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Influence of architectural visual access on emergency wayfinding: A cross-cultural study in China, United Kingdom and United States

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A R T I C L E I N F O

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A B S T R A C T

This study examines the effects of architectural visual access on people's wayfinding behavior and evacuation performance during building emergencies using virtual reality. Fire evacuation experiments were conducted in an immersive virtual metro station, which was based on a real metro station in Beijing, China. A total of 226 participants, positioned among evenly or unevenly distributed crowd, were asked to evacuate the station that was designed with low or high visual access, manipulated through building design features (e.g., changing wall materials, removing columns in hallways). Crowd was presented in the virtual metro station by incorporating non-player characters assigned to different evacuation routes. To explore the possible influence of cultural background on participants' wayfinding behavior, experiments were conducted in London, Beijing, and Los Angeles. The results showed that improving architectural visual access could improve participants' virtual evacuation performance during emergencies; it could also influence participants' directional choices during evacuation, depending on the design strategy used and the spatial characteristics of the building. In addition, participants' tendency of following the crowd was reduced when there was an alternative route with high architectural visual access.

1. Introduction

Enhancing human safety during emergencies is a critical goal for designers as building design could greatly influence the outcomes of emergencies. Previous incidents have evidenced that inappropriate design choices could result in undesired emergency consequences. For example, in the Station Nightclub fire of 2003, the single doorway inside the vestibule largely limited the rate of egress and caused severe congestion [1]. During the Daegu Subway fire of 2003, the lack of emergency lighting and signage greatly increased the evacuation difficulty [2]. In order to improve human safety and building performance in emergencies, a solid understanding of interactions between human behavior and building design during emergencies is indispensable [3].

When a building emergency occurs, it is crucial for people to quickly make decisions and respond appropriately, such as "drop, cover, and hold on" during earthquakes, "run, hide, fight" during active shooter incidents, and evacuating to a safe place during fires. For people to be able to stay away from the danger and reach safe places, wayfinding, denoting "man's ability to reach spatial destinations in novel as well as in familiar settings" [4], is of great importance [5]. Many environmental and personal factors can impact people's wayfinding behavior. Examples include signage and corridor configuration, crowd flow, and people's familiarity with the building, which have been extensively studied in the literature [6–9]. Weisman [10] proposed that four types of building factors could affect people's wayfinding in built environments, including (1) the usage of signage, (2) plan/layout configuration, (3) the level of architectural differentiation (i.e., the extent to which one location looks different from others), and (4) visual access (i.e., the ability to see through or out of a setting). Past research also evidenced that participants were likely to exhibit distinct behaviors under different visual access conditions [11], which are contingent upon a variety of factors, such as presence of hazards (e.g., smoke), indoor lighting conditions, individual's location and visual acuity, as well as building design [12–14]. Understanding how visual access affects people's wayfinding behavior during building emergencies could benefit a wide spectrum of applications, including design of buildings and development of evacuation simulation tools [15].

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2. Background

As mentioned in Section 1, visual access in buildings could be affected by a variety of factors. To represent reduced or zero visual access caused by smoke, eye-patches and glasses were commonly used in prior studies to conduct human-subject experiments [16,17]. For example, Guo et al. [15] conducted experiments in a classroom, where participants were asked to evacuate under conditions of zero or good visual access by wearing or removing eye-patches. The results revealed that participants tended to select routes unoccupied by others under good visual access, whereas they explored their surroundings using their hands and bodies without considering the congestion level in the zero-visual access condition. In another study, Isobe et al. [11] conducted evacuation experiments in a room, where participants were asked to wear eye-patches to simulate the smoke effect and the behavioral data was used to develop a lattice gas model. The results demonstrated that adding more exits did not necessarily facilitate evacuation under zero visual access condition, as only the first discovered exit was used by most of the participants. Failure of electricity supply systems could also greatly diminish visual access during building emergencies. Jeon et al. [14] analyzed the evacuation process in an underground transportation facility under different conditions of indoor lighting and smoke levels, using eye-patches with different opaqueness. Their experiments showed that smoke had stronger influence on participants' evacuation performance (e.g., speed and distance) than indoor lighting. Where people are located in a building is another influencing factor on the level of visual access they could obtain. It has been shown that people tend to choose the exits that are visible to them and that are open and they can see through [18].

Visual access can be influenced by building design as well (denoted as architectural visual access in this study), hence influencing interactions between human behavior and buildings. Gärling et al. [19] conducted evacuation experiments in a university building and found that with lower level of architectural visual access (openness of building layout), participants' performance in the orientation test improved less over time. Seidel [20] found that in the airport environment, wayfinding was easier for participants arriving at the gate, if they had direct visual access to the baggage claim area. Different levels of architectural visual access could also affect people's route choices during their wayfinding process. According to the Theory of Affordances [21], an object is perceived in relation to what it affords an individual (i.e., what the object offers to an individual to achieve his/her goal). Thus, the level of architectural visual access conveys certain meanings, which could affect people's decision-making (e.g., route and directional choices). For example, Carpman et al. [22] conducted a video simulation experiment in a hospital environment and found that compared with available signage, architectural visual access (presence of an entrance) had a stronger influence on the participants' route choices. In another study, it was found that fire exit doors that were faced with murals, even though visible to the participants, might not be perceived as doors and caused confusion for the participants [23]. That being said, how different levels of architectural visual access affect people's wayfinding behavior during emergencies still remains underexplored [24]. Moreover, since various design strategies (e.g., locations of walls, columns, stairs) could affect visual access, multiple decision points with varying architectural visual access conditions could be included in the experiments to examine the influence of architectural visual access on wayfinding behavior. A decision point is a location which provides a possibility for a change in direction because of the availability of more than one directional choice [25]. While multiple decision points have been used to investigate the effect of signage on emergency wayfinding [6,26], many prior studies focusing on visual access included no more than one decision point [27, 28].

When conducting wayfinding tasks during building emergencies, people are often accompanied by others. It has been demonstrated that people have a following (also referred to as *herding* in literature) tendency in emergency evacuations [29,30]. Following behavior refers to that an evacuee chooses the most congested route because that route is the most popular choice [30]. Prior studies found that following behavior is correlated to environmental factors (e.g., number of evacuees near exits, visual access of exits) [9,31]. It was shown that when people perceived high visual access and low uncertainty (e.g., number and location of exits), they would tend not to follow the crowd and choose an alternative visible route [31]. However, to the best of our knowledge, this finding has only been examined via surveys or non-emergency drills. Further investigations on the correlation between following behavior and architectural visual access using controlled emergency evacuation experiments are needed.

To study the influence of architectural visual access and following tendency on emergency wayfinding, people's cultural background is an important factor that should be considered. Social norms, which vary from one culture to another, may well influence people's behavior during emergency situations [32]. Thus, research findings may be limited to the cultural context where the observation is made [33]. For example, one study found that the participants from the Czech Republic, Turkey, Poland, and the U.K. had different response times in unannounced evacuation drills [34]. In another study, significant differences were found between Chinese and American participants' usages of elevator/stairs during emergency evacuations: the proportion of American participants who considered using elevators was much higher compared with the Chinese participants [35]. Along this line, it is possible that architectural visual access may influence the emergency wayfinding behaviors of people with different cultural backgrounds to different extents.

Driven by the above-mentioned motivations, three research questions are addressed: (1) how does the level of architectural visual access (thereafter referred to as *visual access*) resulting from building design strategies (e.g., manipulating the positions of columns, materials of walls) impact people's wayfinding behavior during emergency evacuations? (2) how does people's tendency of following or avoiding the crowd differ under different visual access conditions; and (3) how do people's cultural backgrounds influence their wayfinding behavior during emergency evacuations under different visual access conditions?

A variety of research methods have been used in prior studies to investigate human behavior during building emergencies, including emergency drills, laboratory-controlled experiments, behavioral models and simulations, animal experiments, post-event surveys and interviews [36]. However, these methods bear several intrinsic limitations, such as scarcity of available data, inaccurate representation of human behavior, and difficulty of measuring the impact of various factors on human behavior [37]. Virtual Reality (VR) technology, on the other hand, provides a promising approach in this research area. VR refers to a real or simulated environment in which the perceiver experiences telepresence [38]. VR has the capability of providing safe and non-invasive environments, as well as the flexibility of retaining many variables in the environment [39]. Thus, using VR can enable experimenters to manipulate building attributes, such as signage [7], corridor configuration [40], and elevators [41] easily and precisely in virtual environments. While VR may not perfectly replicate real building emergency scenarios, it has been shown that VR can cause emotional arousal, increase stress levels and provide a reasonable level of sense of presence [37,42,43]. Therefore, we used immersive virtual environments (IVEs) for our investigation.

The paper is organized as follows: Section 3 describes the methodology used in this study. Section 4 presents the experimental results. Discussions around the results, limitations of this study, and directions for future research are presented in Section 5. Finally, Section 6 concludes the paper.

3. Research methodology

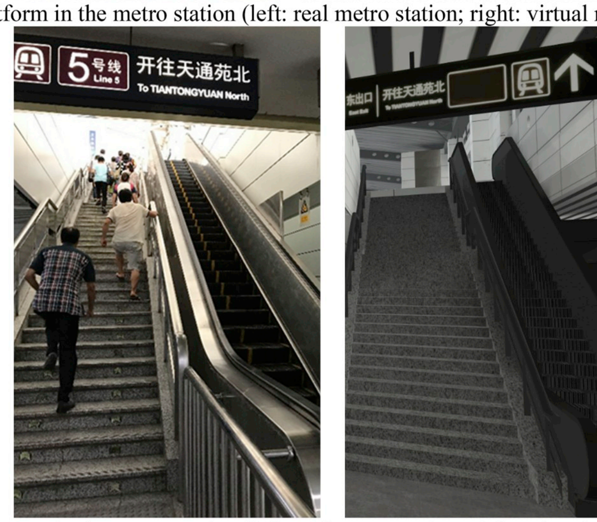
3.1. Experiment design

To study the influence of visual access on emergency wayfinding, this experiment examines participants' evacuation behavior through a hypothetical evacuation scenario due to a train fire in a virtual metro station. As pointed out in Section 2, prior studies that investigated the impact of visual access during building emergencies were based on over-simplified environments. Since people dynamically make decisions and adjust their evacuation strategies during building emergencies [44], simplified indoor environments such as a single room with only one decision point may not precisely reflect people's wayfinding behavior. Therefore, in this study, a virtual metro station was modeled, which was based on an existing metro station in Beijing, China, as shown in Fig. 1.

The metro station consists of two floors: the ground floor and the underground floor, as shown in Fig. 2. There are two platforms on the two sides of the railway (shown in dark grey in Fig. 2) on the ground floor. Based on the architectural drawings, both platforms are 122 m long. The platform where the starting point (shown in Fig. 2) is located is 4.1 m wide, whereas the width of the other platform is 6.7 m. Moreover, there are six staircases and escalators connecting the two floors. The length of each staircase/escalator is approximately 10 m. Each staircase is 2.7 m wide and each escalator is 1.8 m wide. As each staircase is paired with an escalator (shown in Fig. 1b), a pair of staircase and escalator is denoted as staircase (e.g., Staircase 1) thereafter. Additionally, the metro station has three exits, all of which are on the ground floor. The routes to approach the exits is illustrated in the next paragraph. Finally, on the ground floor, Hallway 1 (part of the platform) is approximately 22 m, Hallway 2 is approximately 64 m, and the segment from the end of Hallway 2 to Exit 1 is approximately 28 m long. On the underground floor, the ticket lobby (surrounded by the lower end of the six staircases) has an area of approximately 25 m × 25 m.

The virtual fire modeled in this study was based on a fire accident happened at the Tsim Sha Tsui station in Hong Kong on February 10, 2017, which resulted in 17 injuries [45]. While we did not intend to exactly replicate this incident in the present study, we used it as a reference to develop the following evacuation scenario: The virtual fire initially broke out in the second compartment of the train (consisted of six compartments) approaching the metro station, then it spread to other compartments. When the train stopped and the doors opened, the smoke further spread to the metro station, as shown in Fig. 3. An emergency announcement was broadcasted in both Chinese and English. The length of the Chinese broadcast audio clip was 18 s, which is similar to the length of English broadcast audio clip (19 s). The starting point of the evacuation was set to be at the midpoint of the platform on the ground floor, as shown in Fig. 2. Participants were set to face the railway at the starting point and the train on fire approached the participants from the left side. At this point, participants had to make a directional choice, thus the starting point was also denoted as Decision Point 1 (DP 1): they could either take Staircase 1 to go to the underground floor (i.e., Route 4 or 5) or go to Hallway 1 on the other side of DP 1 (i.e., Routes 1, 2, or 3). If participants chose Route 1, 2 or 3, they had to make another directional choice after they arrived at the intersection of Hallways 1 and 2, marked as DP 2 in Fig. 2. At this point, participants could choose to keep going forward via Hallway 2 and evacuate the station via Exit 1 (invisible from DP 2) on the ground floor (i.e., Route 2), or they could go downstairs using Staircase 2 in Hallway 2 (i.e., Route 1 or 3). Once participants chose either Route 1 or 3, they would be on the underground floor and had to navigate to DP 3 and use one of the two staircases (i.e., Staircase 3 or 4) to evacuate the station via Exit 2 or 3. If participants chose Route 4 or 5 at DP 1 and went to the underground floor via Staircase 1, likewise, they would need to move to DP 3 and choose Staircase 3 or 4 to evacuate the metro station. Therefore, as

(a) The platform in the metro station (left: real metro station; right: virtual metro station)



(b) The staircase in the metro station (left: real metro station; right: virtual metro station)

Fig. 1. Comparisons of the real and virtual metro station.

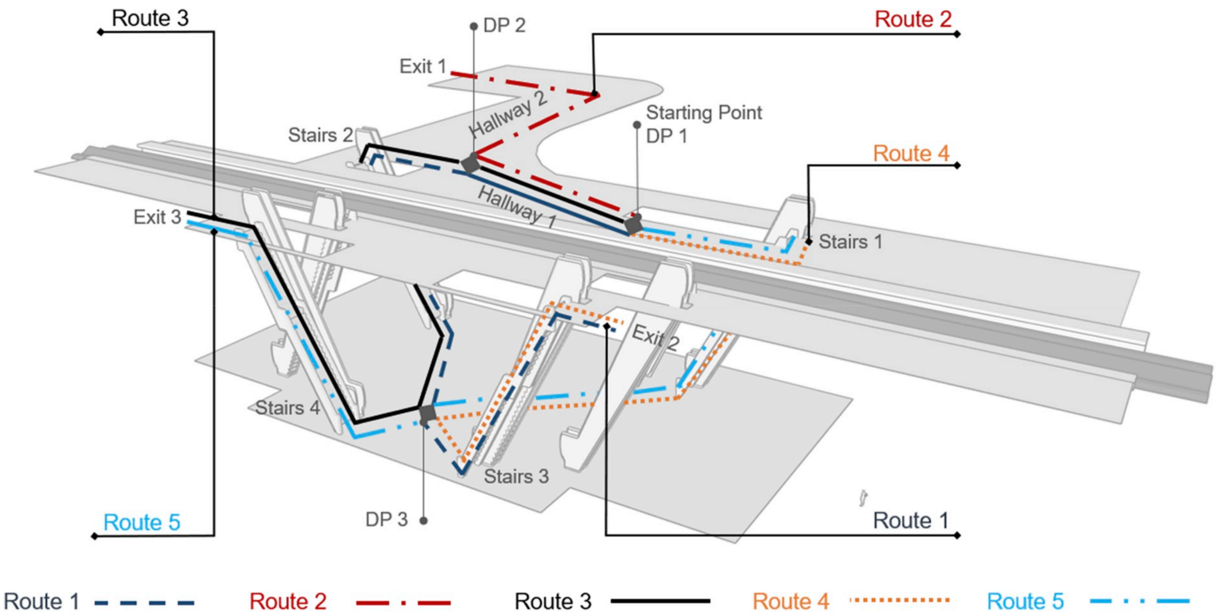
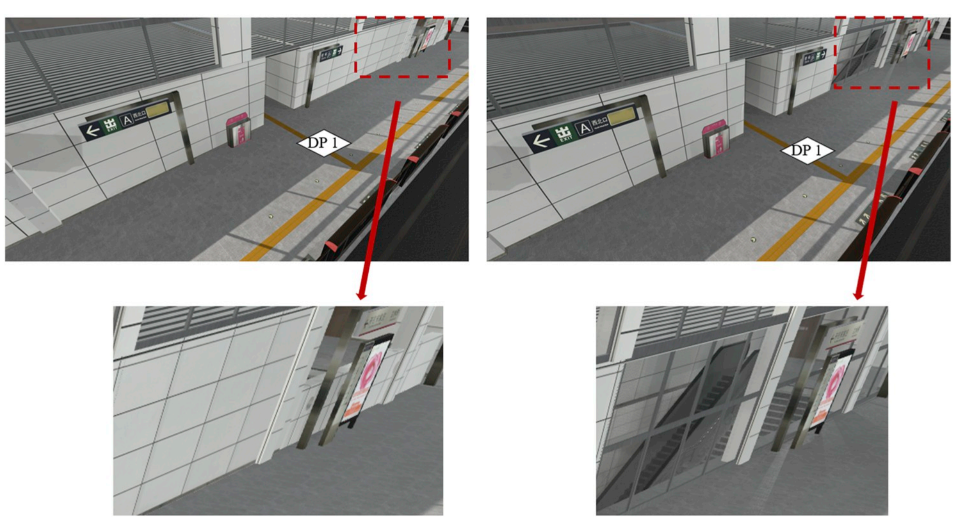


Fig. 2. Illustration of the metro station layout, decision points and evacuation routes (not to scale).

Fig. 3. Illustration of the virtual fire and smoke.

discussed above, there are five possible evacuation routes in total, which are presented in Fig. 2. The approximate length of each route is as follow: Routes 1 and 3: 111 m, Route 2: 103 m, and Routes 4 and 5: 105 m. At each DP, both routes are marked with signage, which has arrow pointing to a direction along with corresponding words (e.g., exit) in both Chinese and English, hence can be understood by participants in all three locations.

Additionally, it is worthwhile to point out that while at all of the three DPs, participants needed to choose from two available directions, the decision-making conditions at each DP were different: (1) For DP 1, participants needed to make an immediate decision after being immersed in the IVE and perceiving the fire, without any further exploration of the environment; (2) For DP 2, participants needed to make a decision after entering Hallway 2 from Hallway 1. Thus, they



(a) Low visual access (b) High visual access

Fig. 4. Design strategy taken to manipulate visual access at DP 1.

had more time to observe the environment compared with DP 1, but they still needed to make a quick decision since DP 2 was close to the intersection of Hallways 1 and 2; (3) For DP 3, when participants reached the underground floor, they needed to travel a relatively long distance to arrive at DP 3 and make the final directional choice. Thus, compared with DPs 1 and 2, participants had more time when moving to DP 3 to perceive the environment and adjust their decisions. Inclusion of several DPs with varying conditions is a unique contribution of this study.

Visual access in the station was manipulated by several design strategies and resulted in another version of the station, as shown in Fig. 4 – 6 (details are shown in the zoomed-in images). First, since Staircase 1 near the platform was not visible at DP 1, the solid wall next to Staircase 1 was replaced by a glass wall (marked with a red rectangle in Fig. 4b), so that participants could see Staircase 1 through the glass wall. Second, at DP 2, the columns in Hallway 2 were removed to improve the visual access (Fig. 5). To further increase the visual access of Hallway 2, the solid wall along the right side of Hallway 2 was also replaced by a glass wall so that participants could see the sky and the outdoor environment through the glass wall, and the ticket booths were moved to make them visible from DP 2. It is important to note that while visual access was improved, Exit 1 was still not directly visible from DP 2. Likewise, on the underground floor, columns were removed and the solid wall next to Staircase 4 was replaced by a glass wall so that participants could see Staircase 4 through the glass wall (Fig. 6). Ticket vending machines by the wall were also moved not to block participants' sight through the glass wall. One important note is that while two directions were available at each DP, the visual access was mainly improved for one of the directional choices (i.e., Staircase 1 at DP 1; Hallway 2 at DP 2; and Staircase 4 at DP 3). The reason was to examine whether the increased visual access of a direction would encourage people to choose it during emergency evacuation.

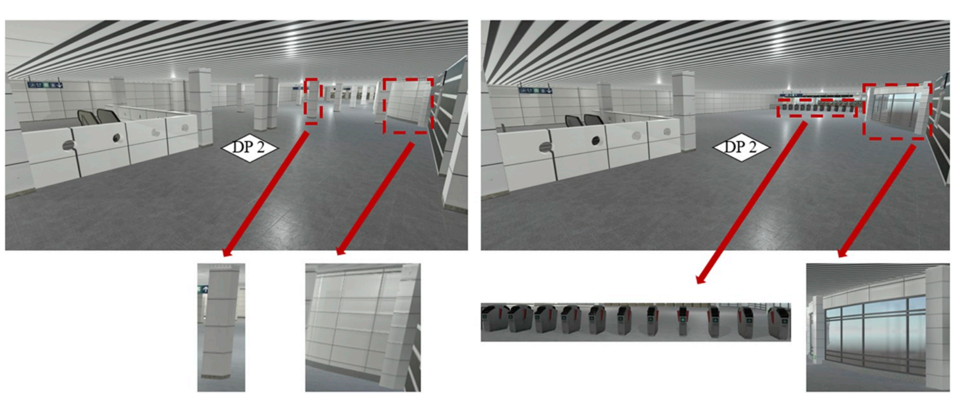
Other evacuees were also included in the IVE by incorporating non-player characters (NPCs). In total, fifty-three NPCs were included. The NPCs varied in their gender, age and appearance, and moved at a constant speed varying from 0.7 m/s to 2.8 m/s, based on the Chinese national code for metro safety evacuation [46]. Since the NPCs did not cause congestion in the IVE, their movement could represent a reasonable speed in a free-of-congestion evacuation scenario; this might differ from people's speed in real-world building emergencies, where there might be congestion. The NPCs were positioned at pre-determined locations at the metro platform (46 out of 53) or in the train compartments (7 out of 53) at the beginning of the experiment. These pre-determined locations for the NPCs remained the same in all experiments. The NPCs were set to have a view angle of 120°. They had idle animation (looking around) when standing at their initial locations, in order not to have them stand completely still and look unrealistic. NPCs at the platform started to evacuate once the fire and smoke were within their view angle with a distance less than 15 m. NPCs in the train started to evacuate once the train fully stopped and the doors opened. During the evacuation process, the NPCs ran to a series of predetermined locations following their assigned evacuation routes, until their final destinations (i.e., exits) were reached. To investigate how visual access influences people's wayfinding behavior and to isolate the impact of crowd, in one condition, NPCs were set to split almost evenly between two available directions at each DP. To examine how different visual access levels would affect people's tendency of following or avoiding the crowd, in the second condition, NPCs were set to split unevenly (approximately 80% vs. 20%) between the two directions at each DP. For the second condition of NPCs' evacuation process*, it is important to mention* that, in order to examine if evacuees would avoid the crowd if alternative direction with high visual access was available, at each DP, the majority of the NPCs were set to choose the direction that was not made more visible in the high visual access condition, while the minority of the NPCs chose the direction that was made more visible in the high visual access condition. NPCs' directional choices at each DP and route choices are summarized in Tables 1 and 2, shown in both numbers and approximate percentages.

Thus, there were four experimental scenarios in total: (1) Scenario A: low visual access with even distribution of NPCs; (2) Scenario B: high visual access with even distribution of NPCs; (3) Scenario C: low visual access with uneven distribution of NPCs; and (4) Scenario D: high visual access with uneven distribution of NPCs.

3.2. Participants

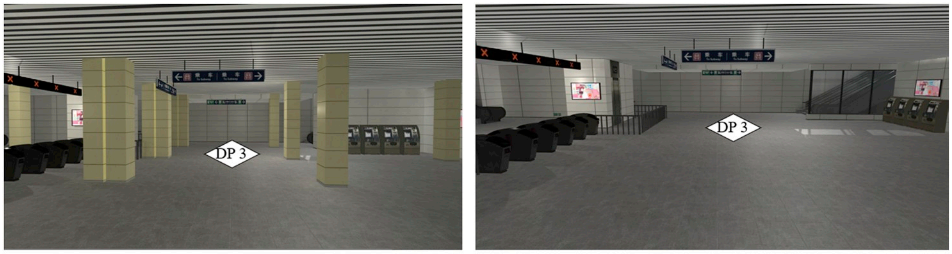
To investigate the impact of cultural background on people's emergency wayfinding behavior, the data collection was carried out in three different locations, including London, U.K., Beijing, China and Los Angeles (LA), U.S. These three locations were selected for data collection because: first, London, Beijing, and LA are three cities in three different continents, representing three distinct locations; second, compared with American and British cultures, Chinese culture is considered to have more collectivism than individualism [47], which might affect people's following or avoiding tendency during evacuations; third, London, Beijing and LA all have metro systems. However, the metro systems in these three cities vary in their scale and ridership: metro systems in Beijing have the largest size and ridership, followed by London, and then LA [48,49]. Such a difference could also potentially influence people's wayfinding behavior when they experience emergencies in metro stations.

This study was approved by the University Park Institutional Review Board (UPIRB) of University of Southern California. Emails, flyers, personal solicitation, and outlets on social media were used to recruit participants. Participants in Beijing received 30 CNY as monetary incentives, while those participated in London and LA did not receive any



(a) Low visual access (b) High visual access

Fig. 5. Design strategy taken to manipulate visual access at DP 2.



(a) Low visual access (b) High visual access

Fig. 6. Design strategy taken to manipulate visual access at DP 3.

Table 1
Directional choices of NPCs at each decision point.

Directional choices	DP 1		DP 2		DP 3	
	Hallway 1	Staircase 1	Staircase 2	Hallway 2	Staircase 3	Staircase 4
NPCs evenly distributed	27 (51%)	26 (49%)	14 (52%)	13 (48%)	20 (50%)	20 (50%)
NPCs unevenly distributed	43 (81%)	10 (19%)	34 (79%)	9 (21%)	35 (80%)	9 (20%)

Table 2
Route choices of NPCs during evacuation process.

Route choices	Route 1	Route 2	Route 3	Route 4	Route 5
NPCs evenly distributed	7 (14%)	13 (24%)	7 (14%)	13 (24%)	13 (24%)
NPCs unevenly distributed	27 (51%)	9 (17%)	7 (13%)	8 (15%)	2 (4%)

compensation. To participate in the experiment, participants had to meet several criteria, including: (1) no heart-related illness, (2) no wrist/hand injuries, (3) no previous uncomfortable VR experience, and (4) normal or corrected-to-normal vision. In total, 226 participants (66 in London, 83 in Beijing, and 77 in LA) were recruited in this study. Based on the Scenarios A through D described in Section 3.1, participants were divided into Groups A through D depending on their assignments to the scenarios. Sample size and demographic information of the participants, including their locations, age and gender, in each of the experimental groups are shown in Table 3.

3.3. VR apparatus and simulations

The equipment used in the experiments included two computer workstations and a HTC Vive VR system [50]. The two computer workstations were connected in a local area network, using Photon Server software [51]. One computer workstation was used as the client and was connected to the HTC Vive VR system to run the VR experiment; the other computer workstation worked as a server that controlled the execution of the VR experiment and recorded the data (i.e., participants' virtual evacuation time, distance and trajectory) during the experiment [52]. The HTC Vive VR system included a head-mounted-display (HMD), which was used for the visual display of the IVE, a controller for self-navigation in the IVE at a constant moving speed of 2.4 m/s (which was decided during pilot studies based on speed's contribution to motion sickness in VR), two base stations for positioning the HMD and the controller, and a headphone connected to the HMD to provide audio stimuli (e.g., emergency broadcasting, fire alarm, etc.). Participants could change their orientation in the IVE by changing their head orientation in the physical world and they could move in the IVE by using the controller (participants could not go through any objects in the IVE and they did not need to open any doors during the evacuation).

3D Studio Max software [53] was used to model and render the virtual metro station. Then, the model was imported to Unity3D game engine [54] to create the fire emergency scenario using the embedded particle system in Unity3D. The duration, size, and speed of the virtual fire and smoke were manually predefined in the embedded particle system in Unity3D, to make the virtual fire and smoke visible and look realistic in the IVEs. NPCs were modeled in 3D Studio Max software, and their evacuation routes were preprogrammed in Unity3D. The Raycast technique was used to model NPCs' vision to activate their behavior and allow them to avoid collision with other NPCs and the building elements (e.g., walls). Participants' interactions with the environment (e.g., navigating in the station) were also incorporated in Unity3D. The location of the participants in the metro station were updated and recorded per second during the experiment.

Table 3
Experimental groups sample sizes and demographics.

Group	Sample size	Age		Location	Male	Female
		M	SD			
Group A	59	25.5	6.1	London	9	9
				Beijing	12	10
				LA	9	10
Group B	56	24.1	5.9	London	9	7
				Beijing	11	9
				LA	10	10
Group C	55	25.7	8.3	London	8	7
				Beijing	11	10
				LA	9	10
Group D	56	23.4	5.6	London	9	8
				Beijing	11	9
				LA	9	10

3.4. Procedure

Prior to the experiment, participants read and signed an IRB-approved consent form, which described that the aim of the study was to investigate how building design and social interactions would influence occupants' responses during emergency situations. Participants were asked to complete a screening survey, which included questions related to their basic health conditions to determine their eligibility for participation, as described in section 3.2. Participants who did not meet all of the criteria were thanked and dismissed from the experiment. If considered eligible, participants were allowed to proceed to complete a pre-experiment questionnaire, which asked their basic demographic information (e.g., gender, age, nationality, current country of residence, etc.), their positive and negative emotions measured with the Positive Affect and Negative Affect Scale (PANAS) [55,56], and their simulator sickness measured with the Simulator Sickness Questionnaire (SSQ) [57].

Upon completion of the pre-experiment survey, participants were instructed to put on the HMD and went through training to practice operations in an IVE. It is important to note that the training environment, which was an empty open space, was different from the experimental environment (i.e., the virtual metro station). Once participants felt familiar with the VR operations, they were asked to take off the HMD and read the experiment instructions. The instructions informed the participants that their task during the experiment was to find a way to evacuate the metro station, but no specific evacuation instructions or guidelines (e.g., following the signage or crowd) were given. Once participants finished reading the instruction and obtained any necessary clarification from the experimenter, they were randomly assigned to one of the four experimental groups by counterbalancing the number of males and females in each group, to make sure that gender would not be a confounding variable when comparing the results of different experimental groups.

In the virtual environment, participants were placed at the platform and were surrounded by NPCs, as shown in Fig. 7. Participants also started to evacuate the station using the routes they chose. Once the participants completed the evacuation task by reaching any of the exits in the station, they were asked to take off the HMD and continue to complete a post-experiment survey. In the post-experiment survey, information collected from participants' responses included (1) the importance ranking of different factors (i.e., visibility of exits, ticket booths, staircases, distance to fire, and directions indicated by the crowd flow and signage): for their directional choices at each DP; (2) the ratings of the importance of visual access and crowd flow on their directional choices at each DP; (3) their positive and negative emotions measured with PANAS [55,56]; (4) their simulator sickness measured with SSQ [57]; (5) their sense of direction measured with the Santa Barbara Sense of Direction Scale (SBSOD) [58]; (6) their sense of presence in the IVE measured with the presence questionnaire (PQ) [59]; (7) their level of wayfinding anxiety measured with the Lawton's spatial anxiety scale [60]; and (8) their past experiences of evacuation in building emergencies, including real emergencies and emergency drills. Each participant only took part in the experiment once. After completing the post-experiment survey, participants were thanked and dismissed.

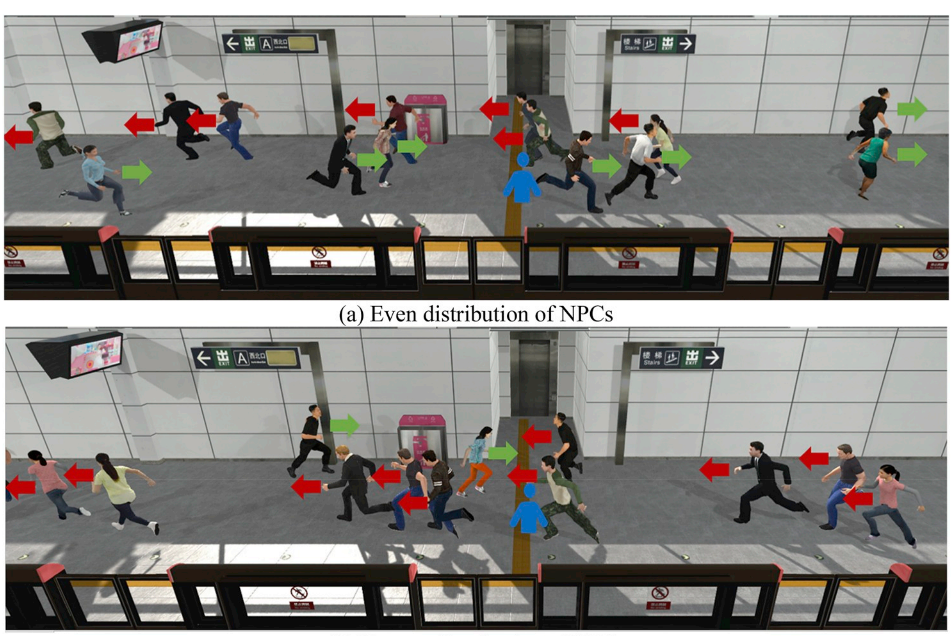
3.5. Data analysis

Chi-square test was used to analyze how visual access and culture affected participants' wayfinding behavior, as well as if there was any group difference because of its capability of describing the relationship between two nominal variables. When Chi-square test could not be used due to insufficient sample size, Fisher's exact test was used instead, to compare participants' route and directional choices in different groups. Independent samples t-test was used for between-group comparisons, including participants' evacuation performance, their evaluation of various factors that influenced wayfinding, as well as whether there was any difference in age, sense of presence, sense of direction etc. Additionally, one sample t-test was used to analyze the change of participants' emotions and simulator sickness during the experiment. Shapiro-Wilk test was used to examine whether the data was normally distributed. If the normality requirements were not satisfied for parametric statistical tests (independent samples t-test and one sample t-test), nonparametric statistical tests, Mann-Whitney U test and Wilcoxon Signed Rank Test were used for between-group comparisons and within-group comparisons, respectively. The significance level was set as 0.05 and marginal significance level was set as 0.10. All data analysis was conducted using SPSS 25 [61].

4. Results

To analyze the impact of visual access on participants' wayfinding and following/avoiding behavior, Groups A and B, Groups C and D were compared, respectively. Prior to analyzing the results, the comparison between Groups A and B, Groups C and D was conducted, in terms of participants' age, gender, education level, sense of direction, wayfinding anxiety, sense of presence, change in simulator sickness and change in emotions during the experiment. The results showed that there was no difference between Groups A and B, and between Groups C and D, in any of the above-mentioned measures, which eliminated the possible influence of these factors on the difference between the groups.

It was found that after the experiment, participants' ratings of being



(a) Even distribution of NPCs

(b) Uneven distribution of NPCs

Fig. 7. Participant and NPCs at the platform (blue man shows the participant at the starting point/DP 1, arrows show the evacuation direction of NPCs). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

enthusiastic (z = −5.059, p < 0.001), determined (z = −2.107, p = 0.035), and nervous (z = −3.030, p = 0.002) significantly decreased, and being alert (z = 3.673, p < 0.001), distressed (z = 2.093, p = 0.036), and scared (z = 2.001, p = 0.045) significantly increased. The results showed the virtual fire emergency did in fact evoke participants' emotional arousals. Moreover, participants' responses to the presence questionnaire reported an average PQ score of 141.81 (SD = 17.57) from the range of 30 (no presence) to 210 (presence as reality). Compared with the PQ score in prior studies (e.g., mean = 98.11, SD = 15.78 in Ref. [59], and mean = 90.30, SD = 14.5 in Ref. [62]), our results suggested that the inclusion of NPCs, visual (e.g., virtual fire and smoke) and audio stimuli (e.g., emergency broadcasting and alarm) did impose an adequate sense of emergency on participants.

4.1. Influence of visual access on emergency wayfinding with even distribution of NPCs (Groups A and B)

4.1.1. Route and directional choices

Whether the low and high visual access influenced the participants' route choices in Groups A and B were analyzed first. Fisher's exact test was used for analyzing the participants' route choices, which revealed that overall, participants' choices of the 5 evacuation routes were not significantly different between Groups A and B (p = 0.428 > 0.10), indicating that visual access did not affect participants' choices among the 5 evacuation routes, as shown in Fig. 8. While the overall patterns of route choices were similar between the two groups, it is critical to further investigate the participants' directional choices at each DP, as the participants' decisions at DPs fundamentally determined their evacuation trajectories and the visual access was manipulated at the DP level, not at the route level.

Directional choices of participants in London, Beijing and LA at DP 1 were compared. Chi-square test showed that in Group A, the directional choices of London, Beijing, and LA participants at DP 1 did not have any significant difference (χ^2 (2, 59) = 0.245, p = 0.885). However, the results revealed that in Group B, the directional choices of participants from the three locations were significantly different at DP 1 (χ^2 (2, 56) = 9.333, p = 0.009), as shown in Fig. 9. Compared with Beijing and LA participants, more London participants chose to go to Staircase 1 (with improved visual access).

To further explore how various factors influenced directional choices at DP 1, participants' subjective evaluations of these factors were analyzed. The results showed that at DP 1, there was no significant difference in the evaluation of these factors between the two groups (all p > 0.10). Additionally, to investigate the difference between London participants and Beijing/LA participants at DP 1, the subjective evaluation of London participants who took Staircase 1 in Group B was compared with those of Beijing and LA participants who did not take Staircase 1 in Group B. The results of Mann-Whitney U test revealed that London participants who took Staircase 1 in Group B considered that 'visibility of staircase' was significantly more important in their directional choice at DP 1 than those of Beijing and LA participants who did not take Staircase 1 in Group B (U = 253, z = 2.647, p = 0.009). To further look into the influence of 'visibility of staircase', the subjective evaluation of London participants who took Staircase 1 in Group B was compared with those of Beijing and LA participants who took Staircase 1 in Group B as well. The results showed that the ranking of 'visibility of staircase' was not significantly different (U = 67, z = 0.878, p = 0.426). The evaluation of "visibility of staircase" by Beijing and LA participants in Groups A and B who took Staircase 1 at DP 1 was also compared, and no significant results were found (U = 69.5, z = −0.573, p = 0.586). The above results indicated that at DP 1, participants who took Staircase 1 in Group B was indeed because of its improved visual access. More London participants choosing Staircase 1 in Group B indicated that more London participants perceived this improvement of visual access.

Chi-square test showed that overall, visual access had a marginally significant effect on participants' directional choices at DP 2 (χ^2 (1, 72) = 2.794, p = 0.095). Compared with the participants in Group A, more participants in Group B went to Hallway 2, which was made more visible in Group B by removing the columns, relocating ticket booths and changing the wall material in Hallway 2. Moreover, participants' higher preference of Hallway 2 in Group B was consistent in London, Beijing and LA, as shown in Fig. 10.

Participants' evaluation of influencing factors on their directional choices at DP 2 was also analyzed. The results showed that there was a significant difference in the participants' evaluation of 'direction indicated by signage' between Groups A and B (U = 837, z = 2.173, p = 0.030). Participants in Group A considered the direction indicated by signage more important in their decision making, compared with those in Group B.

With respect to DP 3, participants could arrive at this location via two possible routes: (1) go to Hallway 1 at DP1, then take Staircase 2 at DP 2 to go to the underground floor and reach DP 3; or (2) go to Staircase

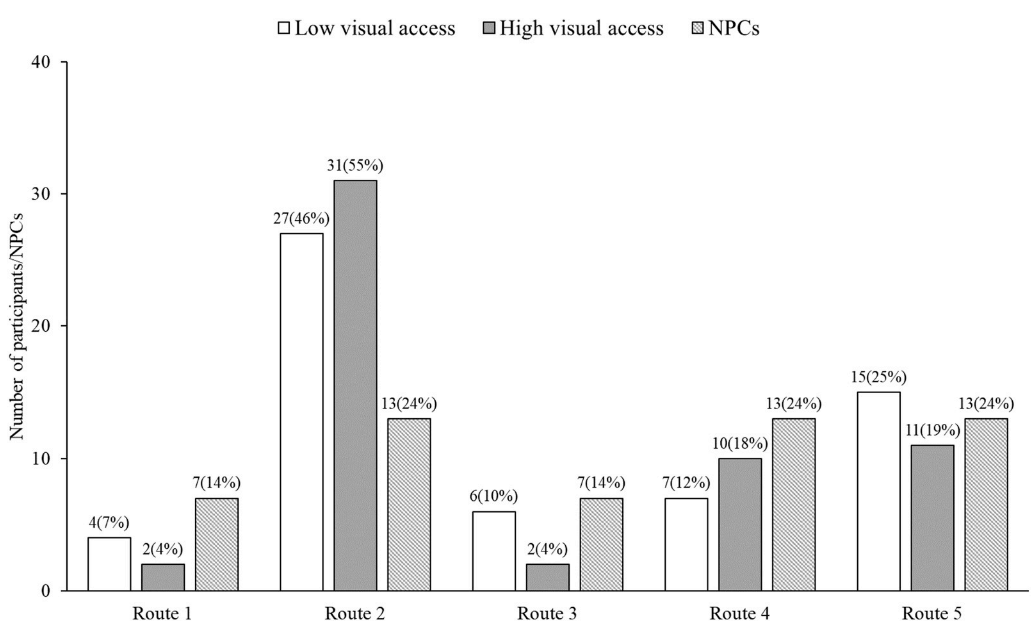


Fig. 8. Route choices of participants in Groups A and B and NPCs.

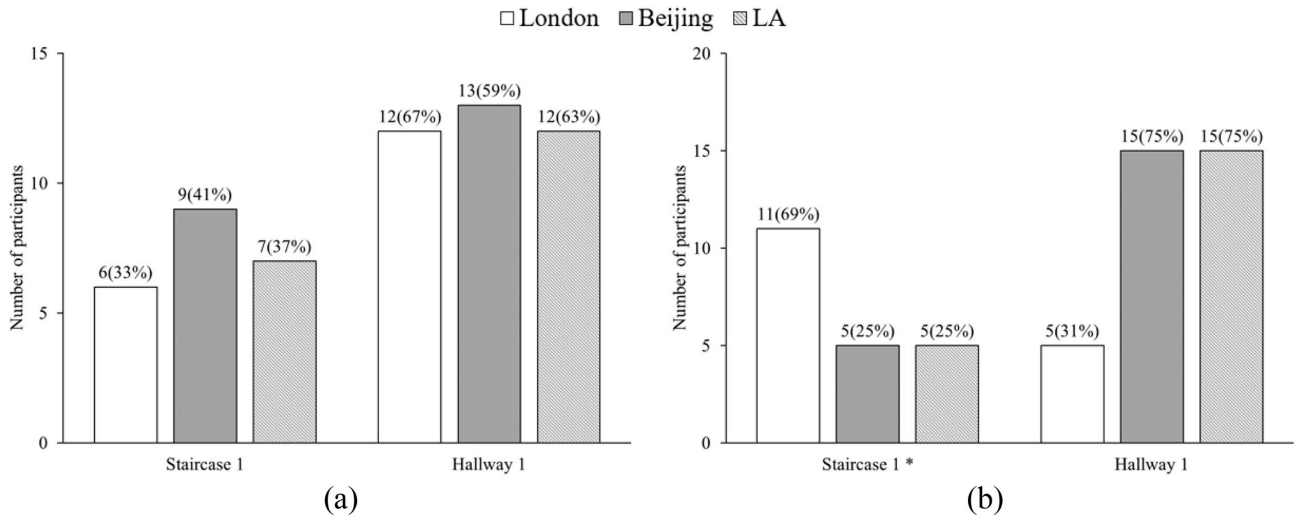


Fig. 9. Directional choices of London, Beijing, and LA participants at DP 1 (a) Group A; (b) Group B (* denotes the direction with improved visual access).

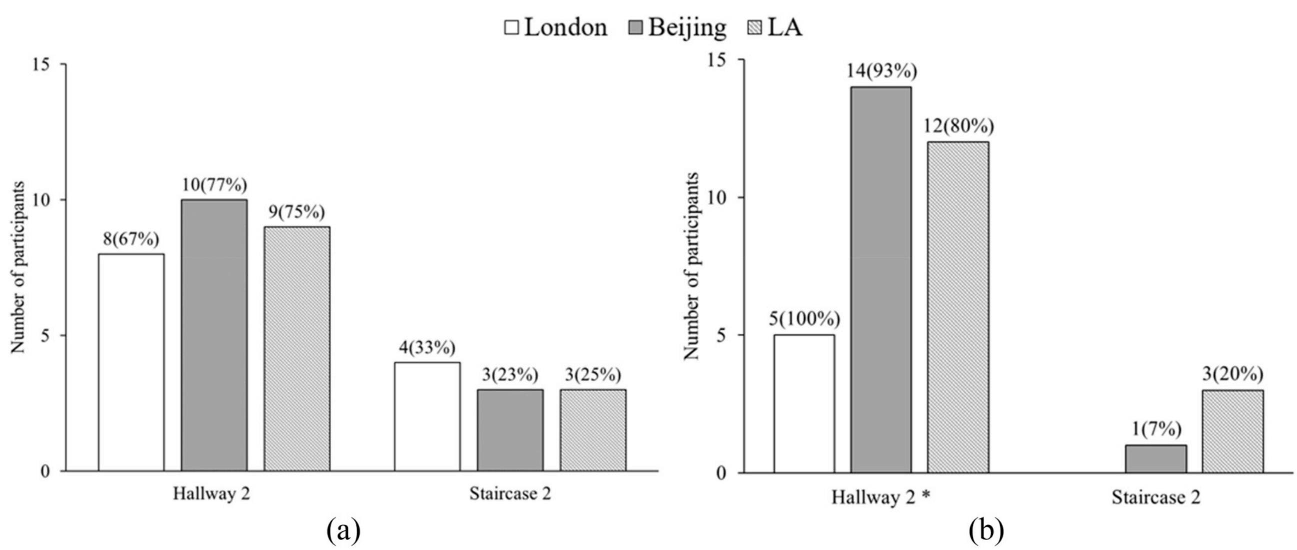


Fig. 10. Directional choices of London, Beijing, and LA participants at DP 2 (a) Group A; (b) Group B (* denotes the direction with improved visual access).

1 at DP 1 and then navigate to DP 3 on the underground floor.

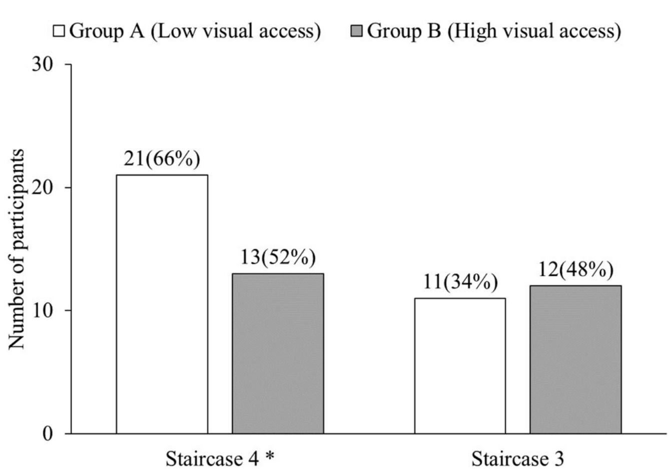


Fig. 11. Directional choices of participants at DP 3 in Groups A and B (* denotes the direction with improved visual access in Group B).

Regardless of the way they reached DP 3, all participants were combined together to analyze their directional choices at DP 3. Fig. 11 shows participants' directional choices at DP 3 in the two groups. The result of the Chi-square test showed that participants' directional choices were not significantly different at DP 3 (all $p > 0.1$) between Groups A and B or among the three locations. Moreover, the subjective evaluation of the influencing factors were not significantly different between the two groups.

4.1.2. Virtual evacuation performance

Three measures, namely virtual evacuation time, distance and speed, were used to assess participants' virtual evacuation performance. Evacuation time is a critical parameter in emergencies [63], evacuation distance is related to people's travel paths, which are also an important factor for people's safety [64], and speed describes the relationship between time and distance. In this study, virtual evacuation time was defined as the time that a participant spent from hearing the fire alarm to arriving at one of the exits, which is consistent with the definition of evacuation time in the literature (i.e., sum of the time to receive warning, time to respond to warning, delay time, and movement time) [65,66]. Virtual speed was defined as a participant's total movement distance divided by his/her total evacuation time, which was affected by participants' stoppage during the evacuation to make directional choices, the time participants spent before starting evacuation, etc. Nevertheless, since participants' moving speed in the IVE was set to be constant (2.4 m/s), their virtual evacuation time, speed and performance in the experiments may not exactly reflect their actual performance in real-world emergencies.

To examine how participants' virtual evacuation performance differed in the two groups and to eliminate the influence of different length of each route, an analysis of participants' virtual evacuation performance was conducted for each individual route. The only difference between Routes 1 and 3 or Routes 4 and 5 was the directional choice at DP 3, which did not impact the overall route distance. If analyzed separately, the sample size for each route would be too small to conduct the statistical test, hence Routes 1 and 3 as well as Routes 4 and 5 were combined for the analysis. The results are presented in Table 4. It was revealed that visual access had a significant effect on the virtual evacuation time of participants who took Routes 1 and 3, Route 2, and Routes 4 and 5 (all $p < 0.05$). Participants in Group B had significantly less virtual evacuation time compared with those in Group A. Additionally, participants who took Routes 1 and 3 ($p = 0.005$) and Route 2 ($p < 0.001$) in Group B had significantly higher virtual evacuation speed compared with those in Group A. Moreover, it was found that participants who took Routes 4 and 5 in Group B travelled significantly less distance compared those in Group A ($p = 0.021$).

4.2. Influence of visual access with uneven distribution of NPCs (Groups C and D)

4.2.1. Route and directional choices

Participants' route choices in Groups C and D were first analyzed to evaluate whether manipulation of visual access influenced their following or avoiding tendency during the evacuation process. Fisher's exact test showed that the choice of the 5 possible evacuation routes varied significantly between Groups C and D ($p = 0.015$). As shown in Fig. 12, in Group C, the most frequently chosen route was Route 1, which was also taken by the large majority of the NPCs. Nevertheless, in Group D, Route 2, which was made more visible in the experiment, was the most frequently chosen even though it was taken by only 9 of the 53 NPCs.

To further analyze the influence of visual access on participants' following and avoiding tendency, their directional choices at each DP were compared. Participants' directional choices at DP 1 in both Groups C and D are shown in Fig. 13, and there was no significant difference among London, Beijing and LA participants (all $p > 0.10$). This result indicated that participants followed the crowd in both groups. This result was also correlated by participants' evaluation of the influencing factors, which showed that crowd flow was the most influential factor and there was no significant difference in the evaluation of other factors between the two groups (all $p > 0.10$), which implied that crowd flow dominantly influenced participants' directional choices in both groups at DP 1.

Directional choices of participants at DP 2 in Groups C and D are shown in Fig. 14. It was found that unlike London and LA participants who tended to choose Hallway 2 (which was made more visible) in Group D, Beijing participants' directional choices did not vary between the two groups: the majority of Beijing participants (around 63%) took Staircase 2 in both groups. Additionally, in their subjective evaluation, Beijing participants in both groups agreed that they considered the crowd as an important factor and the evaluation of the importance of crowd was consistent in the two groups ($p > 0.10$).

Additionally, Fig. 15 shows participants' directional choices at DP 3, and there was no significant difference among the participants in London, Beijing and LA (all $p > 0.10$). Fisher's exact test showed that there was marginally significant difference in the directional choices between Groups C and D ($p = 0.057$). The analysis indicated that most participants followed the crowd at DP 3 when the visual access was low. On the contrary, when the alternative direction was made more visible, more participants, compared with those in Group C, chose to evacuate via the more visible direction. However, the analysis of participants' subjective evaluation of the influencing factors did not reveal any significant difference at DP 3 between the two groups (all $p > 0.10$).

4.2.2. Virtual evacuation performance

To further examine how visual access influenced participants' virtual evacuation performance with uneven distribution of NPCs, participants' virtual evacuation time, distance and speed were compared and analyzed, as shown in Table 5. Since very few participants in Groups C and D took Routes 4 and 5 (3 in Group C and 3 in Group D), no statistically reliable conclusions could be drawn, hence these two routes were not included in Table 5 and the analysis.

It was found that visual access did not have a significant effect on the virtual evacuation performance of participants who took Routes 1 and 3 (all $p > 0.10$). On the contrary, for Route 2, which was the route taken by minority of the crowd, there existed significant difference in participants' virtual evacuation time ($p = 0.005$) and speed ($p = 0.002$).

4.3. Interactive influence of visual access and crowd flow (Groups A, B, C and D)

The above results suggest that both visual access and crowd flow could influence participants' wayfinding behavior, hence their interactive influence is considered as well. Fig. 16 shows the participants' evacuation trajectories. With the same level of visual access, crowd flow affected participants' evacuation by causing more participants to follow the crowd under the uneven distribution of NPCs (comparing the green rectangle areas between Fig. 16 (a) and (c), (b) and (d), (e) and (g), and (f) and (h)). However, comparing the red rectangle areas between Fig. 16 (c) and (d), (g) and (h), it was also illustrated that when the level of visual access was high, relatively fewer participants took the evacuation route that was taken by the majority of NPCs. Additionally, the comparison of evacuation time revealed that participants who took Route 2 in Group C spent marginally longer time than those who took Route 2 in Group A ($U = 292.5$, $z = 1.923$, $p = 0.054$), whereas there was no such difference in the high visual access condition ($p > 0.10$).

Table 4
Comparison of virtual evacuation performance for each route between Groups A and B. **p < 0.05. *p < 0.1 (+denotes Mann-Whitney U test was used for the comparison).

Virtual evacuation performance	Routes	Low visual access		High visual access		P
		M	SD	M	SD	
Time (s)	Routes 1 and 3	83.5	13.0	68.1	6.1	0.047 **
	Route 2	65.8	7.7	60.4	7.7	0.001 ** (+)
	Routes 4 and 5	75.9	12.7	68.8	10.8	0.017 ** (+)
Distance (m)	Routes 1 and 3	133.5	13.3	129.4	5.1	0.839 (+)
	Route 2	113.7	7.4	112.3	6.9	0.400 (+)
	Routes 4 and 5	121.1	7.9	116.4	11.5	0.021 ** (+)
Speed (m/s)	Routes 1 and 3	1.6	0.2	1.9	0.1	0.005 **
	Route 2	1.7	0.2	1.9	0.2	<0.001 ** (+)
	Routes 4 and 5	1.6	0.2	1.7	0.2	0.257

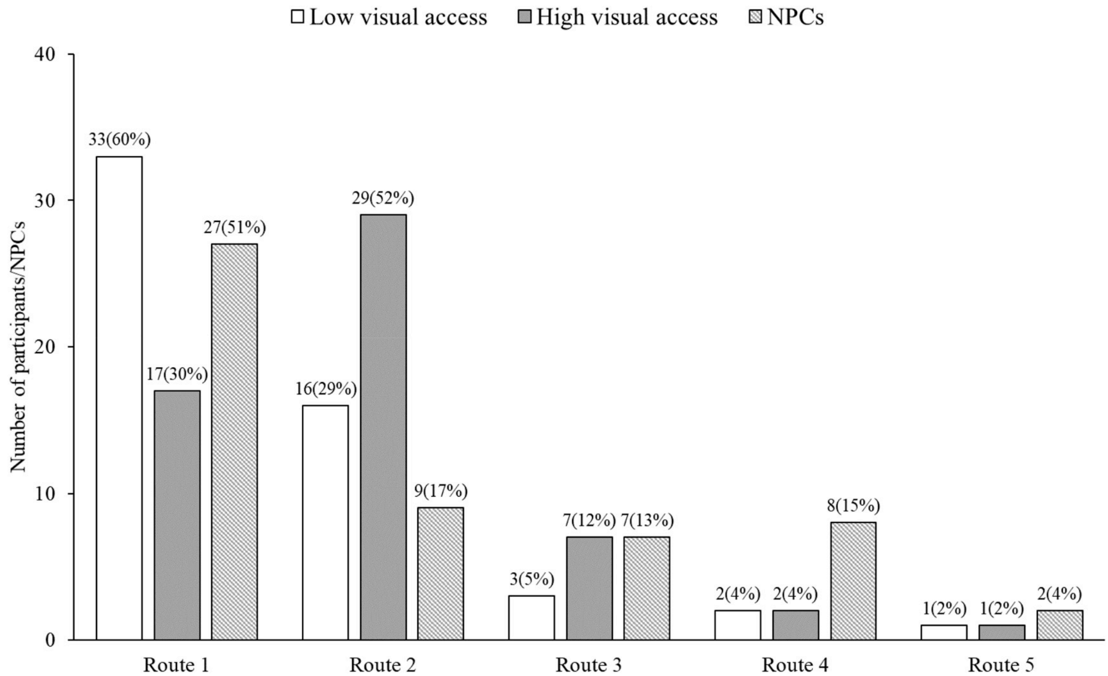


Fig. 12. Route choices of participants in Groups C and D and NPCs.

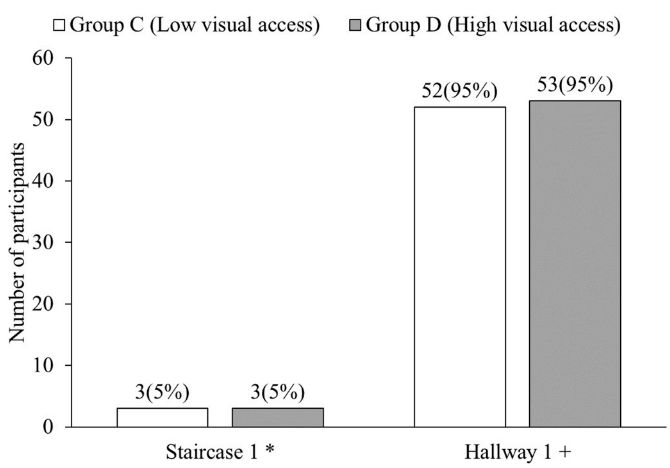


Fig. 13. Directional choices of participants at DP 1 in Groups C and D (* denotes the direction with improved visual access in Group D, + denotes the direction that the majority of NPCs took).

5. Discussions

5.1. Influence of visual access on directional choices during building emergencies

Except for the London participants in Group B, visual access did not influence participants' directional choices at DP 1. One reason might have been related to the participants' stress level when encountering an emergency and unfamiliarity with the environment, which could narrow their attention [67] and impair their ability to process environmental information [68]. At DP 1, participants needed to make a directional choice immediately after they were immersed in an unfamiliar emergency environment, as a result, improved visual access may not be perceived when participants were highly stressed. Another reason might have been the location of building elements as well as the hazards (i.e., fire in this study). At DP 1, Staircase 1 was located in the direction where the train on fire approached from. It was suggested in the literature that the more people are unfamiliar with the environment, the more likely they would choose to stay away from the dangerous area instead of going towards it [69]. Thus, in the high visual access condition, more participants chose to go to Hallway 1 instead of Staircase 1, to avoid getting close to the fire.

At DP 2, Hallway 2 was made significantly more visible in the high visual access condition. Visual access had a marginally significant effect on participants' directional choices at DP 2 when Groups A and B were compared. Participants' evaluation of the influencing factors at DP 2 showed that participants in Group A considered the direction indicated by signage more important in their decision making, compared with those in Group B. This result might also be related to the building characteristics and design strategies used to manipulate visual access at DP 2. When visual access was low, participants' line of sight was partially blocked by columns and solid walls in Hallway 2. Therefore, the signage in Hallway 2 and near Staircase 2, which was at the ceiling level and hence less influenced by the manipulation of visual access, might have been more influential in participants' decision making. This finding is in line with literature: people are more likely to choose the visible direction instead of heading towards another direction that is unknown to them [31].

At DP 3, visual access did not significantly influence participants' directional choices. One factor that distinguishes DP 3 from DP 1 and DP 2 was that the participants had more time to make directional choices at DP 3, compared with DPs 1 and 2. In fact, Staircases 3 and 4 were located symmetrically in relation to DP 3. Thus, in the high visual access condition, even though Staircase 4 was more visible when participants were moving towards DP 3 on the underground floor, they might have adjusted their final decisions when arriving at DP 3, and due to the symmetrical design of Staircases 3 and 4, these two exits became similarly visible at DP 3.

We conclude that visual access could influence participants' directional choices, however this is contingent upon other contextual factors. Thus, several aspects should be taken into consideration in terms of how visual access influences people's directional choices during building emergencies. First, the magnitude of visual access has direct correlation with people's choices. The clearer a direction leads to an exit, the more likely it is to be chosen. Second, when people's stress level is high during building emergencies, their ability to perceive the environmental

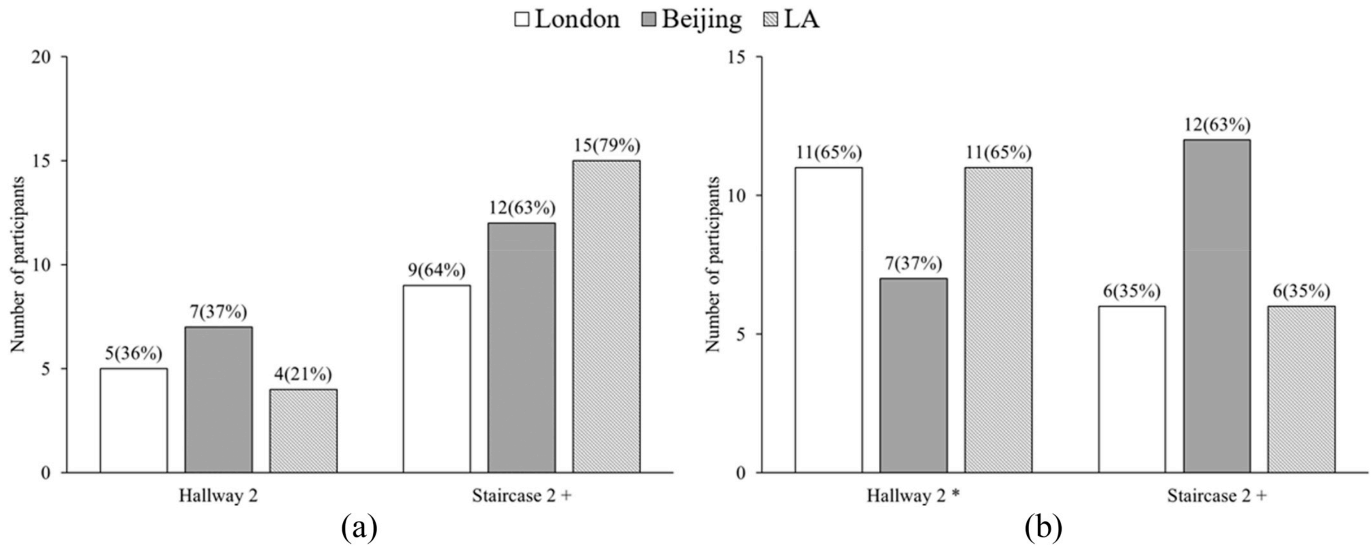


Fig. 14. Directional choices of participants at DP 2 (a) Group C (+denotes the direction that the majority of NPCs took); (b) Group D (* denotes the direction with improved visual access in Group D, + denotes the direction that the majority of NPCs took).

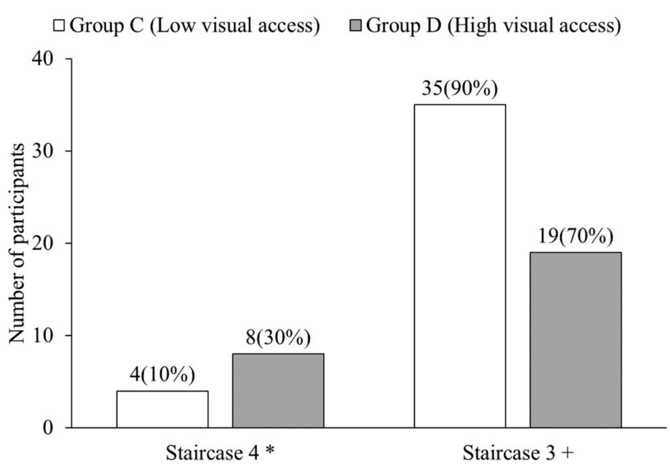


Fig. 15. Directional choices of participants at DP 3 in Groups C and D (* denotes the direction with improved visual access in Group D, + denotes the direction that the majority of NPCs took).

Table 5
Comparison of virtual evacuation performance for each route between Groups C and D. **$p < 0.05$. *$p < 0.1$ (+denotes Mann-Whitney U test was used for the comparison).

Virtual evacuation performance	Routes	Low visual access		High visual access		p
		M	SD	M	SD	
Time (s)	Routes 1 and 3	80.6	11.2	80.1	13.4	0.629 (+)
	Route 2	74.1	16.8	62.8	9.5	0.005 ** (+)
Distance (m)	Routes 1 and 3	134.1	11.8	135.2	9.5	0.507 (+)
	Route 2	116.4	14.0	115.2	13.5	0.831 (+)
Speed (m/s)	Routes 1 and 3	1.7	0.2	1.7	0.2	0.505
	Route 2	1.6	0.3	1.9	0.2	0.002 **

information is likely to be reduced and the effect of visual access might be reduced accordingly. Third, spatial characteristics of the building also determine the effect of visual access. If a route is intrinsically unattractive (e.g., because of its location), improving its visual access may still not motivate people to choose it. These conclusions point to one of the contributions of this study, which is the need for conducting controlled emergency evacuation experiments with multiple DPs, introducing uncertainty to decision making as well as adequate level of complexity that is inherent in real buildings.

5.2. *Influence of visual access on following and avoiding behavior during building emergencies*

At DP 1, the participants in Groups C and D followed the crowd regardless of the visual access level. Majority of the NPCs (approximately 80%) that moved to Hallway 1 provided strong directional information and caused participants to go to Hallway 1 instead of Staircase 1. When people are stressed and unfamiliar with the environment, as the participants likely experienced at DP 1, they would tend to follow the crowd during evacuation [30]. At DP 2, visual access persuaded more participants to choose alternative visible direction rather than solely following the crowd. This finding is in agreement with prior studies [31]. It was also reported in prior studies that if the crowd is moving to an exit that is invisible to evacuees, they may think others know something that they do not, and their tendency of avoiding the crowd is reduced [70]. In Group D, the visual access of Hallway 2 was significantly improved by removing columns, changing wall materials and relocating ticket booths, which provided very strong directional information and might outweighed the effect of crowd flow. Thus, more participants in Group D were attracted to choose Hallway 2 compared with those in Group C. Additionally, at DP 3, visual access also influenced participants' following/avoiding behavior. Compared with those in Group C, more participants in Group D chose the more visible direction. As discussed above, as participants could see both Staircases 3 and 4 lead to outside, some participants decided not to follow the crowd and took the alternative route instead.

In summary, visual access could influence people's following/avoiding behavior and motivate people to move towards more visible directions. This could have important practical implications, such as designing buildings for more efficient evacuation and better estimating required safe egress time in performance-based design.

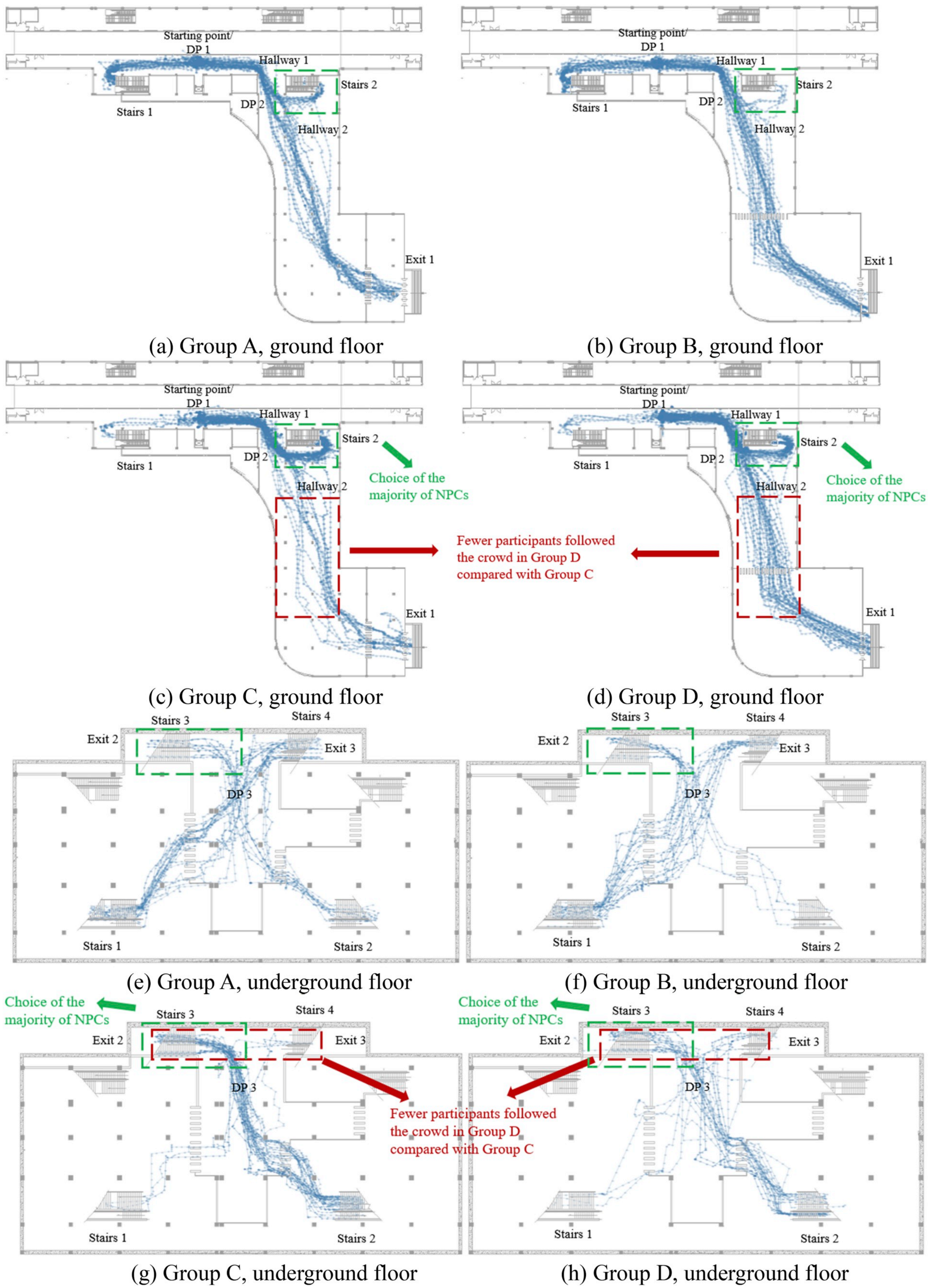


Fig. 16. Evacuation trajectories of participants.

5.3. Influence of visual access on virtual evacuation performance

By comparing participants' evacuation performance between Groups A and B, visual access was found to be positively related to participants' virtual evacuation performance. Evacuation process consists of three phases: (1) awareness of danger by external stimuli (cue validation), (2) validation of and response to environmental factors (decision-making), and (3) movement to/refuge in a safe place (movement/refuge) [71]. These phases greatly determine people's evacuation time and their chances of survival in building emergencies [72]. Apart from going through these phases at the beginning of the evacuation process, people dynamically determine their final destinations during the evacuation process and consistently experience the following phases: perceiving the environment, making decisions, and evacuating [44]. Therefore, improvement of visual access could enhance the participants' evacuation performance in two ways. First, improved visual access could reduce the level of uncertainty perceived by the participants with more visual information about the environment. Since uncertainty is an important factor that prolongs the decision-making phase, the reduction of uncertainty could enable the participants to make quicker decisions during the evacuation process [73]. Second, the removal of obstacles could further facilitate participants' evacuation in the movement phase. Furthermore, evacuation performance is highly related to route choices. In this study, improved visual access caused more participants to choose Route 2, which was shorter compared with the length of other routes, and enhanced the participants' evacuation performance consequently.

Comparing participants' virtual evacuation performances between Groups C and D, it was found that visual access did not have a significant effect on the virtual evacuation performance of participants who took Routes 1 and 3. One major reason that may have contributed to this result had to do with the crowd, since the large majority of the crowd followed Routes 1 and 3 until their final route choices at DP 3. This suggested that, while visual access was different between Groups C and D, the crowd was the most decisive factor for the participants who took Routes 1 and 3 in Groups C and D. Therefore, regardless of the visual access, crowd dominantly determined the participants' virtual evacuation performance and resulted in similar results between the two groups. However, it was also found that for participants who took Route 2 in Groups C and D, even though their virtual evacuation distance was similar between the two groups, high visual access still helped to improve their virtual evacuation performance.

5.4. The interaction effect of visual access and crowd flow on emergency wayfinding

Two reasons might have caused the participants to follow the crowd with the same level of visual access (Groups A and C, Groups B and D comparison). First, during building emergencies, especially in an unfamiliar environment, following behavior is common to occur [9]. Second, crowd flow conveys directional information that might be easier to be perceived compared to the static information (e.g., signage, visual access) [74], hence imposing major influence on participants' wayfinding behavior during evacuation. Additionally, as presented in Section 4.3, participants in Group C who took Route 2 had longer virtual evacuation time compared with those in Group A. This result was probably due to the fact that in the low visual access condition, the participants who took Route 2 (avoiding the crowd at DP 2) spent more time making this decision as there was more uncertainty in the environment. Therefore, it prolonged the process to make the decision of avoiding the crowd. In the high visual access condition, however, the improvement of visual access made Hallway 2 more visible, which shortened the decision-making process for the participants to choose Hallway 2. Hence, visual access and crowd flow are indeed two interrelated factors and their influence on wayfinding behavior depends on one another. When applying the findings on visual access and crowd flow, they should be considered collectively instead of independently.

5.5. The cultural impact on emergency wayfinding

Overall, London, Beijing, and LA participants had similar evacuation route choices, with a few exceptions at certain DPs. First, with even distribution of NPCs, the visual access improvement of Staircase 1 was perceived by more London participants compared with Beijing and LA participants. This result might be related to London participants' relatively richer prior experience with metro stations, which could lower the stress level they experienced during the experiment [75]. In fact, the experiments were conducted in university campuses in Beijing and LA, while the data collection location in London was very close to a major connection point in the metro system of London. Therefore, London participants were likely to have more experience with metro stations than Beijing and LA participants. Second, at DP 2, while London and LA participants tended to avoid the crowd and went to a more visible direction in Group D, the following behavior of Beijing participants remained at a high level even in Group D. One possible reason for this finding may be attributed to the fact that China has a culture with lower level of individualism compared with the U.S. and the U.K. [47], which resulted in a higher tendency of following in emergencies. However, as presented above, London, Beijing and LA participants did not have consistent differences during their evacuation process, therefore, whether their cultural background impacted their evacuation behavior should be further investigated.

5.6. Limitations and future work

While this study presents interesting findings on the influence of visual access and people's cultural backgrounds on wayfinding during building emergencies, there are limitations associated with the study that require future investigations. First, while we included virtual fire, smoke and emergency announcement in the IVEs to represent the fire scenario, unlike real fires, the virtual fire and smoke did not affect participants' mobility and no thermal and olfactory stimuli were provided. Meanwhile, participants' movement in the IVEs was achieved by using a controller and was set at a constant speed. To enhance the sense of presence that participants experience in the IVEs, future studies could provide more stimuli channels (e.g., thermal, olfactory, and haptic feedback) to make the virtual fire scenario more comparable to real fire emergencies. In addition, to evaluate evacuation performance more realistically, alternative equipment (e.g., VR treadmill) could be used for participants to move in the IVEs. Second, while this study is one of the few that collected data in multiple countries, the findings in this study were based on data collected from participants in three locations only, thus validity of the results on people from other cultural backgrounds as well as other factors, such as elders, children would require further investigation. Third, the results of this study suggest that both participants' stress level and familiarity with the building could affect emergency wayfinding. However, to further evaluate these effects, future studies could monitor participants' stress levels (e.g., using physiological measurements [43]) during the experiment and integrate different levels of familiarity with the building into the design of experiments. Fourth, the main objective of this study was to understand the influence of visual access on people's evacuation behavior rather than develop practical solutions to manipulate visual access in actual buildings. Therefore, it is important to note that some of the strategies used in this study (e.g., removing columns in the hallway) were purely for research purposes and might not be practical or possible to implement in real buildings. However, the study results may provide useful insights into the impact of design strategies on visual access and emergency wayfinding during the design stage of unconstructed buildings. Finally, this study was conducted in a virtual metro station with 53 NPCs, where no congestion was caused by the crowd. As spatial characteristics and level of crowdedness both play a significant role in the influence of visual access, whether people would behave consistently during emergencies in other environments, including different types of indoor spaces, such as educational buildings, office buildings and museums, could be studied in future research.

6. Conclusions

An emergency evacuation experiment was conducted in a virtual metro station in three different locations (i.e., London, Beijing and Los Angeles) to understand how visual access and people's cultural background influence their wayfinding behavior during building emergencies by comparing two levels of visual access in two different crowd conditions. There were three points in the metro station where the participants needed to make directional choices, and multiple design strategies (e.g., changing wall materials, removal of columns, relocating ticket booths) were used to manipulate visual access, which, to the best of the authors' knowledge, have not been explored in prior studies. Participants' route and directional choices, virtual evacuation performance (i.e., virtual evacuation distance, time, and speed) and subjective assessments (e.g., emotional responses, simulator sickness, sense of presence, wayfinding anxiety, etc.) were collected during the experiment. Our results showed that improving visual access did attract people to go to a more visible direction during the evacuation, while the magnitude of the effect depended on the significance of visual access improvement. The clearer a direction leads to an exit, the more likely people choose to take that direction. Moreover, improving the level of visual access could facilitate people's environmental perception and decision-making process and encourage them to choose visible routes over the ones taken by the crowd, although such effect may vary in different cultures and emergency situations. The results also revealed that increasing the level of visual access in indoor environments could improve people's evacuation performance during emergencies (i.e., shorten the evacuation distance and time and increase the speed). Furthermore, the results indicated that Beijing participants tended to have higher following tendency compared with London and LA participants.

CRediT authorship contribution statement

Runhe Zhu: Methodology, Software, Formal analysis, Investigation, Validation, Writing - original draft. **Jing Lin:** Methodology, Software, Formal analysis, Investigation, Validation, Writing - original draft. **Burcin Becerik-Gerber:** Conceptualization, Methodology, Resources, Writing - review & editing, Supervision, Funding acquisition. **Nan Li:** Conceptualization, Methodology, Resources, Writing - review & editing, Supervision, Funding acquisition.

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Appendix A. Supplementary data

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