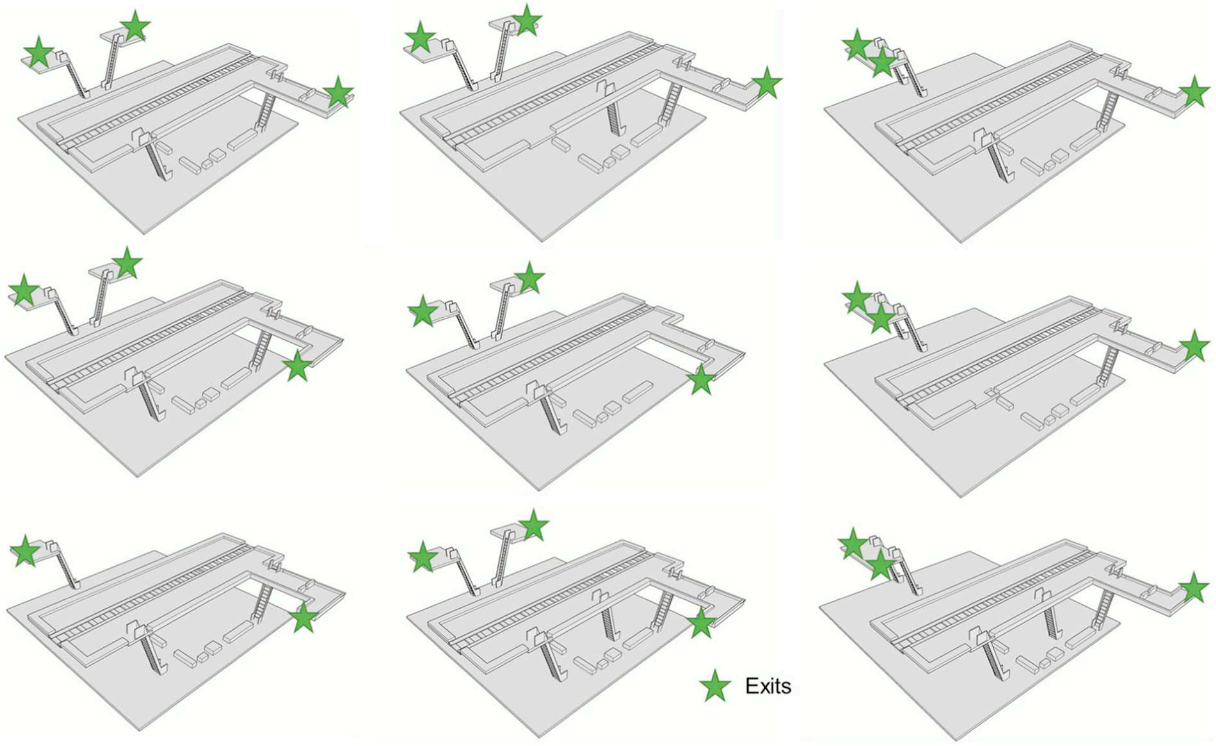

Fig. 8. Sketch maps showed to participants in Groups 5 and 6 after the exploration task (the upper-left sketch map was the correct one).

of those participants who selected the correct map were considered valid results and analyzed in this study. This was to ensure that findings of this study were not influenced by a potential confounding factor, namely the accuracy of prior spatial knowledge.

All participants were then asked to conduct an evacuation task in the virtual metro station by reaching one of the exits as soon as possible. After reading read an instruction manual of the evacuation task, the participants were immersed in one of the two experimental IVEs, associated with two different crowd flow patterns, based on their group assignment (Table 1). Participants were initially positioned at DP 1 together with the crowd (avatars) as a metro train was approaching the platform, which triggered the fire emergency. Participants could decide when to begin evacuating and which evacuation route to take. Once they arrived at an exit, a message saying “You have completed the VR experiment” popped up in the IVE, and they were instructed to take off the HMD.

At the end of the experiment, the participants were asked to fill out a post-experiment questionnaire, which included PANAS, SSQ, the Santa Barbara sense of direction scale (SBSOD) [42], the presence questionnaire (PQ) [43], and the Lawton's spatial anxiety scale (LSAS) [44].

2.6. Data analysis

The participants' route choices and their directional choices at each DP were analyzed by logistic regression analysis [45,46], due to its capability of assessing the relationships between nominal variables. Linear regression with collinearity diagnose was applied to analyze evacuation time, distance and speed, due to its capability of assessing the relationships between nominal variables and scale variables [45]. One sample *t*-tests [47] were used to analyzed whether participants' emotions changed significantly after the experiment. Independent samples tests across the six study groups, including one-way ANOVA [48] and Kruskal-Wallis test [49], were used to analyze group differences in age, and subjective evaluation by standard scales (PANAS, SBSOD, SSQ, PQ and LSAS). For each comparison, the homogeneity of variances of each dataset across different groups was checked. Data with homogeneous variances were analyzed using one-way ANOVA. Data with unequal variances were analyzed using the Kruskal-Wallis test. Box plots were used to identify outliers of evacuation time, distance and speed due to insensitivity of quartiles to outliers [50]. The outliers of evacuation time (6 data points), distance (5 data points) and speed (4 data points) were excluded from the respective statistical analysis of these variables in this study. For all analyses, the significance level was set as 0.05 and the marginal significance level was set as 0.10. All analyses were conducted using SPSS 22 software [51].

3. Results

3.1. Participants

Three participants failed to select the correct sketch map, and their data were excluded from the results. A total of 123 participants were considered in the following analysis. The demographics and subjective assessment of these participants are summarized in Table 2. Results of independent samples tests on potential confounding factors, including participants' age and their subjective assessments, showed that none of these factors was significantly different across different groups (all *Sig.* > 0.10).

Table 3
Evacuation route choices by participants in different groups.

Study group	Route 1	Route 2	Route 3	Route 4	Route 5	Total
1	1	10	2	1	7	21
2	11	7	1	2	1	22
3	–	–	–	–	20	20
4	–	–	–	4	16	20
5	2	16	–	–	2	20
6	2	14	2	1	1	20
Total	16	47	5	8	47	123

Table 4
Multinomial logistic regression analysis of participants' evacuation route choices.

Predictor	χ^2	df	Sig.
Intercept	0.000	0	NA
Crowd flow	18.943	4	0.001
Spatial knowledge	108.067	8	0.000
Likelihood ratio test	123.192	12	0.000
Goodness-of-fit test	7.435	8	0.491
Correct percent of prediction	70.7%		

Note: Goodness-of-fit test was based on deviance. β, *SE* β and e^{β} were different for regression model of each route and hence were not reported here in detail. Cox & Snell R^2 was 0.633. Probability for entry in stepwise was 0.10.

3.2. Evacuation route choice, and directional choice at DPs

Evacuation route choices by participants in different groups were summarized in Table 3. Multinomial logistic regression analysis was applied with stepwise of two independent variables and their interaction effect to examine their effects on participants' choice of evacuation routes. The results are shown in Table 4. The results suggested that both the completeness of spatial knowledge ($\chi^2(8) = 108.067$, Sig = 0.000) and pattern of crowd flow ($\chi^2(4) = 18.943$, Sig = 0.001) significantly affected participants' evacuation routes, and that their effects on evacuation routes were independent.

The directional choices by participants at each DP (Table 5) were analyzed by binary logistic regression analysis in stepwise. Probability for entry in stepwise was 0.10. The results, as shown in Table 6, suggested that participants' directional choice at DP 1 was significantly affected by completeness of spatial knowledge ($\chi^2(2) = 41.351$, Sig = 0.000). Their directional choice at DPs 2 and 3 was significantly affected by both completeness of spatial knowledge (DP 2: $\chi^2(1) = 6.235$, Sig = 0.013; DP 3: $\chi^2(2) = 15.248$, Sig = 0.000) and

Table 2
Demographics and subjective assessments of participants.

Measurement		Group 1	Group 2	Group 3	Group 4	Group 5	Group 6
Gender	Male	11	12	10	10	10	10
	Female	10	10	10	10	10	10
Age		24.2	22.2	22.5	22.9	22.3	23.6
SBSOD		73.4	73.4	73.4	65.9	68.5	62.2
LSAS		29.0	29.1	28.3	28.2	28.2	26.5
PQ		132.0	132.8	128.4	128.8	131.8	132.6
SSQ (average change of total score)		3.3	2.1	12.6	4.4	9.8	10.6
PANAS (average change of emotions)	Scared	0.4	0.2	0.8	0.6	0.4	0.1
	Alert	−0.1	0	0.5	0.4	−0.3	−0.3
	Afraid	0.3	−0.1	0.4	0.1	0.1	0.2
	Nervous	−0.1	−0.1	0.5	0.1	0.1	−0.1
	Jittery	0.3	0.2	0.5	−0.1	−0.2	0.3

Table 5
Directional choices at each DP by participants in different groups.

Study group		1	2	3	4	5	6
DP 1	Staircase 1	8	3	20	20	2	2
	Hallway 1	13	19	–	–	18	18
DP 2	Hallway 2	10	7	–	–	16	14
	Staircase 2	3	12	–	–	2	4
DP 3	Staircase 3	2	13	–	4	2	3
	Staircase 4	9	2	20	16	2	3

Table 6
Binary logistic regression analysis of participants' directional choices at DPs.

	β	SE β	(Wald) χ^2	df	Sig.	e^β
DP 1	Correct percent of prediction			87.8%		
Spatial knowledge			41.351	2	0.000	
	−4.883	0.794	37.830	1	0.000	0.004
	1.312	0.674	3.793	1	0.051	3.714
Likelihood ratio test			93.208	2	0.000	
Goodness-of-fit test			1.457	1	0.229	
DP 2	Correct percent of prediction			76.5%		
Intercept	−1.022	0.317	10.415	1	0.001	0.360
Spatial knowledge	−1.486	0.595	6.235	1	0.013	0.226
Crowd flow	1.379	0.620	4.944	1	0.026	3.972
Likelihood ratio test			12.853	2	0.002	
Goodness-of-fit test			0.553	2	0.758	
DP 3	Correct percent of prediction			82.9%		
Intercept	−0.945	0.375	6.367	1	0.012	0.389
Spatial knowledge			15.248	2	0.000	
	−2.932	0.772	14.439	1	0.000	0.053
	−0.506	0.888	0.325	1	0.568	0.603
Crowd flow	2.446	0.736	11.031	1	0.001	11.541
Likelihood ratio test			33.733	3	0.000	
Goodness-of-fit test			5.354	4	0.253	

Note: Goodness-of-fit test was based on Hosmer and Lemeshow Test.

pattern of crowd flow (DP 2: $\chi^2(1) = 4.944$, Sig = 0.026; DP 3: $\chi^2(2) = 11.031$, Sig = 0.001).

3.3. Evacuation time, distance and speed

The evacuation time, distance and speed of all participants are summarized by groups in Table 7. Linear regression analysis was applied to analyze the relationship between crowd flow, spatial knowledge and evacuation time, distance and speed, and the results are summarized in Table 8. As can be seen in this table, the evacuation time was significantly affected by completeness of spatial knowledge ($\beta = -4.859$, Sig. = 0.000) and its interaction with pattern of crowd flow ($\beta = 1.765$, Sig. = 0.000). The evacuation distance was similarly affected by completeness of spatial knowledge ($\beta = -1.421$, Sig. = 0.000) and its interaction with pattern of crowd flow ($\beta = 1.044$, Sig. = 0.006). In addition, the evacuation speed was (marginally) significantly affected by completeness of spatial knowledge ($\beta = 0.131$, Sig. = 0.000), pattern of crowd flow ($\beta = 0.052$, Sig. = 0.062), and the interaction between them ($\beta = -0.060$, Sig. = 0.000).

Table 7
Evacuation time, distance and speed of participants in different groups.

Study group		1	2	3	4	5	6
Time (s)	Mean	71.30	76.90	57.07	63.10	54.40	55.35
	SD	9.82	10.96	4.31	11.93	5.07	8.93
Distance (m)	Mean	122.48	128.09	124.63	127.44	118.97	120.44
	SD	6.64	11.39	5.43	9.64	8.96	9.21
Speed (m/s)	Mean	1.71	1.65	2.16	2.07	2.20	2.21
	SD	0.17	0.16	0.22	0.29	0.21	0.23

Table 8
Linear regression analysis of participants' evacuation time, distance and speed.

		R^2	F	df	β	SE β	Sig.
Time	Model	0.723	62.480	(2, 114)			0.000
	Intercept				69.870	2.304	0.000
	Spatial knowledge				−4.859	0.480	0.000
	Interaction				1.765	0.362	0.000
Distance	Model	0.351	8.071	(2, 115)			0.001
	Intercept				123.204		0.000
	Spatial knowledge				−1.421	0.490	0.004
	Interaction				1.044	0.371	0.006
Speed	Model	0.732	44.343	(3, 115)			0.000
	Intercept				1.672		0.000
	Spatial knowledge				0.131	0.012	0.000
	Crowd flow				0.052	0.027	0.062
	Interaction				−0.050	0.012	0.000

Note: Interaction means the interaction between completeness of spatial knowledge and patterns of crowd flow.

4. Discussions

4.1. The influence of completeness of spatial knowledge on evacuation performance

To sum up, the results of this study revealed that the wayfinding decisions the participants made during evacuation were facilitated by their spatial knowledge. Specifically, participants with partial spatial knowledge had strong tendency to evacuate via the route they were familiar with (36 out of 40 along Route 5, as shown in Table 3). Especially at DP 1, all participants with partial spatial knowledge chose Staircase 1 (Table 5), despite that the opposite direction would lead to the shortest route. The preference of the participants to follow the familiar route, regardless of its length, was probably related to their inclination to use procedural knowledge. According to the landmark-route-survey (LRS) model [52], which is the longest standing model of spatial knowledge representation [53], procedural knowledge is a type of spatial knowledge stored in human cognitive map that facilitates wayfinding by egocentric strategies [54,55]. During the exploration task, participants in Groups 3 and 4 had acquired procedural knowledge along Route 5. When the fire emergency occurred, the participants may tend to use their procedural knowledge by actively searching for Route 5 and evacuating via this route. It is noteworthy that this finding was consistent with findings from several prior studies conducted under normal condition [56,57]. This suggested that the mental stress aroused by the fire emergency in the experimental IVE did not significantly affect the retrieval and integration of procedural knowledge by the participants over the course of evacuation. In addition, participants with partial spatial knowledge may tend to rely on the intuitive decision-making system to make wayfinding decisions [58]. As a result, they were inclined to be influenced by the spatial knowledge already available to them and choose the route that they knew was “safe”, rather than to seek for additional environmental cues and try out alternative routes they were unfamiliar with, even though that may mean giving up “better” route or directional choices.

To the contrary, the large majority of participants with complete spatial knowledge (30 out of 40) evacuated via Route 2 (Table 3), which was the optimal route with the shortest distance and no vertical movement. According to the LRS model [52], participants who fully explored the metro station would have survey knowledge about the entire space, which would enable them to use the analytical decision-making system to make informed wayfinding decisions [58]. The results indicated that this was probably the case, as the participants with complete spatial knowledge were much more likely to search for and take the optimal route, despite that their intuition or the crowd flow pattern may have indicated otherwise.

With respect to participants with none prior spatial knowledge, their route and directional choices were significantly more random and unpredictable, compared with those who had partial or complete knowledge. Moreover, their evacuation speed was significantly lower. Considering the constant movement speed of all participants in the IVEs, such difference was caused by extra delay time during the course of evacuation, suggesting that the participants with none spatial knowledge needed more time to perceive the environment and search for environmental cues, and were more hesitant in making wayfinding decisions. Such hesitation time would be shortened by spatial knowledge, which could accelerate the spatial cognition, such as active attention, of an indoor space and the assessment of the completeness of evacuation goal (exits) [59]. This finding was in contrast to a prior study which, based on a relatively easier evacuation task involving limited and simplified spatial information, reported no significant effect of spatial knowledge in reducing evacuees' hesitation time [60]. This suggested that the access to prior spatial knowledge would become more critical when the evacuation needed to be carried out in complex environments with higher level of difficulty. This was probably because, compared to simple environments, in complex environments people would have more alternative evacuation directions and be exposed to a larger amount of distracting directional information, making it more difficult for them to sense and analyze the environmental cues and make optimal wayfinding decisions. These difficulties, however, would be partly mitigated when people could use prior spatial knowledge, which would subsequently shorten their hesitation time. Future research could further examine how prior spatial knowledge shortens the hesitation time during emergencies, the possible mediating processes of which may include accelerating the spatial cognition by landmarks [56] and using egocentric strategies to evacuate [61].

4.2. The interaction effect between completeness of spatial knowledge and pattern of crowd flow

The interaction of completeness of spatial knowledge and pattern of crowd flow had significant negative influence on participants' evacuation time, distance and speed (Table 8). The results suggested that the participants were more hesitant in making wayfinding decisions when they were influenced by the interaction effects of completeness of spatial knowledge and pattern of crowd flow. This may be related to the fact that the directional information the participants retrieved from their prior spatial knowledge was inconsistent with the directional information they perceived from the crowd flow pattern, causing them to hesitate to act promptly.

Meanwhile, the interaction effect of completeness of spatial knowledge and pattern of crowd flow was insignificant on participants' evacuation route choices and directional choices at DPs. Completeness of spatial knowledge and pattern of crowd flow had independent influence on evacuation route, and together they could be used to predict the route choice of 70.7% of the participants in this study (Table 4). In addition, participants' directional choice at DP 1 was only affected by spatial knowledge (Table 6), while their successive directional choice at DPs 2 and 3 were affected by both pattern of crowd flow and completeness of spatial knowledge. That the pattern of crowd flow did not affect participant's directional choice at DP 1 may be because the participants were initially exposed to the emergency situations and positioned close to the fire hazards, so they had higher mental stress and consequently required higher level of certainty when making the directional choice [62]. As a result, they were inclined to rely on their own spatial knowledge. The directional information conveyed by the crowd flow was relatively less trustworthy, partly because there was little social bond between the avatars and the participants which would be vital to establish the influence [63]. As the participants moved away from the hazards, the level of mental stress decreased, hence they could bear more uncertainty and would make decisions in a more analytical way at the successive DPs.

4.3. Validity of findings

The construct validity [64] in this study was ensured in three aspects. First of all, the dependent variable, namely participants' evacuation performance, was measured using five relevant, complementary, clearly defined and technically measurable variables, including route choice, directional choice, evacuation time, distance and speed. Second, the independent variables, namely the completeness of spatial knowledge and pattern of crowd flow, were set in highly controlled IVEs after being tested and validated in pilot experiments. Third, participants in Groups 3, 4, 5 and 6 were tested for the accuracy of their spatial knowledge, which ensured the cognitive map the participants formed during the exploration task was a precise representation of the space they had explored.

With respect to the statistical validity, the sample size in this study was comparable with prior experimental studies in the area [65–67]. In addition, based on the sample size and at the significance level of 0.05, the statistical power of the analyses in this study was assessed to be as follows [68,69]: 100.0% for one-sample *t*-tests, 93.8% for independent samples tests, 98.1% for linear regression analysis, and 91.9% for logistic regression analysis. This statistical power assessment indicated that the possibility of reporting significant results when the real results were insignificant was 5% and that the possibility of reporting insignificant results when the real results were significant was between 0 and 8.1% depending on which statistical method was used. Thus, the significant statistical relationships found in this study were highly reliable and a few insignificant results may need further justification [70,71]. The outliers of evacuation time, distance and speed were excluded in the statistical analysis in this study.

It is noteworthy that three participants failed to select the correct sketch map after the exploration task, and their data were excluded from the statistical analysis in order to avoid introducing possible influence of a confounding factor, i.e. accuracy of prior spatial knowledge. That being said, the experimental data associated with these participants were reviewed. The sketch maps they selected involved different errors including incorrect number and location of staircases and incorrect location of exits. All three participants were in groups associated with evenly split crowd flow pattern, which was a coincidence as the participants were not aware of their group assignment and had not seen the avatars when they selected the sketch map. In addition, although no statistical conclusion could be drawn due to the small sample size, the evacuation time, distance and speed of these participants were not obviously different than the average of other participants that chose the same routes, and their self-reported assessments were apparently not outliers among all data points.

Moreover, random group assignment and measurement of confounding factors (Table 2) were applied to ensure the internal validity of this study. The results showed that six study groups were not significantly different in terms of gender or any other confounding factors.

Last but not least, the ecological validity of the virtual experiment was assessed with PQ and PANAS. The average scores of PQ, as shown in Table 2, indicated that the sense of presence experienced by participants when they were immersed in the IVE was medium-high [43,72]. In addition, results of one sample *t*-tests on change of emotions, as shown in Table 2, indicated that participants experienced significant emotional arousal in the IVE. Specifically, they self-reported higher levels of scary ($M = 0.390$, $t = 4.898$, $Sig. = 0.000$), jittery ($M = 0.163$, $t = 1.755$, $Sig. = 0.082$) and afraid ($M = 0.138$, $t = 1.862$, $Sig. = 0.065$) after completing the virtual evacuation task. Yet, considering that the participants in this study were mostly university students, the external validity of the reported findings to people with different demographics, such as the elderly, less educated or physically challenged people, may need to be tested in future research.

4.4. Practical implications, limitations and future work

There are a few practical implications that could be derived from the findings of this study. First of all, in reality the daily commuters who possess partial spatial knowledge of metro stations account for a great portion of the total metro ridership. The fact that they have strong tendency to follow their familiar route to evacuate under emergency situations suggests that their evacuation route choices are highly predicted, and so are the choices by regular commuters who possess complete spatial knowledge and are likely to identify and take the optimal routes. This implies that metro authorities could survey the makeup of their passengers, predict in case of emergency evacuation the routes to be taken by passengers based on their spatial knowledge, and develop the emergency response plans accordingly. Crowd evacuation simulation could play an important role in this regard and hence deserves more attention in future research. For instance, simulation tools using agent-based modeling approach [73] and random utility theory [74] could take the completeness of spatial knowledge and pattern of crowd flow as inputs of the simulation and prediction of crowd evacuation, therefore transferring research outcomes about individual evacuees' behavior into knowledge about the crowd behavior that professionals are concerned about and can action upon in the emergency response practice. Secondly, the route and directional choices that passengers make during evacuation may not be optimal, especially for those who do not have complete spatial knowledge. This suggests that certain measures may need to be taken to provide these passengers with additional directional instructions and guide them to make alternative choices. By doing so, however, the possible negative influence of conflicting directional information revealed in this study that may delay the passengers' decision making and slow them down should be taken into consideration. Thirdly, participants without spatial knowledge tend to move more slowly and their wayfinding decisions are less predictable, which indicates that they could be the major challenge for metro authorities to manage the evacuation process. These passengers, lacking a cognitive map of the indoor space, rely heavily on environmental cues to make their wayfinding decisions. Therefore, clear display of directional information through means such as exit signs and staff instructions should target these passengers during emergency evacuation. Admittedly, this study bears several limitations that are noteworthy. External validity to people with different demographics requires to be further tested in future research. Thus, the current findings may not necessarily be applicable to certain groups of people such as the elderly or the physically challenged. In addition, the level of mental stress was not measured in real time in this study. Future research could be done to examine the interaction effect of the completeness of spatial knowledge and level of mental stress aroused by emergencies on people's use of different decision-making systems and their consequent evacuation behavior. In addition, as passengers enhance their completeness of spatial knowledge through spatial exploration, how do differently types of spatial knowledge, including landmark, procedural and survey knowledge, accrue in this process and their respective impacts on the passengers' evacuation behavior is another question that is worthy of investigation in future research.

5. Conclusions

An evacuation experiment was conducted in a virtual metro station in this study to analyze the influence of the completeness of spatial knowledge and pattern of crowd flow on passengers' evacuation performance when a fire emergency broke out in the metro station. Five wayfinding performance measures, as well as the emotional responses, sense of direction, wayfinding anxiety, simulator sickness and sense of presence of all participants were collected and analyzed. The results showed that the influence of the completeness of spatial knowledge was significant on all measures of participants' evacuation performance, and that the influence of the pattern of crowd flow was significant on participants' evacuation speed, route choice, and directional choices at two DPs. The interaction effect of completeness of spatial knowledge and pattern of crowd flow was found significant on participants' evacuation time, distance and speed. These findings could advance the existing understanding of human evacuation behavior, and provide important practical implications for passengers' safety and emergency preparedness in metro stations.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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