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Do people follow the crowd in building emergency evacuation? A cross-cultural immersive virtual reality-based study

Jing Lin[a], Runhe Zhu[b], Nan Li[a,*], Burcin Becerik-Gerber[b]

[a] Department of Construction Management, Tsinghua University, Beijing 100084, China
[b] Department of Civil and Environmental Engineering, University of Southern California, Los Angeles, CA 90089, United States

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ABSTRACT

This study aimed to examine the influence of crowd flow on human evacuation behavior during building fire emergencies, when evacuees perceive high uncertainty in the environment and experience mental stress. Evacuation experiments were conducted in an immersive virtual metro station, in which each participant was presented with one of three different patterns of crowd flow and asked to complete an evacuation task. The patterns of crowd flow were represented by non-player characters that split differently at each wayfinding decision point in the metro station. The experiments were conducted in Beijing, Los Angeles and London. The results showed that uneven splits of crowd flow motivated participants under mental stress to follow the majority of the crowd. This influence of crowd flow was generally consistent over the course of evacuation, and such consistency could be reinforced by stronger directional information conveyed by the crowd flow as well as positive feedback from the outcomes of previous wayfinding decisions. The results also indicated that the influence of crowd flow was significant in all three cultures represented by the three cities, however, the impact of culture on how participants would respond to the directional information conveyed by the crowd flow was insignificant.

1. Introduction

Fires in public buildings and facilities could cause severe fatalities and injuries [1]. As learned from past incidents [2], effective wayfinding by evacuees is critical to improve the efficiency of evacuation and reduce fatalities and injuries. The wayfinding ability of evacuees and their wayfinding decisions are subject to the influence of a variety of physical, psychological, environmental and social factors. Among the social factors that have been examined in the literature, crowd flow has been recognized as an influential and complicated factor, which has drawn increasing attention in the academia [3,4]. Prior research on the influence of crowd flow, however, has reported mixed findings. It is traditionally believed that, when making wayfinding decisions during an emergency, people have the tendency to follow the crowd instead of making independent decisions, resulting in the herding phenomenon [5]. The herding phenomenon could cause congestion on the route chosen by the crowd [6] and consequently slow down the evacuation in building emergencies [5,7]. When no congestion is caused, on the contrary, following the crowd may save people the time to evacuate [8]. Yet, a few other studies found no herding phenomenon [9–11] or even avoiding phenomenon [12] when people evacuated from building emergencies. Such a discrepancy in previously reported findings suggests that further research is needed to advance the understanding of how human evacuation behavior is influenced by the crowd flow.

An important mediator variable for the influence of crowd flow on the behavior of evacuees is their mental stress. When people are situated in a highly uncertain environment, their stress level is likely to be high, which would decrease their cognitive abilities to perceive the environment and process information [13]. Besides, prior research found that when people are under a high level of stress, they might use a different decision-making process than when they are under normal conditions [14]. Mental stress during emergency evacuation is closely related to people's perception of uncertainty in the environment [13]. Uncertainty during evacuation can stem from various factors [15], such as complexity of the spatial layout, unfamiliarity with the space, vague impacts of crowds split among multiple directions, and conflicting directional information perceived from the environment. Under these circumstances, evacuation route choices made by evacuees could be resulted from their strategic cognitive process (wayfinding strategies), intuition or both [13,15]. That being said, except for several descriptive case studies of real-world incidents, the majority of prior research that examined the influence of crowd flow used surveys [6,16], drills

* Corresponding author.
E-mail address: nanli@tsinghua.edu.cn (N. Li).

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Fig. 1. Snapshots of the real metro station (left) and virtual metro station (right).

[17,18] or conducted evacuation experiments in relatively simple environments [10,19,20]. The design of these studies did not focus on creating significant uncertainty to evoke mental stress, hence whether they did prompt participants' realistic behavioral response is debatable.

Besides, the environment and the associated uncertainty perceived by evacuees are dynamic as they move along the evacuation routes. This would likely lead to changes in the level of mental stress experienced by the evacuees [15], and subsequently influence their herding tendency. Moreover, evacuees usually need to go through multiple decision points (DPs) and make multiple decisions. Prior research has pointed out that when people make successive decisions, they may be influenced by the outcomes of previous decisions, which serve as a positive or negative feedback that may strengthen or weaken their decision-making preferences [21]. Whether this phenomenon also applies to evacuation behavior, and as a result, how consistent is the influence of crowd flow on evacuees' wayfinding decision-making over the course of evacuation, are questions yet to be answered.

Culture is another factor that may affect the influence of crowd flow on human evacuation behavior. People with different cultural backgrounds may show different herding tendencies [22]. Besides, people from different cultures may have received different emergency response training that is adapted to the unique threats their cities or countries are faced with [23]. Thus, people from different cultures may be impacted by crowd flow differently. That being said, whether the above hypothesis is true, and how culture would interact with crowd flow to impact human evacuation behavior, have largely remained to be explored.

Prior research, prohibited by legal and moral constraints to expose people to real building emergency scenes, has employed several methods to study human evacuation behavior. These methods include post-emergency investigation [24,25], fire evacuation drill [17,18], hypothetical survey [6,16] and animal experiment [26]. Using these methods, researchers are able to evoke people's emotional and behavioral responses to building emergencies, collect data for evacuation behavioral analysis, and hence advance the understanding of people's wayfinding decision-making during evacuation as well as the impacts of various factors that altogether shape people's evacuation behavior [27,28]. However, the above research methods bear certain limitations [29], such as the scarcity and/or incompleteness of real behavioral data, high cost, difficulty in setting controlled experimental environment, and debatable similarity between human and animal subjects. A more comprehensive review and comparison of these methods can be found in [27]. With the fast development of virtual reality (VR) technology in recent years, VR-based experiments have been introduced as an alternative method to study human behavior during building emergencies [27]. A number of studies have tested this method in wayfinding-related experiments and repeatedly confirmed its efficacy [30,31]. VR-based experiments have also been proven effective in arousing people's mental stress by immersing them in high-fidelity virtual immersive environments (IVEs), and evoking their behavioral responses to virtual emergencies, providing the opportunity for collecting virtual evacuation behavior data with relatively high ecological validity [32,33].

Motivated by the aforementioned gaps, this study aims to answer three research questions: (1) Do people follow the crowd to make route choices during building evacuation when faced with high uncertainty? (2) How consistent is the influence of crowd flow on people's directional choice-making over the course of evacuation? and (3) How does culture interact with crowd flow and affect people's evacuation behavior? To answer these research questions, a VR-based experiment was designed and conducted in this study. Participants of the experiment were exposed to a virtual fire emergency in a multi-story metro station, and were instructed to performance an evacuation task. During evacuation, they could see crowds of non-player characters (NPCs) that split at each wayfinding decision point, forming three patterns of crowd flow. The same experiment was conducted in three cities located in different continents. All details of the experimental design are presented in Section 2. It is followed by Section 3 that reports the experiment results, which are further discussed in Section 4. Section 5 concludes the paper.

2. Methods

2.1. Experimental design

The experiment used an IVE of a metro station, which was modeled based on a real metro station in Beijing, China, as shown in Fig. 1. The virtual metro station, with an area of approximately 6600 m^2. It had a relatively complex layout and multiple wayfinding DPs that led to different exits, which was likely to create significant uncertainty for the participants, who were unfamiliar with the environment during the emergency evacuation. The station had two floors (a ground floor and an underground floor), and three exits (denoted as Exits 1, 2 and 3). In case of emergency, there were five different evacuation routes (denoted as Routes 1, 2, 3, 4 and 5, illustrated in Fig. 2) from the metro platform to one of the three exits, depending on the directional choices made at three DPs (denoted as DPs 1, 2 and 3). At DP 1, where they would be initially positioned at the beginning of the experiment, participants could choose to either go to Hallway 1 on the same floor, or go downstairs using Staircase 1. At DP 2, which was located at the end of Hallway 1, 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 on the underground floor between Staircases 3 and 4, participants could choose either staircase to reach Exits 2 or 3. To differentiate the participants who took different routes to reach DP 3, this DP is hereafter referred to as DP 3a if participants passed DP 2 before reaching this DP, or as DP 3b if otherwise. At each DP, exit signs were visible that showed that all alternative directions would lead to exits, although the exits were not directly visible from the DPs and information about the distance to exits was not available. On each exit sign, as shown in Fig. 3, an arrow was used to point to a direction, along with descriptive text in both English and Chinese.

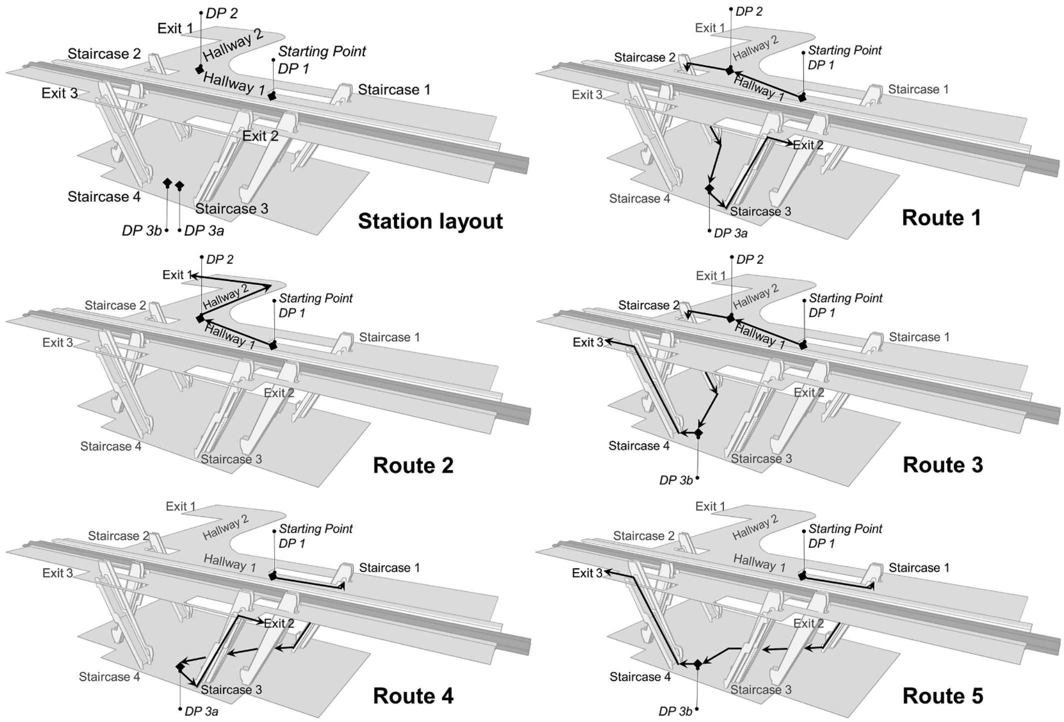

Fig. 2. Layout of the virtual metro station and five available evacuation routes.

This study designed one independent variable (crowd flow) with three different levels (Patterns 1, 2 and 3). All participants were divided into three study groups (Groups A, B and C), and each group was presented with one of three patterns of crowd flow. The dependent measures of participants' wayfinding performance included their evacuation route choices, and their directional choices at the three DPs. As illustrated in Fig. 4, the three patterns of crowd flow differed in terms of how NPCs in the IVE split between the two directional alternatives at each DP. Under Pattern 1, all NPCs would choose the same direction (100-0 split); under Pattern 2, the NPCs would have an 80-20 split; and under Pattern 3, the NPCs would split evenly (50-50 split).

2.2. Participants

To take part in this study, participants should not have any heart-related illness, wrist/hand injuries, or uncomfortable VR experiences in the past, and should have a normal or corrected-to-normal vision. Emails, flyers, personal solicitation and outlets on social media (e.g. WeChat) were used to recruit participants. The experiments were conducted in three cities across different countries, including Beijing, Los Angeles (LA) and London. None of the participants had prior experience with the virtual metro station. Participation in this study was voluntary. Those who participated in the study in Beijing received 30 CNY as monetary incentives, while participants in LA and London did not receive any compensation. The present study was approved by the University Park Institutional Review Board (UPIRB) of University of Southern California (USC).

Prior to the experiment, the participants were randomly divided into three study groups with the constraint of having equal numbers of males and females in each group. A few participants did not show up at the experiment due to personal reasons, and one participant failed to complete the experiment due to a misunderstanding of the instructions. A total of 169 participants completed the experiment. The basic information of the participants in each group is summarized in Table 1.

2.3. Apparatus

The experiment was conducted in the Department of Construction Management at Tsinghua University in Beijing, the Department of Civil and Environmental Engineering at the University of Southern California

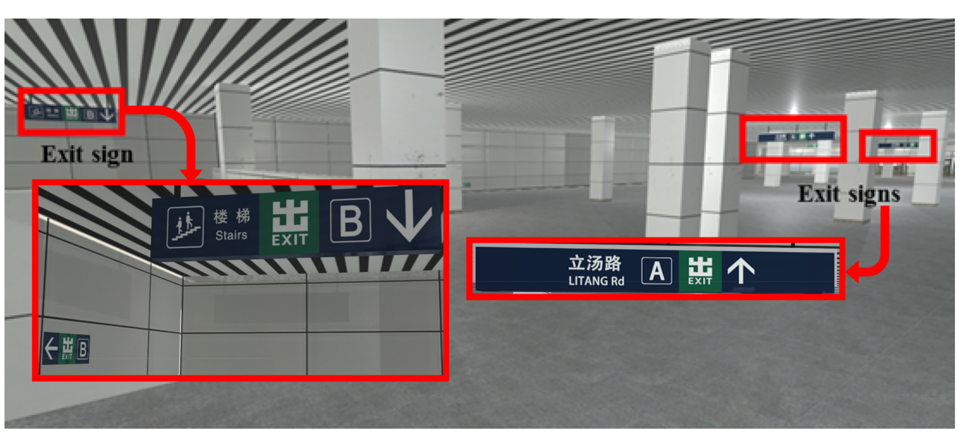

Fig. 3. Evacuation signage in the virtual metro station.

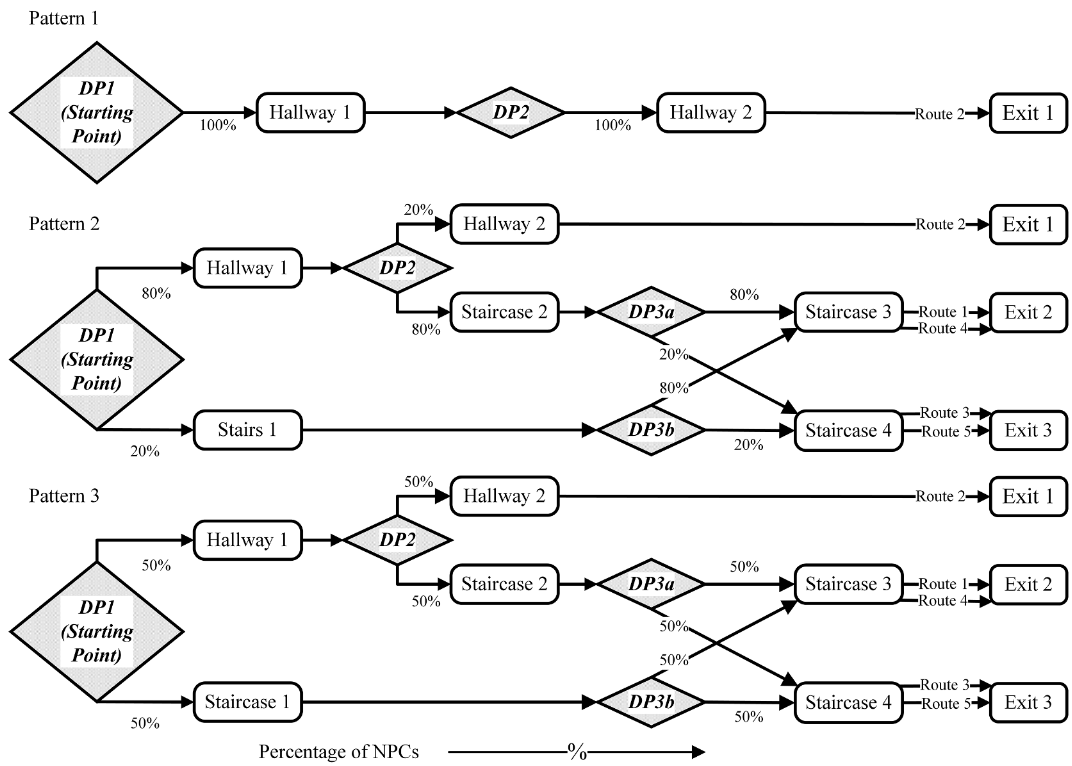

Fig. 4. Three patterns of crowd flow and associated routes taken by NPCs (note: the percentage attached to each arrow indicates the proportion of NPCs that choose this direction at the last DP).

Table 1
Basic information of participants in three study groups.

Study group	Sample size	Age	Location	Gender		Length of residence in the current location	
				Male	Female	≥5 years	< 5 years
A	55	25.80	London	8	7	9	6
		(8.27)	Beijing	12	9	21	0
			LA	9	10	12	7
B	55	25.67	London	8	7	12	3
		(8.29)	Beijing	11	10	21	0
			LA	9	10	11	8
C	59	25.51	London	9	9	12	6
		(6.08)	Beijing	12	10	22	0
			LA	9	10	12	7

in LA, and the Alan Turing Institute in London. The equipment used in the experiment included two computer workstations, one of which was connected with the HTC VIVE head-mounted-display (HMD) VR system [34] as a client workstation, and the other one as a server workstation (Fig. 5). The two workstations were connected to the same local area network (LAN) and linked by Photon Server [35], which enabled the server workstation to send commands to the client workstation to control the virtual environment. During the experiment, participants would keep a standing posture and use a controller to navigate in the IVE at a constant speed of 2.4 m per second, which was found in pilot tests as a proper navigation speed in the IVE without causing VR sickness. VR sickness is a type of motion sickness that people may experience in VR environments [36], mainly caused by a sensory disagreement between the expected motion and experienced motion. VR sickness was reported in several prior VR-based behavioral studies [37,38], in which it could cause discomfort to some participants, influence their behavior in IVEs, and in extreme cases force them to terminate the experiment. Participants' orientation in the IVE was determined by the orientation of HMD, which was synchronized with the participants' head movement. For both eyes, the resolution of the displays was 1080 (horizontal) × 1200 (vertical) pixels. The headphone of the VR system was used to provide audio stimuli (i.e., emergency broadcasting and fire sound) in the IVE.

3D Studio Max [39] was used to model and render a virtual metro station based on 2D drawings of a real metro station in Beijing (Fig. 6). Unity3D game engine [40] was used to build and control the experimental IVE, and record the trajectories of participants. The emergency broadcasting in the IVE included fire alarm and emergency evacuation instructions repeated in both Chinese and English. The virtual fire emergency was used to create additional uncertainty in the environment and evoke mental stress on participants, who were unfamiliar with the environment. Such virtual fire scenes were used in prior studies and found to be valid to evoke mental stress [29,33].

The NPCs in the IVE were modeled and rendered with high fidelity in order to improve the sense of presence experienced by participants, and as a tradeoff, the number of NPCs was limited to 53 (with a crowd density of approximately 0.16 NPCs/m^2 at the platform) to avoid overloading the graphical processors (GTX 1080) of the workstations. All NPCs were automatically generated at predetermined positions, either at the platform or inside the metro compartments, at the beginning of the experiment. Each NPC would begin evacuation as soon as they perceived fire hazards within their proximity. The route choices of the NPCs were predetermined to create the crowd flow patterns needed in the experiment. Based on their gender and age, the NPCs were set to move at constant speeds that ranged from 0.7 m/s to 2.8 m/s in accordance with the Chinese specification of metro station evacuation [41].

2.4. Procedure

At the beginning of the experiment, participants were required to read and sign an IRB-approved consent form. After giving their consent,

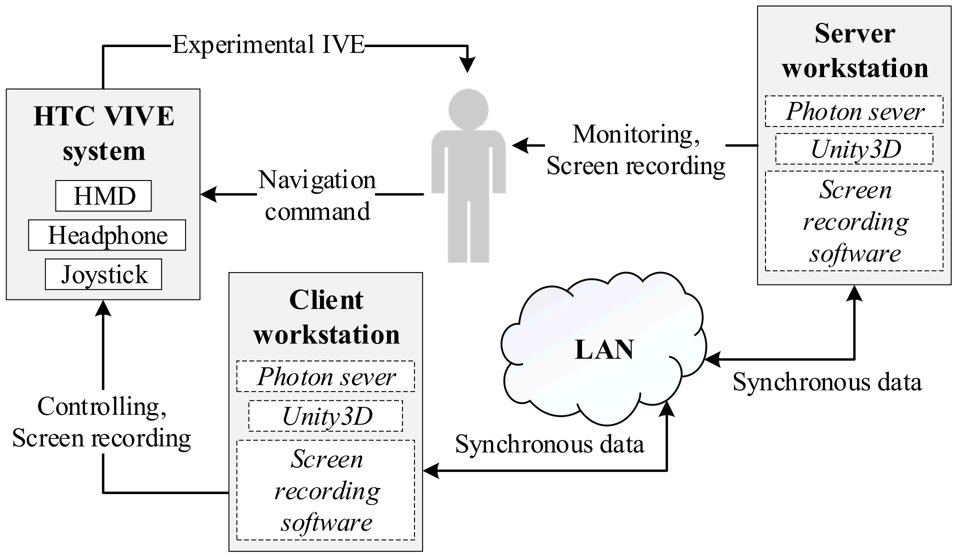

Fig. 5. Architecture of the VR-based experimental system.

participants were asked to complete a screening survey, which asked about their basic health conditions. If they did not meet the aforementioned requirements, they were thanked and dismissed from the study. Otherwise, they continued to go through the following procedure. Participants were first asked to fill in a pre-experiment questionnaire, which asked about their basic demographic information, emotions measured with positive affect and negative affect scale (PANAS) [42,43], and VR sickness measured with simulator sickness questionnaire (SSQ) [44]. PANAS scores were used to evaluate the ecological validity of the VR experiment, and SSQ scores were used to control the variable of VR sickness. The participants were informed that they could quit the experiment at any time if they felt uncomfortable in the IVEs.

Then, after reading an instruction manual of how to navigate in the IVE using the HMD and controller, the participants were instructed to put on the HMD to be immersed in a training IVE. The training IVE presented an empty open space, the purpose of which was to familiarize participants with the sense of immersion in virtual environments and the navigation operations. Participants could contact the experimenter if they had any navigation problems during training.

Subsequently, the participants were instructed to read instructions about the experiment. The instructions asked them to conduct an evacuation task in a virtual metro station by reaching one of the exits as soon as possible. Once participants finished reading the instructions, the experimenter started the experiment by immersing the participants in one of the three IVEs (associated with crowd flow Patterns 1, 2 or 3) based on participants' group assignment (Groups A, B or C). In the IVE, participants first found themselves at the metro platform, together with the crowd (NPCs). Then, a metro train approached the platform with some of its compartments burning. At the same time, participants began hearing emergency broadcasting in the station. Participants decided on their own when to begin evacuating and via which route. Once they reached an exit in the metro station, a message saying "You have completed the VR experiment" popped up in the IVE. The participants were then instructed to take off the HMD.

Lastly, the participants were asked to fill in a post-experiment questionnaire, which asked them to rank a list of factors (including visibility of exits, ticket booths and staircases, distance to fire, direction indicated by crowd flow, and direction indicated by signage) that may have impacted their directional choices at each DP, and to rate on a scale of 1–5 the importance of crowd flow to their directional choices at each DP. The questionnaire also asked participants to fill in PANAS and SSQ, and report their sense of direction measured with the Santa Barbara sense of direction scale (SBSOD) [45], sense of presence in the IVE measured with the presence questionnaire (PQ) [46], wayfinding anxiety measured with the Lawton's spatial anxiety scale (LSAS) [47],

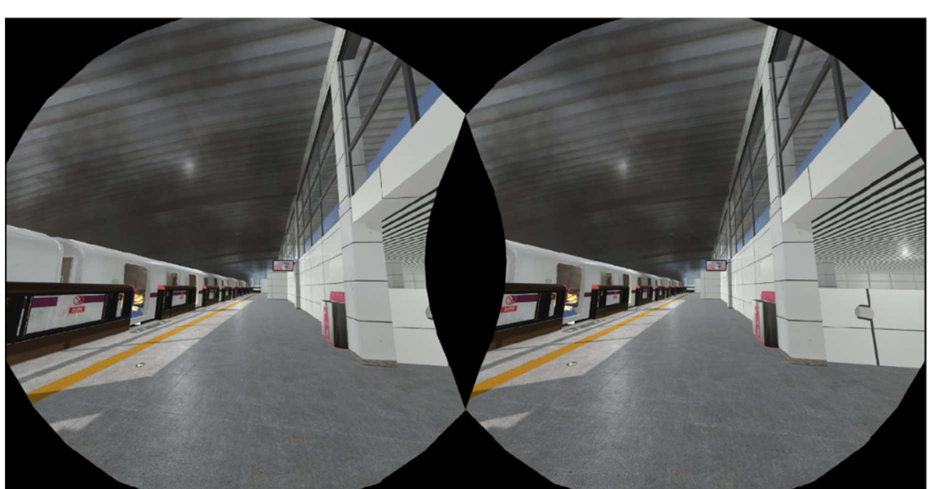

Fig. 6. The stereoscopic view of the IVE from the HMD.

Table 2
Participants' route choices in Group A.

Route choices	Route 1	Route 2	Route 3	Route 4	Route 5
Percentage of participants (%)	90.91	3.64	3.64	1.82	0.00
Percentage of NPCs (%)	100.00	0.00	0.00	0.00	0.00

and past experiences of emergency evacuation and drills.

2.5. Analysis

Crosstabs analysis [48] was used to analyze participants' route choices and their directional choices at each DP, due to its capability of assessing the relationships between two nominal variables. Specifically, the effect of crowd flow on participants' route choices and directional choices at each DP, and the effect of culture on their route choices were analyzed using crosstabs analysis. In addition, independent tests, including one-way ANOVA [49] and Kruskal-Wallis test [50] were used to analyze: (1) whether the subjective evaluation by standard scales (PANAS, SBSOD and LSAS) were significantly different across the three study groups, and (2) whether the rating and ranking of the importance of crowd flow were significantly different across the three study groups. 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. One sample T test was used to analyze whether the rankings of the importance of crowd flow were higher than the rankings of the importance of signage and whether emotions and VR sickness changed significantly over the course of the VR experiment. The significance level was set at 0.05 and the marginal significance level was set as 0.10, which is standard practice recommended by classic statistical textbooks [51] and in line with prior evacuation behavioral studies [32,52]. All data analyses were conducted using SPSS 25 software [53].

3. Experiment results

3.1. Validity assessment

First of all, to assess the ecological validity of the experiment, participants' subjective evaluation of PANAS, SSQ and PQ was analyzed. One-sample T tests on the responses showed that their overall positive emotions significantly reduced ($\mu = -1.130$, $t = 2.354$, sig. $= 0.020$). The range of change of positive and negative emotions was from -4 (strongest to no feeling) to 4 (no feeling to strongest). Meanwhile, while their overall negative emotions remained stable, among the specific negative emotions, the levels of *distressed* ($\mu = 0.142$, $t = 2.078$, sig. $= 0.039$), *scared* ($\mu = 0.148$, $t = 2.040$, sig. $= 0.043$), *alert* ($\mu = 0.314$, $t = 3.592$, sig. $= 0.000$), and *jittery* ($\mu = 0.172$, $t = 2.300$, sig. $= 0.023$) increased significantly during the experiment. The results indicated that the fire emergency IVE had negative effects on participants' emotions, which was a sign that the participants had experienced mental stress. The results also showed that the VR sickness of participants barely changed during the VR-based experiment ($\mu = 3.264$, SD $= 10.077$). The range of change of VR sickness was from -120.54 (heavy to no feeling) to 120.54 (no feeling to heavy) according to the SSQ [44]. In addition, the participants reported a PQ score of 140.840 on average (SD $= 17.230$). The range of sense of presence was from 30 (no presence) to 210 (presence as reality). Compared with the scores of PQ reported in prior studies, the sense of presence participants experienced in this experiment was medium-high [46,54]. In short, the above results suggested that the experiment was successful in evoking mental stress among participants, and had reasonable ecological validity.

In addition, group differences in the confounding factors (gender, age, emotions, VR sickness, sense of presence, sense of direction and wayfinding anxiety) may affect the results of this experiment. To analyze whether such group differences existed, one-way ANOVA was conducted to compare the following variables across the three study groups: participant's gender, age, sense of direction, wayfinding anxiety, change of VR sickness and positive and negative emotions during the experiment, and sense of presence. The results showed that the three groups did not significantly differ in terms of the above variables (all Sig. > 0.10), which suggested that all data collected in the experiment were not biased by any confounding factors.

3.2. Group A

The participants in Group A were presented with Pattern 1 of crowd flow in the IVE, in which all NPCs took Route 1 to evacuate. The results, as summarized in Table 2, show that 90.91% of the participants evacuated via Route 1, indicating that the participants had a strong tendency to follow the crowd during evacuation. Moreover, most participants chose the same direction as NPCs did at all DPs (98.18% at DP 1, 96.29% at DP 2, 96.15% at DP 3a, and 100.00% at DP 3b). Compared with those who did not follow NPCs, participants who did follow them reported the crowd flow to be much more important to their directional choices at the DPs (Table 3).

3.3. Group B

The participants in Group B were presented with Pattern 2 of crowd flow in the IVE, in which the NPCs had an 80-20 split at each DP, as shown in Fig. 4. The majority of the NPCs took Route 1. The experiment results, as summarized in Table 4, showed that 60.00% of the participants also took Route 1, which indicated that the participants had a strong tendency to follow the crowd during evacuation. Moreover, most

Table 3
Participants' directional choices at the DPs in Group A.

DP	Alternative directions	Number of participants	Number of NPCs	Importance of crowd flow	
				Ranking	Rating
DP 1	Hallway 1	54	53	1.76 (1.23)	1.24 (0.80)
	Staircase 1	1	0	5.00 (-)	4.00 (–)
DP 2	Hallway 2	2	0	3.50 (0.71)	4.00 (1.41)
	Staircase 2	52	0	1.92 (1.19)	1.23 (0.65)
DP 3a	Staircase 3	50	0	1.92 (1.24)	1.24 (0.62)
	Staircase 4	2	0	3.50 (2.12)	3.00 (2.83)
DP 3b	Staircase 3	1	0	2.00 (–)	1.00 (–)
	Staircase 4	0	0	–	–

Note: The range of rankings was between 1 and 6, with 1 being that the participant found crowd flow the most important among six different factors, and 6 being the least important; The range of ratings was between 1 and 5, with 1 being that the participant strongly agreed that he/she made the directional choice by following the crowd flow, and 5 being that the participant strongly disagreed. The numbers in parentheses are standard deviations (SDs).

Table 4
Participants' route choices in Group B.

Route choices	Route 1	Route 2	Route 3	Route 4	Route 5
Percentage of participants (%)	60.00	20.09	5.45	3.64	1.82
Percentage of NPCs (%)	51.20	16.00	12.80	16.00	4.00

participants chose the same direction as 80% of the NPCs did at all DPs (94.55% at DP 1, 69.23% at DP 2, 91.67% at DP 3a, and 66.67% at DP 3b). Compared with those who did not follow NPCs, participants who did follow them reported crowd flow to be much more important to their directional choices at the DPs (Table 5).

3.4. Group C

The participants in Group C were presented with the Pattern 3 of crowd flow in the IVE, in which the NPCs had a 50-50 split at each DP, as shown in Fig. 4. The results, as summarized in Table 6, showed that 45.76% of the participants evacuated via Route 2, which suggested that when crowd flow did not provide any indicative directional information, participants would prefer to stay on the same floor to evacuate than to go downstairs [6]. Specifically, 62.71% of the participants chose Hallway 1 at DP 1, 72.97% of the participants chose Hallway 2 at DP 2, and 60.00% and 68.18% of the participants chose Staircase 4 at DP 3a and DP 3b, respectively. The participants generally reported they considered crowd flow as an important factor (within top three among all factors) when they made directional choices (Table 7).

4. Discussions

4.1. Participants' evacuation route choices

To analyze the effect of crowd flow on participants' route choices, the splits of participants among all routes were compared across Groups A, B, and C, as illustrated in Fig. 7.

Crosstabs analysis of participants' routes choices (Routes 1, 2, 3, 4 and 5) in different study groups (Groups A, B and C) showed that route choices had a significantly strong correlation with patterns of crowd flow (Table 8). Specifically, Route 2 was the most used route in Group C, chosen by 45.76% of the participants. The results of Group C indicated that participants preferred routes without vertical movement (Route 2 in the experiment) in an unfamiliar emergency environment, which was also supported by a previous survey-based study [6]. However, the majority of the participants in Groups A and B evacuated through Route 1, which was the route taken by the majority of NPCs. The results indicated that when the crowd was unevenly split, participants tended to follow the majority of crowd. This was probably because dynamic information could be more easily perceived by humans than static information [55], especially when they are faced with high uncertainty and their ability of attention is diminished [15]. As a result, compared to other sources of directional information in the metro station, such as signage, crowd flow was better perceived by the participants and thus more influential on their evacuation route choices.

Table 6
Participants' route choices in Group C.

Route choices	Route 1	Route 2	Route 3	Route 4	Route 5
Percentage of participants (%)	6.78	45.76	10.17	11.86	25.42
Percentage of NPCs (%)	12.50	25.00	12.50	25.00	25.00

Moreover, a comparison of participants' route choices between Groups A and B using crosstabs analysis further showed that evacuation route choices were significantly affected by the patterns of crowd flow (Table 8). The percentage of participants following the route suggested by crowd flow in Groups A (90.91%) and B (60.00%) was significantly different. This was probably caused by the difference of directional information conveyed by the two different crowd flow patterns in Groups A and B. For Group A, the directional information conveyed by the crowd flow could be that a route taken by none of the NPCs would unlikely lead to an exit, which when perceived by the participants would prevent them to take such route. Moreover, when making directional choices under pressure, participants may have also experienced inattentional blindness [56] on static directional information, hence focusing on the only route taken by the NPCs and ignoring other alternative routes. For Group B, the directional information conveyed by the crowd flow could be that at each DP both directions may lead to an exit, although they may not be equally favorable. This may have prompted some of the participants to consider additional sources of directional information, such as signage, to facilitate their directional choice-making.

4.2. Participants' directional choices at the decision points

Participants' evacuation trajectories including their directional choices at each DP are illustrated in Fig. 8, and compared across the three study groups. Participants' rating of the importance of crowd flow to their directional choices at each DP and their ranking of the importance of crowd flow among a list of factors are shown in Fig. 9. For each DP, crosstabs analysis was used to analyze the effect of crowd flow on the participants' directional choices, and one-way ANOVA analysis was used to compare the participants' evaluation of the importance of crowd flow across the three study groups.

The results showed that, at DP 1, participants' directional choices were significantly different across the three groups (Table 8). The self-reported importance of crowd flow to participants' directional choices was also significantly different at DP 1 among the three study groups

Table 5
Participants' directional choices at the DPs in Group B.

DP	Alternative directions	Number of participants	Number of NPCs	Importance of crowd flow	
				Ranking	Rating
DP 1	Hallway 1	52	42	2.21 (1.43)	1.44 (0.70)
	Staircase 1	3	11	3.00 (1.00)	3.33 (1.15)
DP 2	Hallway 2	16	8	3.69 (1.53)	2.50 (1.26)
	Staircase 2	36	35	2.03 (1.23)	1.31 (0.47)
DP 3a	Staircase 3	33	27	2.30 (1.38)	1.52 (0.97)
	Staircase 4	3	7	2.00 (1.73)	1.67 (1.15)
DP 3b	Staircase 3	2	8	2.50 (2.12)	2.50 (2.12)
	Staircase 4	1	3	1.00 (-)	1.00 (-)

Note: The range of rankings was between 1 and 6, with 1 being that the participant found crowd flow the most important among six different factors, and 6 being the least important; The range of ratings was between 1 and 5, with 1 being that the participant strongly agreed that he/she made the directional choice by following the crowd flow, and 5 being that the participant strongly disagreed. The numbers in parentheses are SDs.

Table 7
Participants' directional choices at the DPs in Group C.

DP	Alternative directions	Number of participants	Number of NPCs	Importance of crowd flow	
				Ranking	Rating
DP 1	Hallway 1	37	27	2.38 (1.31)	1.86 (1.13)
	Staircase 1	22	26	2.68 (1.75)	2.09 (1.02)
DP 2	Hallway 2	27	14	2.67 (1.52)	1.70 (1.10)
	Staircase 2	10	13	3.00 (1.49)	1.60 (0.70)
DP 3a	Staircase 3	4	7	3.25 (1.50)	2.25 (1.26)
	Staircase 4	6	6	3.50 (1.76)	2.17 (1.17)
DP 3b	Staircase 3	7	13	3.14 (1.57)	2.42 (1.39)
	Staircase 4	15	13	2.93 (1.62)	1.87 (1.06)

Note: The range of rankings was between 1 and 6, with 1 being that the participant found crowd flow the most important among six different factors, and 6 being the least important; The range of ratings was between 1 and 5, with 1 being that the participant strongly agreed that he/she made the directional choice by following the crowd flow, and 5 being that the participant strongly disagreed. The numbers in parentheses are SDs.

(Table 9). The reason was that the majority of the participants in Groups A and B followed the crowd whereas participants in Group C were notably influenced by the signage. On one hand, the underlying directional information of Pattern 1 was that only the direction chosen by the crowd was safe, whereas other directions might be inaccessible, unsafe or have longer distance [16]; The underlying directional information of Pattern 2 was that both directions chosen by the crowd were accessible, whereas the direction chosen by the majority of the crowd might be safer or have shorter distance. Both patterns of crowd flow encouraged participants to follow the majority of the crowd. This herding tendency was further strengthened by the mental stress of participants [57], which was caused by the virtual fire emergency that represented a highly uncertain and unfamiliar environment. On the other hand, participants were more likely to seek and rely on other sources of directional information because both directions chosen by the crowd were considered accessible under Pattern 2. It is noteworthy that while the density of the crowd in the IVE was relatively low, a higher density may create congestion in certain routes and lower the accessibility [58]. Under such circumstances, people's avoiding tendency instead of herding tendency may increase [3,4], which may force people to consider alternative routes including those not used by the crowd [19], as such routes could be less crowded and hence safer [6]. Over half of participants in Group C (62.71%) chose Hallway 1 at DP 1, despite the fact that both directions were shown on an exit sign visible from DP 2 and that the crowd split between Hallway 1 and Staircase 1 evenly, as shown in Fig. 10. Although where Hallway 1 and Staircase 1 led was not visible to participants at DP 1, the two directions towards Hallway 1 and Staircase 1 were still different in two aspects: (1) the train on fire approached the platform from the direction of Staircase 1 and (2) taking Stair 1 would require vertical movement [6]. Thus, participants might have decided to avoid fire and vertical movement and hence chosen Hallway 1.

For those participants who chose Hallway 1 at DP 1, crosstabs analysis results showed that their directional choices at DP 2 were significantly different across the groups (Table 8). As their trajectories showed, the large majority of those from Group A followed the crowd to take Staircase 2, while a number of them took Hallway 2. This number, however, significantly increased in Group B, and became the majority in Group C. The lower following rate at DP 2 in Groups B and C could be explained by three possible reasons. First, prior research reported that people tend to prefer hallways than staircases [6], therefore, when participants saw that some of the NPCs went to Hallway 2, unlike in Group A, they considered it a feasible evacuation path and hence tended to choose it. Second, the participants were influenced by directional information conveyed by other sources of information, particularly the exit signs in Hallway 2 (as shown in Fig. 3). This was evidenced by participants' rankings of the influencing factors on their directional choices: participants who chose Hallway 2 at DP 2 ranked signage over crowd flow in terms of the importance to their directional choice-making at DP 2 ($t = 1.728$, $sig = 0.091$). This suggested that

Table 8
Correlations between evacuation choices and study groups.

Variable 1	Variable 2	φ	N	Sig.
Routes choices	Study groups	0.736	169	0.000
Routes choices	Study groups in London	0.674	48	0.005
Routes choices	Study groups in Beijing	0.799	64	0.000
Routes choices	Study groups in LA	0.805	57	0.000
Routes choices	Groups A and B	0.308	110	0.003
Directional choices at DP 1	Study groups	0.446	169	0.000
Directional choices at DP 2	Study groups	0.585	143	0.000
Directional choices at DP 3a	Study groups	0.525	98	0.000
Directional choices at DP 3b	Study groups	0.341	26	0.221

Note: φ denotes Pearson Chi-Square between variables 1 and 2. N denotes the total sample size in each analysis. Sig. denotes the asymptotic significance (2-sided) of φ.

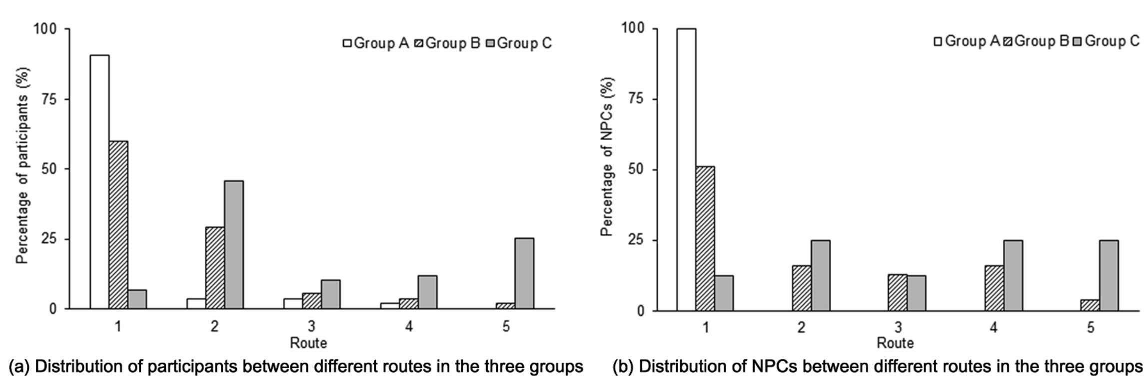

Fig. 7. Route choices of participants and NPCs across three study groups.

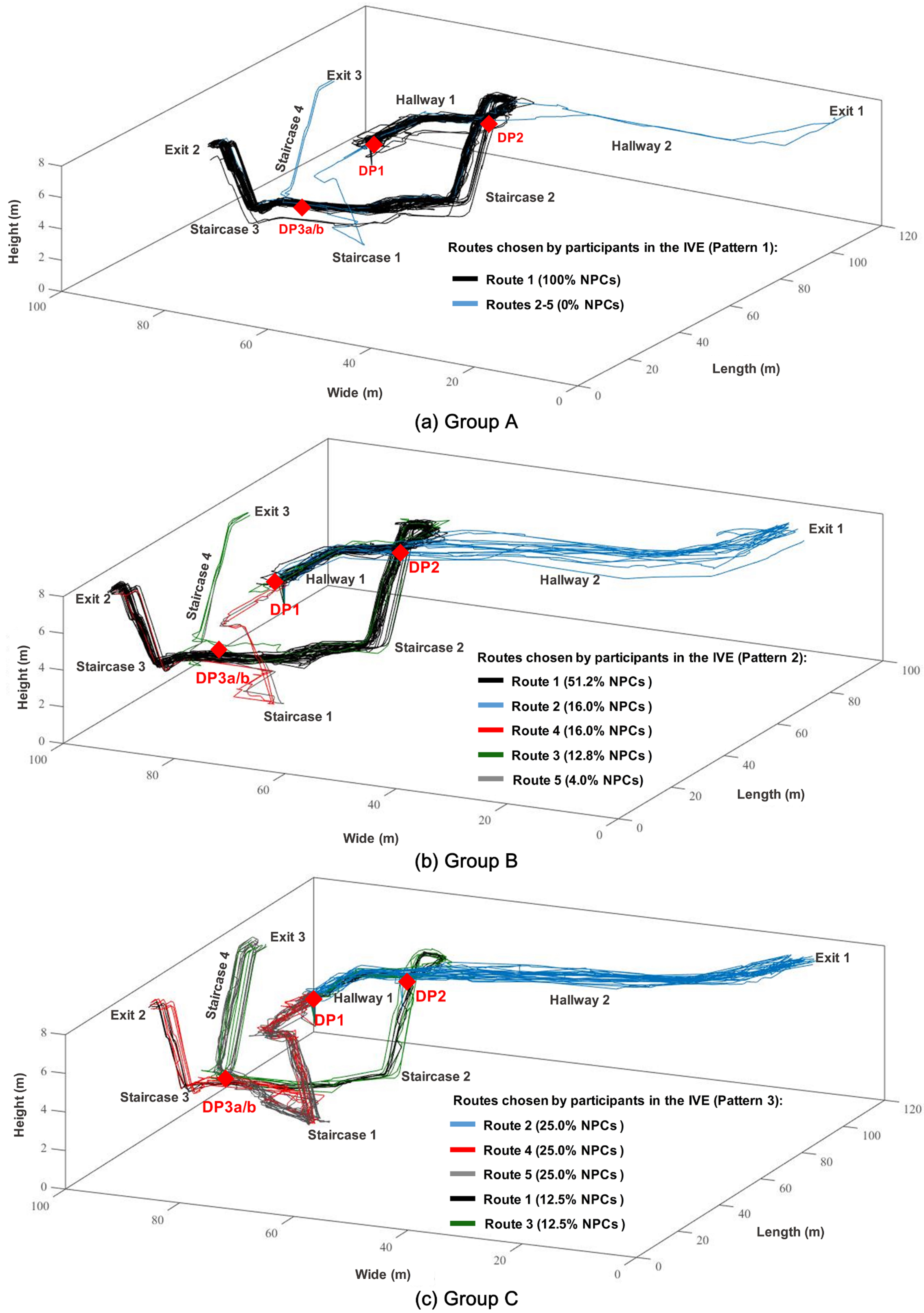

Fig. 8. Comparison of trajectories of participants across three study groups.

when the NPCs split between two directions, the influence of crowd flow relative to other factors was reduced, and participants would rely more on other factors for their directional choice-making. Third, the participants could see DP 2 before reaching the position and having to make their directional choice, therefore, they had more time to perceive the environment and collect available directional information. Being farther away from the fire compared to DP 1, they were also faced with less uncertainty and under less pressure. These factors may have led the participants to make more independent and informed decisions, resulting in lower flowing rates at DP 2.

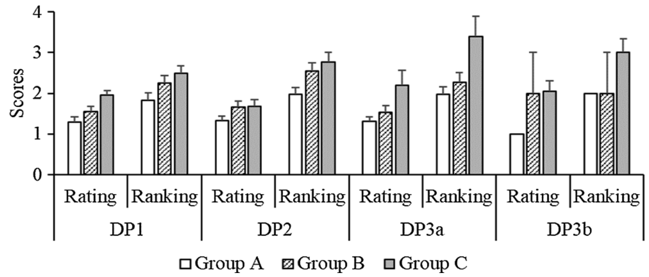

Fig. 9. Participants' evaluation of the importance of crowd flow to their directional choices at each DP.

Table 9
Cross-group comparison of participants' self-reported importance of crowd flow.

DP	Self-reported importance of crowd flow	F	Df	Sig.
DP 1	Rating (5-point scale)	7.079	(2, 166)	0.001
	Ranking (among 6 factors)	3.345	(2, 166)	0.038
DP 2	Rating (5-point scale)	2.248	(2, 140)	0.109
	Ranking (among 6 factors)	3.828	(2, 140)	0.024
DP 3a	Rating (5-point scale)	4.166	(2, 95)	0.018
	Ranking (among 6 factors)	4.625	(2, 95)	0.012

Note: F denotes the F-statistic of one-way ANOVA analysis, the ratio of between-groups to within-groups mean squares. Df denotes the degree of freedom (between-groups, within-groups). Sig. denotes the possibility of rejecting the null hypothesis of the F- statistic. A larger rating value or smaller ranking value indicates higher importance.

Among the participants who took Staircase 2 to the underground floor and arrived at DP 3a, the majority of those from Groups A and B followed the crowd and chose Staircase 3. For participants in Group C, however, Staircases 3 and 4 had similar attraction, probably because these two staircases were symmetric in relation to DP 3a. Crosstabs analysis results showed that the effect of crowd flow on participants' decision at DP 3a was significant (Table 8). Participants' evaluation of the importance of crowd flow to their directional choices at DP 3a was significantly different across the three groups (Table 9).

Lastly, only very few participants in Groups A and B went downstairs at DP 1 via Staircase 1. The number of participants in Groups A and B who arrived at DP 3b was too small to yield any statistically meaningful analysis of their decisions at this DP. Staircase 4 was more attractive to participants in Group C (68.18%). However, results of crosstab analysis between the participants' choices at DPs 3a and 3b in Group C showed that the choices of Staircases 3 or 4 were not significantly different (Sig. $>$ 0.10). Considering the symmetric locations of Staircases 3 and 4, the results indicated that people may not have a biased preference between symmetric choices.

4.3. Consistency of the effect of crowd flow

During building emergencies, people usually need to go through multiple DPs and make successive decisions, as participants of this study did, before reaching safe locations. The effect of crowd flow on the participants' directional choices was compared between successive DPs in order to understand how this effect may have changed over the course of evacuation. Since Pattern 3 did not provide any directional information in favor of certain directions and the effect of crowd flow could be considered neutral, this comparison only involved experiment results from Groups A and B.

The results showed that, in Group A, 90.91% of the participants decided to follow the crowd at DP 1 and kept doing so at the next two DPs. In Group B, 60.00% of the participants followed the crowd consistently at all DPs, and another 1.82% of the participants kept avoiding the crowd at all DPs. This indicated that, in general, the participants had the tendency to follow the majority of the crowd consistently. Given that the route the participants chose by consistently following the majority of the crowd was not the shortest route, this suggested that participants may have relied more on intuition than strategic cognitive process (wayfinding strategies). It also appeared that the consistency of the effect of crowd flow could be reinforced by stronger directional information conveyed by the crowd flow, possibly because the stronger directional information could make alternative directions seem more uncertain and less attractive [16].

In addition, while the effect of crowd flow on participants' directional choices was consistent across different DPs for participants in Group A, it turned out to be the opposite in Group B. Specifically, in Group A, the percentage of participants who followed the crowd slightly changed from 98.18% at DP 1, to 96.30% at DP 2 and 96.15% at DP 3a; whilst in Group B, this percentage decreased significantly from 94.55% at DP 1 to 69.23% at DP 2, and then bounced back to 91.67% at DP 3a. The inconsistency of the effect of crowd flow in Group B may be explained by several reasons. First, the participants experienced the most mental stress at DP 1, where the fire initially broke out and was close to them, hence in their first reaction they were likely to follow the majority of the crowd. As they approached DP 2, they were out of the immediate proximity of the fire and had less mental stress. Due to reasons discussed in Section 4.2, a number of participants reversed their herding tendency and decided to move to Hallway 2. For those from Group B who kept following the majority of the crowd at DP 2, most of them kept their herding tendency when they reached DP 3a. This was likely due to the fact that they received positive feedback from the outcomes of their decisions made at DPs 1 and 2. Participants did not face obstacles during the evacuation process by following the majority of the crowd, which was a positive signal that may have encouraged them to keep their decision-making preference [13].

4.4. Interaction effect between culture and crowd flow

Considering that some participants in LA and London were immigrants with multicultural background, and that people living in a

Fig. 10. Signage and crowd flow at DP 1 in Group C (the blue avatar represents the participant at DP 1, and the arrows indicate the movement directions of NPCs). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

place for five years could be representative for local culture [59], all participants were first divided into two groups based on whether they had lived in current locations for at least five years. Participants' route choices were compared between these two groups using crosstab analysis, which reported no significant difference (both Sig. > 0.10). Hence, the following analysis of cultural effect considered all participants regardless of the length of their residence in current locations.

To examine the interaction effect between culture and crowd flow, for each study group, crosstabs analysis was conducted to analyze the correlation between route choice and culture. The results indicated that for Groups A, B and C, respectively, there was no significant difference in participants' route choices across Beijing, LA and London (all Sig. > 0.10). This finding appeared somewhat counterintuitive, as the three cities differ significantly in both culture and lifestyle that are normally believed to affect people's herding tendency and attitude towards uncertainties [60], particularly that China is known to have a highly collectivist culture [60] and hence a society with higher herding tendency. A possible explanation of the insignificance of the cultural impact might lie in the fact that people's herding tendency, which is considered as a natural and effective response to crisis [57], would be strengthened in a highly uncertain, ambiguous and complex environment [4,10]. In this experiment, participants had to make decisions in an unfamiliar and stressful environment. As a result, their herding tendency may have increased in all three cultures to a similarly high degree, obscuring the difference across cultures.

In addition, crosstabs analysis was also conducted to analyze the cultural-specific correlation between route choice and crowd flow. The results showed that the route choices were significantly correlated with patterns of crowd flow at a high degree in London, Beijing and LA (Table 8). The results indicate that crowd flow significantly affected the route choices of participants from all three cultures, with slight differences in the magnitude of the effect. It was also suggested that the underlying mechanism of participants' directional choice-making during evacuation might be similar across different cultures, which could be further tested in future research.

4.5. VR-based experiment as an evacuation behavior research method

VR-based experiment is an emerging method for conducting human evacuation behavior research, and has been used in an increasing number of recent studies [33,52,61,62]. This study used the VR-based experiment in such ways that its advantages compared with other competing methods were maximized: First, the effect of culture was studied by replicating the same experiments in three comparable VR lab environments, despite that the three locations were distant from each other; Second, social influence was emulated using crowds of NPCs, whose gestures were animated using motion capture technology to increase the level of realism. The social influence was highly controllable in the IVEs to represent various scenarios for different research purposes; Third, the evacuation behavior was studied in a large indoor space with a complex multi-story layout involving multiple DPs. This was achieved with relatively low overhead in IVE development, demonstrating commendable flexibility and scalability of IVEs to support the study of human evacuation behavior in different spatial contexts. Drawing upon the use of VR-based experiment in this study, it could be concluded that this method can provide a high-fidelity, cost-efficient and highly operable methodological solution to evacuation behavior research.

Admittedly, VR-based experiment is still faced with certain challenges, such as the gap between real and virtual worlds, inter-individual differences in ease of interaction with IVEs and discomfort caused by VR sickness [28]. However, the continuing evolution of VR technology is expected to address these technical challenges in the near future, and make VR-based experiment a more promising method for evacuation behavior research. For instance, the most recent advancement of VR technology has led to multi-sensory IVEs, such as heating and smell-included IVEs [63], and improved interoperability with various data sensing technologies, such as motion tracking [64] and eye tracking [65], providing researchers with a richer set of tools to investigate human behavior during building emergencies.

In short, the VR technology provides researchers with an effective method to study human evacuation behavior. The knowledge gained from VR-based experiments about the behavior of individual evacuees could be used to: (1) improve the accuracy and granularity of crowd evacuation simulation, which in turn could support performance-based fire safety design of buildings; (2) guide the development of evacuation training programs, which are useful to prepare building users for possible emergency situations; and (3) facilitate the planning of emergency response operations such that the evacuation process could be managed in a fast and effective manner should building emergencies happen.

5. Conclusions

In this study, an evacuation experiment was conducted in a virtual metro station to analyze the effect of crowd flow on human evacuation behavior in highly uncertain environments. Participants' evacuation route choices, directional choices at multiple DPs, their subjective evaluation of the importance of crowd flow, as well as self-reported emotional responses, VR sickness, sense of presence, sense of direction, and wayfinding anxiety were collected and analyzed. Herding phenomenon was found in most of the DPs over the course of evacuation with uneven patterns of crowd flow. Participants generally reported that the directional information provided by crowd flow was critical during their evacuation process. Specifically, it was found that different patterns of crowd flow, by providing different directional information, had different effects on participants' directional choices at the DPs as well as their overall route choices. Without a specific direction indicated by the crowd or signage, participants tended to evacuate by avoiding fires and using hallways rather than staircases. Participants would make random directional choices in symmetric environments. It was also found that participants who followed the majority of crowd at the beginning would likely keep such tendency at successive DPs, indicating noticeable consistency of influence of crowd flow over the course of evacuation. Preference change of directional choices was observed in Pattern 2, which might be caused by the variance of directional information sources along the evacuation routes in the IVE. The observed influence of crowd flow was comparable across all three cultures where the experiment was carried out, and the influence of culture on evacuation behavior was found to be insignificant.

The present study contributes to the existing literature on crowd flow by examining its influence, when presented in highly uncertain environments, on human evacuation behavior in different cultures, and assessing its consistency over the whole course of evacuation. The findings of this study have several important implications. First, this study found that, under high uncertainty, people tended to follow the majority of unevenly distributed crowd (100-0 or 80-20 split) to evacuate during indoor fire emergencies. As the level of uncertainty changes during evacuation, people's attitude towards following the majority of crowd might change. The findings of prior studies about unevenly distributed crowd, which were based on evacuation under relatively low uncertainty [4,9,11], might not be all applicable in cases where high uncertainty is present, such as indoor fires with complex building layouts, limited architectural visibility, low level of spatial familiarity and involved multiple wayfinding decisions. Second, the findings suggested the similarity of human evacuation behavior across different cultures. Findings of how crowd flow affects human evacuation wayfinding in building emergencies in one culture may bear a certain extent of external validity and could be applied in other cultures. Last but not least, the study demonstrated that VR-based experiment is an effective method for studying human evacuation behavior during building emergencies, which largely enriches the toolkit that researchers can use to advance the understanding of human behavior in various building emergency scenarios.

Admittedly, there are also several limitations in the present study that need to be noted here and addressed in future research. First, although several measurements, including PANAS [29], SSQ [33] and PQ [46], showed notable ecological validity of this VR-based evacuation behavior experiment, obvious differences still existed between the IVEs used in this study and the reality. With the development of VR-related technologies, additional channels of human-computer interaction could be introduced to improve the ecological validity of VR-based human evacuation behavioral studies. Second, there were five alternative routes and three DPs in the present study. Future research could explore a more complex environment with more alternative routes and DPs to further quantify the consistency of effect of crowd flow. Lastly, the density of the crowd in the metro station was limited and hence the crowd did not cause any congestion in the evacuation routes, which may impact their behavior by adding their stress level and reducing the accessibility of some routes. Future research could be done to further assess the consistency of the effect of crowd flow in more complicated and crowded indoor environments and explore the interaction effect of crowd flow with other sources of directional information. These advancements can be used to simulate crowd evacuation in building emergencies and support building emergency management in practice.

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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