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Experimental study on choice behavior of pedestrians during building evacuation

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Abstract

Understanding human behavior in emergency evacuation is a significant issue for layout optimization, crowd management and rescue. In this study, we conducted a series of controlled experiments to study choice behavior of pedestrians considering environment factors (e.g. occupant initial distribution, auditory information, and building layout). We found it was non-symmetrical for pedestrians' exit selection and aisle selection in the room. And there was a strong positive relation between intermediate exit choice and destination choice. Pedestrians' final destinations had significantly effects on evacuation route and intermediate facilities usage. When the final destination was uncertain, the factor of building layout performed more effect than occupant initial distribution. Pedestrian psychology, following the crowd, had a major influence on pedestrians' exit stairs selection, especially when pedestrians were in non-limited visual field environment. Bifurcation point, where a row of pedestrians split into two streams with diametrically opposite movement directions, was a quite biased away from the side of exit. The conclusions are expected to provide valuable advice for crowd management and optimization design such as aisle-seating layout.

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Keywords: building evacuation, choice behavior, aisle, bifurcation point.

1. Introduction

Considerable attention has been paid to the topic of human behavior in evacuation caused by fires, since many serious fatalities in fire occur. This fascinating field involves a wide range of disciplines such as building design, safety engineering, crowd management, physics, psychology, sociology, and computer science etc. In the past few decades, a great many of experimental studies have been performed to either understand human behavior and pedestrian mobility, or collect empirical data in term of evacuation time, pre-movement time, speed, density or flow for the calibration and validation of evacuation models. Meanwhile, a variety of simulation models, such as social force model, cellular automata model, lattice gas model, multi-agent model and network model, have been developed. For a review concerning simulation models, the reader can refer to [1-3]. A detailed discussion of these models is beyond the scope of this paper.

Based on different experimental subjects as well as different methods of data collection, experiment methods can be divided into five categories: field observation [4-6], evacuation drill [7-13], controlled experiment [14-24], experiment based on animals [25-28] and data-collection in real emergency [29-33]. There is its own field of application and shortcomings for each kind of method. Nowadays, due to the well operability of experiments as well as the reliability and accuracy of results, the method of controlled experiment has been widely used.

The evacuation route selection of pedestrians, for example, exit selection as well as other facilities selection (e.g., stairs, aisles, escalators and lifts), not only affects the successful probabilities of individual safety evacuation, but also takes effect

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on crowd evacuation efficiency. Three factors, route characteristics (e.g., distance, capacity of route, movement quality of route), environment information (e.g., visibility, evacuation indicator, sound message) and pedestrian characteristics (e.g., experience, personality, role), are acknowledged to have an impact on travel-path decisions of pedestrians. Cheung and Lam [34] studied the behavior of pedestrian in choosing between escalators and stairways in MTR stations during peak hours focusing on the influence of relative delay. Helbing [35] indicated the phenomenon of nonsymmetrical choice of exits due to herding behavior in panic situation. Furthermore, Altshuler et al [25] demonstrated this phenomenon by means of conducting laboratory experiments using ants. Unfortunately, the rooms were empty in the above studies, and it is not clearly whether nonsymmetrical or not when evacuating from a multi-obstacle room such as classroom.

Evacuation from room with obstacles has also been studied by means of experiments, simulations or a combination of both. Helbing et al [36] and Liu et al [37] analyzed the distribution of pedestrians' evacuation times as a function of their initial positions using experimental and modeling methods. Guo et al [38] use experimental and modeling methods to investigate pedestrians' evacuation route choice in classroom under conditions of both good and zero visibility. Papinigis et al [39] estimated the egress time from the theatre hall based on FDS+Evac program. However, the above studies are all single stage evacuation. There are no internal exits in the evacuation route of pedestrians, the room exits are regarded as final exits. In reality, evacuations from buildings are normally multi-stage since pedestrians will pass through many facilities for leaving a building. And we believe that the choice of transitional facilities is affected by not only the prior factors such as initial pedestrian distribution and internal layout, but also such factors as final destination.

An interesting phenomenon in pedestrian dynamics is kin behavior [40] performing by particular groups, such as family members, friends and classmates. The members usually gather together firstly before evacuation, sometimes even go back to the dangerous area to find or help other members. In general, the performance of particular group will bring negative influences to other pedestrians, for example, moving together or going back will get in other occupants' way, which does reduce the whole evacuation efficiency. Yang et al [40] proposed a cellular automata model to simulate the kin behavior of particular group. Qiu and Hu [41] developed an agent-based crowd simulation system to model the structure aspect of different groups in pedestrian crowds. Two group structures, intra-group structure and inter-group relationships were considered. In addition, Zhao et al [42] simulated sub-group behavior in sports stadium based on agent technology. Ji and Gao [43] explored a crowd evacuation model based on A* Algorithm to simulate the dynamic grouping phenomena with each group having a leader and some followers guided by the leader. Unfortunately, the information with respect to the performance of particular groups in reality with different size, population composition, or initial position, is still limited.

The remainder of this paper proceeds as follows: Section 2 describes the details of the experimental setup. Section 3 covers the experimental results and discussion. Finally, a brief summary including the conclusions and a discussion of future research work is presented in section 4.

2. Experiments

We conducted a series of experiments participated by university students to explore typical choice behavior of pedestrians in building evacuation. 102 students (87 males and 15 females), with age ranging from 18 to 24, took part in the experiments as evacuees.

2.1. Building layout

The group of experiments was carried out in a teaching building illustrated schematically in Figure 1. The evacuation route fell into three successive parts, classroom, passage and alternative stairs. In the classroom, one latitudinal aisle leading to Exit A, and four longitudinal aisles divided all 144 seats into 9 rows and 16 columns as shown in Figure 2. Two identical exits, Exit A and Exit B, with widths of 1.2m, were located in the east wall. Additionally, in Figure 2, it illustrates two types of occupant initial distribution which we used in the experiments, even distribution and non-even distribution.

The passage was 3.4m width and 64.6m length, and both of its ends leaded to exit stairs. The classrooms were located at one side of the passage, and the chosen experimental classroom was a little closer to Exit Stairs A. It was a distance of 19.7m from classroom Exit A to Exit Stairs A, and 31.5m from classroom Exit B to Exit Stairs B.

Stairs A was 2.10m wide and the individual step measured 14.5cm rise and 28cm tread depth. There were two identical flights connected by a mid landing, with the size of 2.30m×4.70m. Each flight consisted of 14 steps. Stairs B was 2.70m wide and the individual step measured 14.5cm rise and 28cm tread depth. There were totally 28 steps interrupted by 2 mid landings (11 steps between upper floor and upper landing, 6 steps between two landings and 11 steps between lower landing and lower floor). The dimensions of upper landing and lower landing were 2.57m×2.75m, 2.6m×2.75m, respectively.

At each end of the passage, an alarm was positioned to give auditory information representing of exit stairs status (open or closed). What needs to be emphasized is that the alarm information was not always in accordance with the status of exit stairs. The alarms may be false or not activated which we controlled intentionally as a variable to study the effect of long-distance auditory information. The alarms are denoted in Figure1 by filled circles.

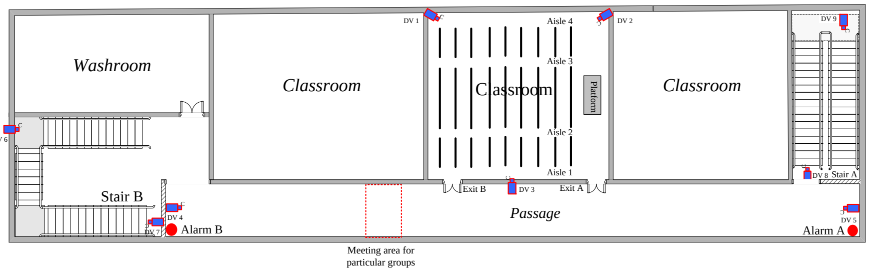
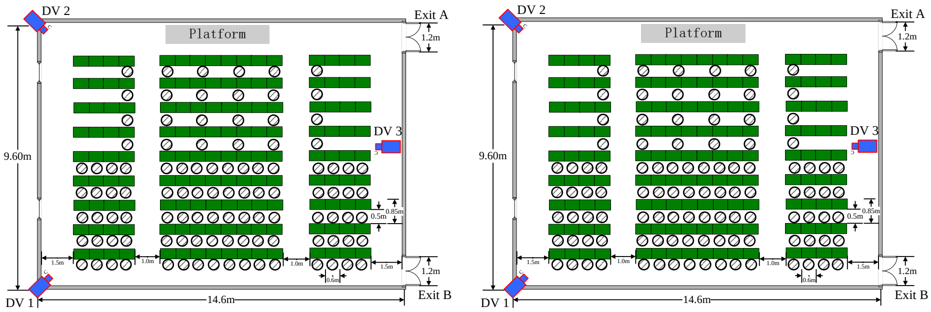


Fig. 1 A schematic illustration of the experimental building



(a) Non-even occupant initial distribution (b) Even occupant initial distribution

Fig. 2 Schematic illustration of the classroom and two kinds of occupant initial distribution

2.2. Experimental procedure

We conducted eight experiments which were divided into two categories: without and with particular groups. The parameters such as alarm status, occupant initial distribution and exit stairs were considered as shown in Table 1. Two types of occupant initial distribution, type A and type B, have been represented in Figure 2. Type A was non-even distribution, that is, there were much more individuals in the back of the classroom than that in the front of the classroom. Type B was even distribution, namely, all students distributed in the classroom nearly evenly.

Table 1 Summary of the experimental variables

No.	Occupant distribution	Alarm status		Exit stairs status		Explanation of alarm B*
		A	B	A	B	
1	type A	ON	ON	open	closed	false
2	type A	ON	ON	open	open	normal
3	type A	ON	OFF	open	open	not activated
4	type A	ON	ON	open	closed	false
5	type A	ON	OFF	open	closed	normal
6	type B	OFF	ON	closed	open	normal
7	type B	OFF	ON	closed	open	normal
8	type B	OFF	ON	closed	open	normal

**The alarm A was always normal during the experiments.*

Note: In the last three experiments, students were told that Exit Stairs A was not available before the experiments.

For without particular group experiments (No.1-5), all participants received the same instructions. Before each experiment, all participants sat on their own seats in the classroom, and started to evacuate as soon as the start signal was given. For each participant, the evacuation process fell into three successive phases. Firstly, he or she moved towards one of the classroom exits. Once the individuals arrived at the exits, they entered into the passage and chose a movement direction based on their available information such as long-rang audible information, the movement direction of other people and their experiences. Then the individuals moved along the passage toward exit stairs, and finally arrived at the destination after moving down exit stairs. Noted that if someone moved to a closed exit stairs, he or she had to go back and evacuate via the other exit stairs to the destination. All individuals wore red hat in order to indentify clearly.

For with particular group experiments (No.6-8), several students were randomly chosen as particular individuals. They had to meet together at the meeting area in the passage (shown in Figure 1) before they moved along the passage to exit stairs, furthermore, they must keep together during left evacuation process. The other ordinary individuals received the same instructions as those in the first experiments. The ordinary individuals wore red hats, and the particular individuals wore hats with different colors according to different group.

In addition, in the second experiment, only Exit Stairs B was available. This was told to all participants before the experiments. So the final destination of participants was certain. They did not estimate which escape direction was available when they arrived at the passage.

2.3. Data collecting method

Nine video cameras were mounted to record the evacuation process, and their positions are dotted in Figure 1. In order to identify every person clearly, the video cameras were placed 2.0m high above the ground to capture the motion of the crowd from an aerial view. All the cameras were synchronously started before each experiment. Each individual recorded his or her finish time when he or she arrived at the destination with the help of time-display at the destination. The start time was identical for each individual with an assumption that the pre-movement time was not considered since the participants were told to start to evacuate as soon as the start signal was given. Then individual evacuation time could be determined as the time interval between the start time and the individual recorded time.

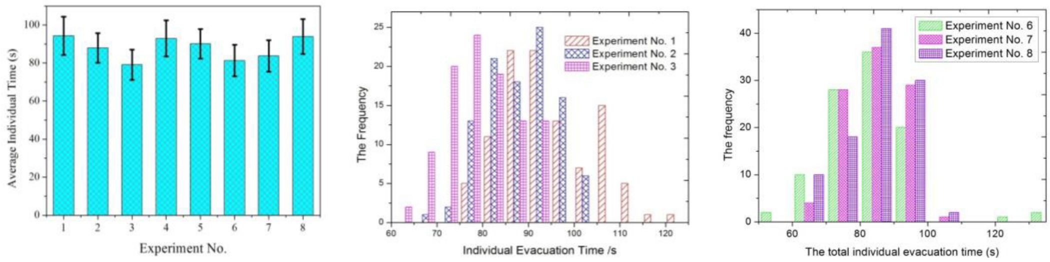
2.4. Additional remark

The participants were very familiar with the building layout, and highly motivated. During the experiment process, they were asked moving as fast as possible. After each experiment, all students came back to the classroom, and there were five minutes to rest, so they did not produce fatigue during the experiments. If anyone felt tired or uncomfortable, he or she could drop out before each experiment. At each experiment, each individual located at different initial position.

3. Results and discussion

3.1. Individual evacuation time

Individual evacuation time was determined as the intervals between start time and recorded time of each participant. Individual evacuation time ranges largely as shown in Figure 3. Figure 3(a) is average individual evacuation time with standard deviation in each experiment. The average individual evacuation time is the smallest in Experiment 3 with the situation that both stairs A and B were available. For the evacuations with particular groups (Experiment No. 6-8), the individual evacuation time is increased with the increase of the number of particular group.



(a) Average individual evacuation time (b) Time in Experiment No.1-No.3 (c) Time in Experiment No.6-No.8

Fig. 3 The descriptive statistic of individual evacuation time

In Figure 3(b), there are quite more people taking long time (more than 100s) to complete evacuation in experiment No. 1 comparing with other situations. This is mainly because a few of people chose a closed route at first with the help of false information. In experiment No. 1, the Exit Stairs B was closed, but the alarm B was activated. Therefore, with the guard of the alarm B, a few of people moved to Exit Stairs B at first. When they found the exit stairs was closed, they had to move back. This caused a relative long evacuation time. We counted the people who chose indirection escape route in experiment No. 1. 18 persons (17.6%) made a mistake with the help of false audible information.

In Figure 3(c), for the second category of experiment, although the destination was certain for each participant before evacuation, there is still a small amount of individual time more than 120s caused by members of particular group. By analyzing carefully the evacuation record video, it can be clearly found there was a gap before particular individual in pedestrian flow in passageway and staircase.

Two factors, individual characteristics and environmental information will cause the wide difference of individual evacuation time. The former determines the evacuation time in term of not only movement ability but also decision-making time. The latter mainly affects the escape route which may be a long distance route or even a false route leading to a closed exit. In our experiments, environmental information is mainly long-range audible information.

3.2. Asymmetry behavior on exit choice

In this section, we will discuss the asymmetry selection behavior of pedestrians. Classroom exits are considered as intermediate exit, while stairs are considered as final exits or destinations. Table 2 summaries the relationship between classroom exit selection and exit stairs selection. The second column is the percentage of the individuals whose initial positions were in Row1-Row4. From Table 2, one can see that, in the first category of experiments (No.1-No.5), even though most individuals situated in the back part of the classroom, the choice percentage of classroom exit A was still quite larger than that of classroom exit B, except the situation in experiment No. 3. This deviation was more apparent for the second category of experiment series (No.6-No.8). Differently, there were much more individuals chose the classroom exit B. This is asymmetry behavior on classroom exit choice.

Table 2 Summary of correlation between classroom exit choice and exit stairs choice

No.	Distribution percentage*	Selection of exit A	Selection of exit B	Selection of stairs A	Selection of stairs B	Remarks
1	26.5%	60 58.8%	42 41.2%	102	0	Stairs B was closed; Alarm B was false
2	26.5%	57 55.9%	45 44.1%	89 87.3%	13 12.7%	
3	26.5%	49 48%	53 52.0%	39 38.2%	63 61.8%	Alarm B was not activated
4	25.7%	57 56.4%	44 43.6%	101	0	Stairs B was closed; Alarm B was false
5	25.7%	53 52.5%	48 47.5%	101	0	
6	42.9%	33 33.7%	65 66.3%	0	99	Stairs A was closed
7	42.9%	35 35.7%	63 64.3%	0	101	Stairs A was closed
8	35.5%	36 38.7%	57 61.3%	0	100	Stairs A was closed

**the distribution percentage is accounted as follows: the number of people occupied the first four seats/ the number of persons in classroom*

For the first category experiments, at the beginning of the evacuation, all individuals sat on their own seats facing the forward part of the classroom. They did not know the status of the exit stairs, namely, their final destinations were uncertain before evacuation. When the start command was given, the individuals stood up and moved towards one of the classroom exits. Compared with people moved to Exit B, the individuals moved to Exit A need not turn-back. Another reason was that the latitudinal aisle leading to Exit A played a great role on evacuation efficiency. Pedestrians moved along the aisles faster than moving between seats. For most individuals except those near Exit B, if they chose Exit B, they had to spend more time passing through many seats between row and row. It was more convenient to move towards Exit A than move towards Exit B due to structure layout. For the second situations (No.6-No.8), before the experiments, all individuals were told that there was only exit stairs B available which was at the side of classroom exit B. It stated that the final destinations of all individuals were deterministic. If pedestrians chose exit A, it meant they chose an indirect escape route and should cost more movement time. Therefore, in this situation, most pedestrians left the classroom through the classroom exit B.

Compared with the factors of initial distribution and building layout, the factor of evacuation destination was a much greater impact on pedestrians' exit choice behavior. Therefore, when the authorities manage crowd evacuation in multi-obstacles buildings such as stadiums and theatres, it is of importance to take pedestrians' final destinations into account.

Besides, when the destination was uncertain, the factor of building layout performed more effect than the factor of occupant initial distribution.

Another interesting result was that pedestrians chose exit stairs asymmetrically, too. In the experiment No.2 and No.3, Exit Stairs A and B were both available. Abnormally, there was a much deviation of the selection percentage between these two stairs. In experiment No. 2, both of the alarm A and B were normal, however, few pedestrians chose Exit Stairs B. In experiment No.3, the alarm B was not activated while Exit Stairs B was open, there was a large percentage of individuals chose it. We counted the pedestrians who moved firstly to a closed stairs exit in experiment No.1, No.4 and No.5. The number of pedestrians who moved firstly to the closed stair exit were 18 (17.6%), 39 (38.6%), 9 (8.9%), respectively. We can see there was also an asymmetry behavior of exit stairs choice.

To explore the reason, we analyzed the video records carefully. We found that the phenomenon of following the crowd was fairly frequent, especially when pedestrians need to make choice about escape route. When evacuees moved out of the classroom, most individuals firstly observed the circumstance around him or her to estimate which exit stairs was better for evacuation. The first individual escaped from the classroom chose one of the movement directions to start next phase evacuation considering two factors: distance and alarm information. However, consequent pedestrians were likely to follow the crowd in front of them, no longer considering the influence of distance and alarm information.

Compared with the factor of distance and alarm information, we found the factor of pedestrian psychology, following the crowd, had a major influence on pedestrians' selection behavior, especially when people were in non-limited visual field environment where pedestrians obtained environmental information using optesthesia rather than audition. Furthermore, the experience as well as unconscious habits were also significant factors.

In addition, there was a strong positive relation between classroom exit choice and exit stairs choice. Figure 4 profiles the relation between classroom exit choice and exit stairs choice. Note that the false selections are also considered in experiment No. 1, 4 and 5. We can see that there is the same choice deviation in classroom exit and exit stairs.

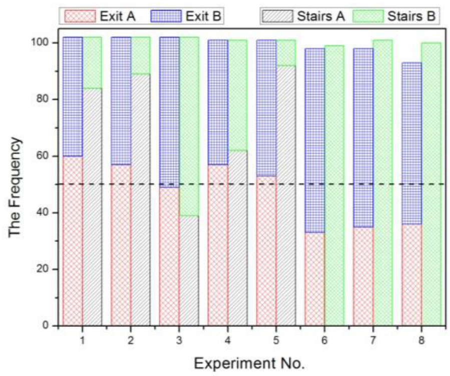


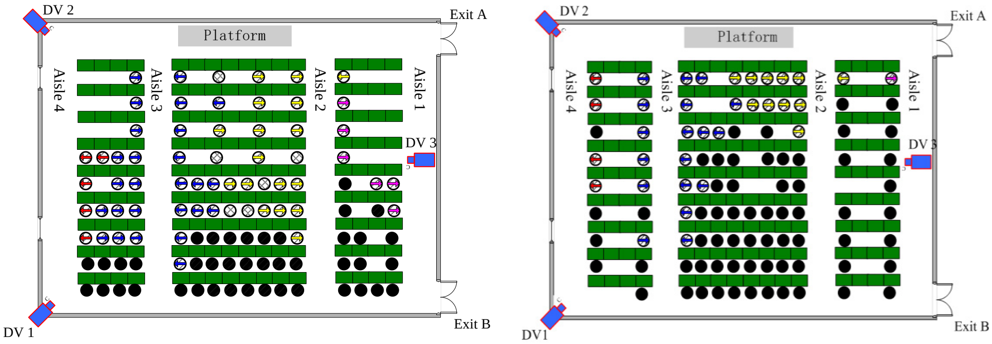
Fig. 4 Relations between classroom exit choice and exit stairs choice

3.3. Choice behavior on classroom aisles

In the classroom, there were 4 longitudinal aisles and a lateral aisle leading to the exit A as shown in Figure1. Evacuees who left the classroom through the exit A would move along one of the longitudinal aisles to the lateral aisle. Meanwhile, most others who chose the exit B moved laterally between seats and seats. Pedestrians walked more slowly in the latter situation due to the limited width between seats and seats.

We analyzed carefully the evacuation route of each individual in the classroom during each experiment. In Figure 5, it illustrates the movement route of each individual in experiment No.1 and No.6, respectively. The circles represent the initial position of each pedestrian. The black filled circles are pedestrians who chose the classroom exit B, and the others chose the classroom exit A. In detail, the circles with pink arrow, yellow arrow, blue arrow and red arrow represent people who passed through the aisle 1, aisle 2, aisle 3 and aisle 4, respectively. The circles filled with crossing lines mean those people took an intricate route which consisted of more than one aisle. Furthermore, Figure 6 illustrates the aisle choice percentage in each experiment.

From Figure 5 and 6, we can find that the aisle choice of pedestrians is also asymmetry. A massive of pedestrians chose Aisle 2 and Aisle 3 which located at the middle part of the classroom, however, only few people chose Aisle 1 and Aisle 4, one side of which was next to the wall. When compared the selection behavior between Aisle 2 and Aisle 3, the selection of Aisle 3 caused a larger proportion. For pedestrians located at lower left part in classroom, they preferred evacuating via Aisle 3 (a longer evacuation route) to via Exit B (a burdensome movement route).



(a) Experiment No.1 (b) Experiment No.6

Fig. 5 Schematic illustration of pedestrians' evacuation route

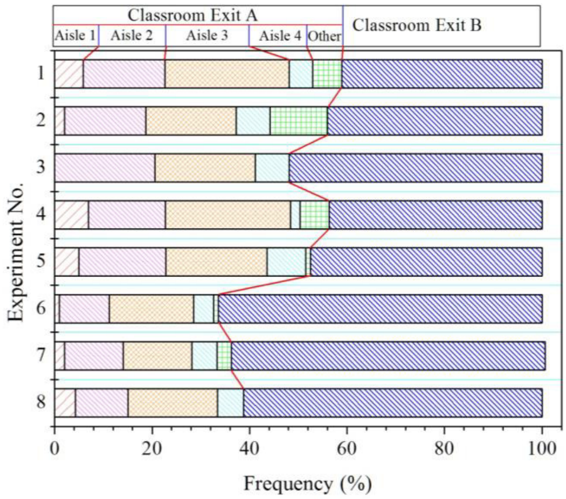


Fig. 6 Summary of aisle choice in the classroom **(Note:** *Other mean the people who take a complex route consist of more than one aisle***)**

3.4. Choice behavior on each row with contiguous seats

For the middle seated area between Aisle 2 and Aisle 3, there were 8 seats connected together in each row. When pedestrians started to evacuate, essentially, they had to choose a movement direction firstly (left to Aisle 3 or right to Aisle 2), which was limited by his or her two direct neighbors. The individual had to choose the same direction if his left and right neighbors moved in the same direction. Therefore, in order to successful removal from the seated area, pedestrians took a cooperation pattern by adjusting the movement direction to accommodate pedestrians around him or her.

A bifurcation point, at which a row of pedestrians will split into two streams with diametrically opposite movement directions, exists in each row within the seated area. Figure 7 is schematic illustrations of all formations in a row with 8 pedestrians.

We counted the percentage of each formation by observing repeatedly the evacuation records, as shown in Figure 8 and Figure 9. In ideally situations, bifurcation point should be symmetric formation (4-4 formation or 2-2 formation). However, we found the bifurcation point was a quite biased away from the side near the classroom exit. This was perhaps caused by individual expected utility-consuming. Two factors, destination information and movement environment (including movement distance and the level of difficulty of movement), would affect the position of bifurcation point. For individuals closer to Aisle 2, those chose left direction meant a circuitous route while others chose the right direction meant burdensome movement between two rows of seats. From the figures, it was suggested that university students preferred burdensome movement to circuitous route when the exits were visible and accessible.

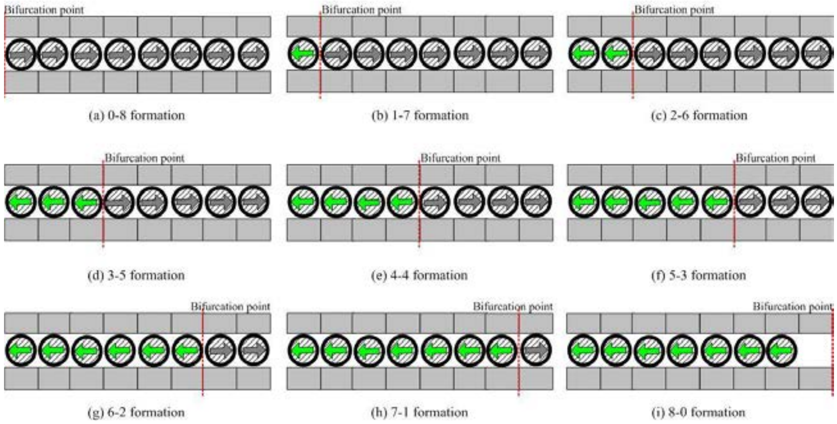


Fig. 7 Schematic illustrations of formations for 8 pedestrians in a row

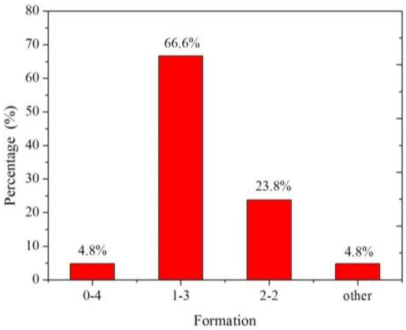


Fig. 8 Formation type for 4 pedestrians in a row

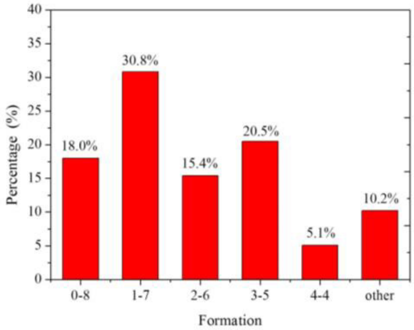


Fig. 9 Formation type for 8 pedestrians in a row

4. Summary

It is essential to conduct experimental study on pedestrian and evacuation dynamics in building evacuation. On one hand, the experimental study is help to understand the psychological and behavioral characteristics of human both in emergency and normal situations. It is able to give the authorities guidelines on crowd management and optimization design of the building access facilities. On the other hand, these scarce data derived from experiments with different methods (field observation, evacuation drill, controlled experiment, experiment based on animals and data-collection in real emergency) can be used to calibrate and validate the developed evacuation models.

In this paper, we carried out a series of evacuation experiments in a teaching building participated by university students. We focused on analyzing the human choice behavior, including the classroom exit selection, the exit stairs selection, as well as the pedestrians' aisle choice in the classroom evacuation. The main results in this study are shown as follows,

(1). It was non-symmetrical for exit selection of pedestrians as well as route selection in multi-obstacle room, which was demonstrated that the facilities were not used evenly even with the good visibility.

(2). Individual evacuation time ranged largely in each evacuation experiment. There were two factors could caused more evacuation time, that is, choosing a closed route at first with the help of false information, and existence of particular group. The average individual evacuation time was increased with the increase of the number of particular group.

(3). There was a strong positive relation between intermediate exit choice and final exit choice. Pedestrians' destinations had significantly effects on evacuation route and intermediate exits when the destinations were certain.

(4). For the selection of exit stairs, compared with the factor of distance and alarm information, the factor of pedestrian psychology, following the crowd, had a major influence on pedestrians' selection behavior, especially when people were in non-limited visual field environment.

(5). In the classroom, pedestrians located in middle seated area tended to choose the aisle which was near the exit at the cost of taking more lateral movement between seats. Bifurcation point, where a row of pedestrians split into two streams with diametrically opposite movement directions, was a quite biased away from the side near the classroom exit.

Experimental study of evacuation dynamics has its complexity and particularity since pedestrians are intelligent agents and experimental scene is difficult to control. Even in the totally same condition, pedestrians may exhibit different escape behavior. Therefore, several factors, such as experience, experiment order, artificial emergency condition, should be considered when we conduct evacuation experiment in future. The conclusions in this paper are expected to provide some valuable advice for crowd safety management both in normal and emergency situations and optimization design of building layout, such as aisle-seating layout.

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