# Wall-following behaviour during evacuation under limited visibility: experiment and modelling

Shuqi Xue

*School of Modern Posts, Xi'an University of Posts and Telecommunications, Xi'an 710061, China*

Rui Jiang

*Key Laboratory of Transport Industry of Big Data Application Technologies for Comprehensive Transport, Ministry of Transport, Beijing Jiaotong University, Beijing 100044, China*

S.C. Wong

*Department of Civil Engineering, The University of Hong Kong, Hong Kong SAR, China*

Claudio Feliciani

*Research Center for Advanced Science and Technology, The University of Tokyo, 4-6-1 Komaba, Meguro-ku, Tokyo 153-8904, Japan*

Xiaomeng Shi

*Jiangsu Key Laboratory of Urban ITS, Jiangsu Province Collaborative Innovation Center of Modern Urban Traffic Technologies, Southeast University, Nanjing 211189, China*

Bin Jia

*Key Laboratory of Transport Industry of Big Data Application Technologies for Comprehensive Transport, Ministry of Transport, Beijing Jiaotong University, Beijing 100044, China*

Corresponding author: Rui Jiang and S. C. Wong

Email addresses: jiangrui@bjtu.edu.cn (Rui Jiang), hhecwsc@hku.hk (S. C. Wong)

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Wall-following is an important means for pedestrians to navigate during evacuation under limited visibility. Empirical and experimental results regarding wall-following behaviour are scarce in the literature. How pedestrians approach a wall, how they decide on a wall-following direction, and how they address conflicts are still poorly understood. To these ends, we performed evacuation experiments in a mock room. Each participant wore a baseball cap covered with an opaque veil to create a limited visibility condition. Experiment results showed the participants stretched out their arms and attempted to search for the wall tactually in 205 of 270 cases, and in the remaining cases, the participants searched for the wall visually rather than tactually. The findings also reveal underlying behaviour pattern of pedestrians on the decision of wall-following direction. Finally, we propose a wall-following model based on the social force model. The simulation results are consistent with the experimental outcomes.

Keywords: Pedestrian evacuation; limited visibility; wall-following behaviour; direction choice; social force model

## 1. Introduction

Safe evacuation is crucial for any mass gathering event. To guarantee safe evacuation, pedestrian behaviour in evacuation must be thoroughly understood in order to develop safety equipment and a reasonable evacuation plan. Previously, a number of experimental and modelling studies have been performed to investigate pedestrian behaviours during an evacuation event (Hirai and Tarui 1977; Okazaki 1979; Helbing et al., 2000; Kirchner et al., 2002; Tak et al. 2018; Porter et al. 2018; Shi et al. 2018; Tavana and Aghabayk, 2019). Some representative findings include herding behaviour, clogging at exits (Helbing et al., 2005; Shiwakoti et al., 2019; Shi et al., 2019), and wall-following behaviour (Isobe et al., 2004). However, most of these studies were conducted in normal visibility condition and pedestrian behaviour under adverse sight was not fully investigated and understood.

Wall-following behaviour has been identified as one of the most common pedestrian way-finding strategies in an unfamiliar environment, especially under limited visibility conditions from power outage or smoke (Jin and Yamada, 1985; Fridolf et al., 2013). There are two possible reasons for this behaviour, as revealed in studies of wall-following animals (Dussutour et al., 2005; Cowan et al., 2006). First, walls can provide a structural guideline to orient pedestrians in locating exits, because common sense tells people that exits are in the walls. Thus, people believe that following the wall will guarantee that they can eventually find an exit, though this approach may be less effective. Wall-following manoeuvre can also help people retrace their steps quickly, especially in low-visibility environmental conditions. Second, walls can serve as support for pedestrians when they are walking or running so as to protect them against potential dangers.

Although wall-following behaviour has been considered in several pedestrian evacuation models (Isobe et al., 2004; Nagatani and Nagai, 2004; Guo et al., 2012; Xue et al., 2016), empirical and experimental results are still scarce. Moreover, many underlying mechanisms of wall-following behaviour especially with respect to people's decision-making aspects are still unexplored. To these ends, we performed evacuation experiments in a mock room to investigate pedestrian wall-following behaviour under limited visibility. Three related questions are answered by the experiment, including how pedestrians approach a wall, how they decide on a wall-following direction, and how they address conflicts under limited visibility condition. Finally, we propose a wall-following model based on the social force model to reproduce pedestrian wall-following behaviour in limited visibility condition.

The remainder of this paper is organized as follows: section 2 presents a review of related work. It is followed by a description of the experiment in section 3 and a discussion of the experimental results in section 4. A simulation model based on the social force model is presented in section 5, and the simulation results are analysed in section 6. Conclusions are given in section 7, elaborating the original contributions and limitation of the findings of this study.

## 2. Related work

Under normal visibility, pedestrians perceive most external information through vision (Hussein and Sayed, 2017). However, when visibility is limited their walking behaviour during evacuation are significantly different. People may become disoriented because they are unable to see the exits or other individuals clearly. In the experiment of Isobe et al. (2004), it was observed that pedestrians tended to touch the wall first and then follow the wall to find the exit. It was also found that pedestrians seldomly change their walking direction before they touched the boundaries. Later, Guo et al. (2012) performed a set of similar experiments in a classroom with internal obstacles (desks, chairs, etc.) to study the route choice of pedestrians during evacuation under good and zero-visibility conditions. It was found that pedestrians always tried to minimize the distance to the exit in their route choices, under either good or zero-visibility conditions. For zero visibility situation, pedestrians generally followed other people in front whom they could touch or feel. A similar experiment was carried out by Cao et al. (2015) in which the typical characteristics of wall-following behaviour in a blind evacuation were investigated in detail. In their experiments, pedestrians tried to touch the wall with their hand(s). Their preferences of wall-following direction after they first touched the wall were analysed. Results indicated that most pedestrians chose to follow the wall with their right hands touching the wall. When conflicts occurred, i.e., pedestrians encountered another pedestrian moving in the opposite wall-following direction, the pedestrians preferred their own direction rather than deferring to the other person. Jeon et al. (2011) conducted an evacuation experiment under four different visibility conditions in an underground facility with 125 participants. The results indicated that when visibility was reduced, participants were inclined to move more closely along the walls. Wall-following behaviour was also found to be an important way-finding tool by Fridolf et al. (2013), who performed an evacuation experiment inside a tunnel filled with artificial smoke. In the work of Zeng et al. (2018), the influence of visibility on pedestrian merging behaviour during stair descent process was experimentally studied. Their results showed that the reduction of visibility would result in a decline in densities and velocities of the pedestrians from the floor.

In Table 1, we summarized the related experimental studies in regard to the researchers, experimental scenario, visibility condition, method to create the visibility condition and simulation model. According to visibility conditions, the experimental studies can be grouped into two categories, namely zero visibility (participants could see nothing by wearing opaque eye-patch) and limited visibility (participants could observe the surroundings in a restricted range with eye-patch, glasses or artificial smoke). Most experiments were conducted in classrooms, and others were conducted in hotel, supermarket and a mock corridor.

Simulation models such as cellular automaton model (CA), lattice gas model (LG) and social force model (SF) were also adopted to reproduce the experimental results. In the work of Isobe et al. (2004), the LG model was extended to simulate pedestrian evacuation under zero visibility, the model is proven capable of identifying the probability distribution of escape times in a dark room. Guo et al. (2012) proposed a CA model to formulate the effect of seats on the capacity of aisles of the classroom and to capture the following behaviour (pedestrians following the boundaries of obstacles and other pedestrians around them) during an evacuation event under zero visibility condition. In the work of Liu et al. (2019) a finer discrete and stochastic floor field CA model was adopted to investigate the impact of visibility on the evacuation process on stairs. The results showed the reduction of visibility would have a remarkable negative influence on the evacuation process on stairs. To mimic the conflict-resolving behaviour of pedestrians in bi-directional flow under limited visibility condition, Guo et al. (2016) modified the driving force of SF model by introducing a turning mechanism and the right-side preference. The spontaneous lane formation observed under limited visibility was successfully reproduced with the improved model.

The previous studies confirmed that wall-following behaviour was important in pedestrian way-finding during evacuation without visibility (Isobe et al 2004, Guo et al. 2012, Cao et al. 2015). However, the wall-following behaviour under limited visibility condition was not well understood and a practical simulation model with explicit rules that can be used to mimic the wall-following behaviour was still needed.

Compared with the previous studies regarding pedestrian evacuation in zero or limited visibility, the main contributions of this study can be summarized as follows.

(1) The wall-following behaviour of pedestrian during an evacuation under limited visibility was experimentally investigated, which was not well understood in the literature;

(2) The experimental findings revealed the underlying patterns of pedestrians on the decision of wall-following direction under limited visibility, which was not examined by the previous empirical studies;

(3) A practical wall-following model based on the SF model was proposed that can be used to mimic the wall-following behaviour of pedestrians during evacuation under limited visibility condition, which was scarce in the literature;

(4)A guidance plan for pedestrian evacuation was proposed and it was verified by the calibrated wall-following model that could significantly facilitate the evacuation process under limited visibility condition.

Table 1. Summary on the literature about visibility of pedestrian evacuation

| Work/Study | Experimental scenario | Visibility condition | Methods to limit visibility | Simulation model |
|---|---|---|---|---|
| Isobe et al. (2004) | Classroom without internal obstacles | Zero | Eye-patch | LG |
| Nagai et al. (2004) | Classroom without internal obstacles | Zero | Eye-patch | LG |
| Guo et al. (2012) | Classroom with internal obstacles (desks, chairs, etc.) | Zero | Eye-patch | CA |
| Shen et al. (2014) | Classroom with internal obstacles | Zero | Eye-patch | None |
| Cao et al. (2015) | An empty room without internal obstacles | Zero | Eye-patch | CA |
| Kobes et al. (2010) | Hotel | Limited | Artificial smoke | None |
| Jeon et al. (2011) | Underground facility | Limited | Eye-patch | None |
| Fridolf et al. (2013) | Railway tunnel | Limited | Artificial smoke | None |
| Guo et al. (2016) | Ring-shaped corridor | Limited | A hat with a towel fastened in the front | SF |
| Cao et al. (2018) | Supermarket | Limited | Glasses | Floor field CA |
| Cao et al. (2018) | Ring-shaped corridor | Limited | Glasses | None |
| Zeng et al. (2018) | Stair in university | Limited | Glasses | None |
| Chen et al. (2019) | Stair | Limited | Eye-patch | None |
| Liu et al (2019) | Stair | Limited | Illumination | Stochastic floor field CA |

## 3. Experimental setup

The evacuation experiment was conducted in an open outdoor area in Beijing Jiaotong University in Beijing, China. The total width of the scenario was W=6.8 m and its length was L=10.0 m. The participants were 30 college students (16 females and 14 males) between 20 and 26 years of age. As shown in Fig. 1, the experiment site was a mock room formed by 28 desks, each of which was 1.2 m, 0.4 m and 0.8m in length, width and height. Using desks to form the boundary of the experimental scenario is a very common practice in the research field of pedestrian behaviour. In this study, we used the desks to form the boundary of a room to investigate pedestrian wall-following behaviour. Considering the size and weight of the desks, we believed it is acceptable to serve as a compensation of a wall in this study.

To create a limited visibility condition, each participant wore a baseball cap with two layers of opaque veil covering, as shown in the top left corner of Fig. 1. This method has been used by Guo et al. (2016) to investigate the counter flows of pedestrians under a limited visibility condition. Due to the two layers of veil, participants could see nothing if directly looking ahead. When they lowered their heads and looked down the floor, the gaps in the brim of the baseball cap could enable participants to observe things within a certain distance. The available vision field scope for the cap was measured. Participants who wear this kind of cap could see 50 to 80 cm away from their heels.

As shown in Fig.1, the exit was formed by removing a desk in the left boundary of the room. As shown in Fig.2, we designed four exits along the boundaries of the room ($A_1$, $A_2$, $B_1$ and $B_2$) and the width of each exit was equal to the length of a desk (1.2 m). We used one of the exits to let a certain number of participants enter the room and then closed the exit. Participants in the room were required to put their veils on and turn round a circle several times before the experiment started. At the same time the supervisors of the experiment created the exit(s) by removing one or two desks from the boundary to form different exit layouts. Thus, each participant was unaware of the number and position(s) of the exit(s) until he or she finished the evacuation, which minimizes the memory effect and cumulative learning behaviour of participants.

In total, we performed 12 trials of this experiment under different scenarios with different numbers of participants. For each trial of the experiment, the number of participants and exit layout were presented in Table 2. Note that Table 2 is not listed in the order the experiments were performed. To minimize the memory effect and cumulative learning behaviour of participants, the experimental trials were scrambled.

Fig. 1. A snapshot of the experiment

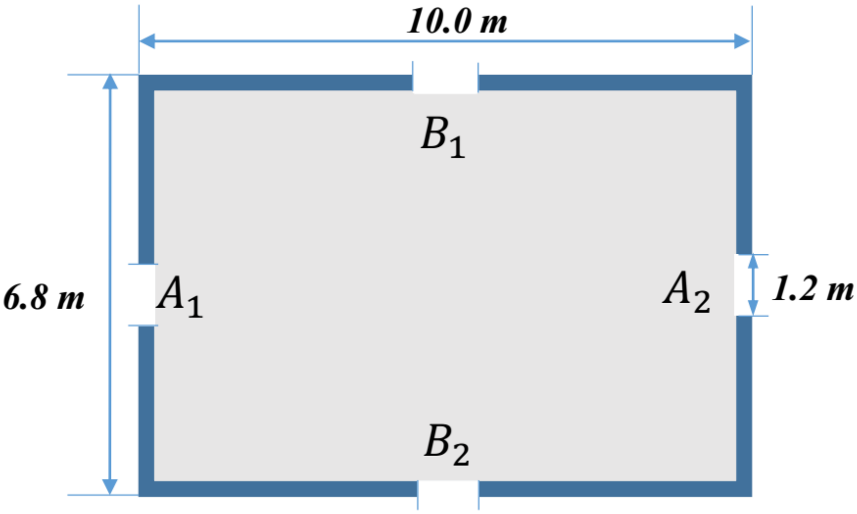


Fig. 2. Scenario setup of the experiment

Table 2. Design of the different experiment scenarios

| Trial | Scenario (exits were adopted) | Participant number |
|---|---|---|
| 1 | Single exit (A1) | 15 |
| 2 | Single exit (A2) | 15 |
| 3 | Single exit (A1) | 30 |
| 4 | Single exit (A2) | 30 |
| 5 | Opposite exits (A1, A2) | 15 |
| 6 | Opposite exits (A1, A2) | 15 |
| 7 | Opposite exits (A1, A2) | 30 |
| 8 | Opposite exits (A1, A2) | 30 |
| 9 | Adjacent exits (A2, B1) | 15 |
| 10 | Adjacent exits (A1, B2) | 15 |
| 11 | Adjacent exits (A1, B1) | 30 |
| 12 | Adjacent exits (A2, B2) | 30 |

The evacuation experiments proceeded as follows.

(1) The participants entered the room and randomly took their places. To obtain a quasi-uniform distribution, the experimenters made some adjustments to their positions.

(2) The participants were asked to put their veils on. To prevent the participants from basing their orientation on their memory of previously observed environmental information, they were instructed to turn in a circle three times clockwise and three times anticlockwise before starting to walk. The participants were required to be as quiet as possible during this step, in part to reduce environmental influence on other participants. The exits were created by removing one or two desks from the boundary in accordance with the designed scenario. To minimize the effect that the noise caused by removing desks might enable participants to hear where exits were created, the experimenters were instructed to quietly remove the desks at the same time when the participants were turning in a circle.

(3) Once they had finished turning around, the participants began to look for the exit(s) and tried to escape as soon as possible. The participants were not allowed

to talk or communicate with the others. Besides, the participants were not allowed help others in other ways.

(4) After all participants had left the room or the evacuation time exceeded the 5-minute cut-off time (the experiment was considered a failure if participants were not able to evacuate within 5 minutes), the experimental trial ended.

The experiment was recorded by a video camera fixed on a tripod on the fourth floor of a building next to the experimental area. The camera was adjusted to cover the whole scene, as shown in Fig. 1.

The pixel coordinates of each participant's movement were extracted from the video using the Tracker software (http://physlets.org/tracker/). Because the video camera was not perpendicular to the experimental area, pixel coordinates were transformed into real world coordinates using a direct linear transformation technique based on Wolf and Dewitt (2000). For a detailed description of this method for pedestrian trajectory tracking, we refer interested readers to Shiwakoti et al. (2015).

## 4. Experimental results

Twelve trials of the experiment were performed, and each participant took part in nine on average. Thus, we obtained N=270 individual cases. All the trials were finished within the 5-minute cut-off time. We analysed the behaviour pattern of each participant in each individual case and tried to answer the following three questions: i) how did the participants find the wall and determine their wall-following direction in the limited vision condition? ii) what was the difference in their walking speed before and after finding the wall? And iii) how did they respond to conflict cues during the wall-following process?

### 4.1 How did participants find the wall and determine the wall-following

**direction?**

Two behavioural patterns were observed during this process: the participants stretched out their arms and searched for the wall with their hand(s) in 205 of 270 cases (76%), and in the remaining 65 cases (24%) participants made a visual search for the wall rather than by stretching out their arms, as shown in Fig. 3. Moreover, the results indicate that in cases in which the participants attempted to touch the wall, 61%, 19%, and 20% of them stretched out their right arm, left arm, or both arms, respectively. During the experiment, all the participants could see things in a restricted distance due to the opaque veil, which means all the participants could make a visual search for the wall. The reasons why most participants stretched out their arms to search for the wall was that with outstretched arms and hands, they could extend their perceptual ranges to find the boundaries more quickly and also outstretched arms provided effective protection from direct collision with walls or other pedestrians. Furthermore, as Fig. 3 shows, in touching cases 61% of participants attempted to touch the wall with their right hands, possibly because of right-handedness.

The method each participant used to find the wall largely determined the direction in which they followed the wall. As Fig. 3 shows, in cases in which the participants attempted to touch the wall with their right hand, 85% followed it in an anticlockwise direction. For cases in which the participants attempted to touch the wall with their left hand, 82% followed the wall in a clockwise direction. For cases in which the participants used both hands, the following direction depended mainly on which hand touched the wall first; that is, if the right hand touched the wall, they followed the wall in an anticlockwise direction; if the left hand touched the wall, they followed the wall in a clockwise direction. The results indicate that more than half of the participants (60%) selected the anticlockwise wall-following direction, and 28% were the “lucky” cases who found the exits directly without following the walls.

When the participants attempted to catch sight of the walls instead of touching them, we observed that their wall-following direction mostly depended on their position when first sighting the wall. The participants would usually turn in a convenient direction to follow the wall (in 78% of cases). For example, in the situation illustrated in Fig. 4, if participant 1 and 2 sight the wall at the current positions, participant 1 will turn to follow the wall in the anticlockwise direction, and participant 2 will turn to follow the wall in the clockwise direction. Moreover, in approximately 22% of cases, the participant tried to touch the wall when they caught sight of it, and thus his or her wall-following direction depended on which hand was nearer to the wall.

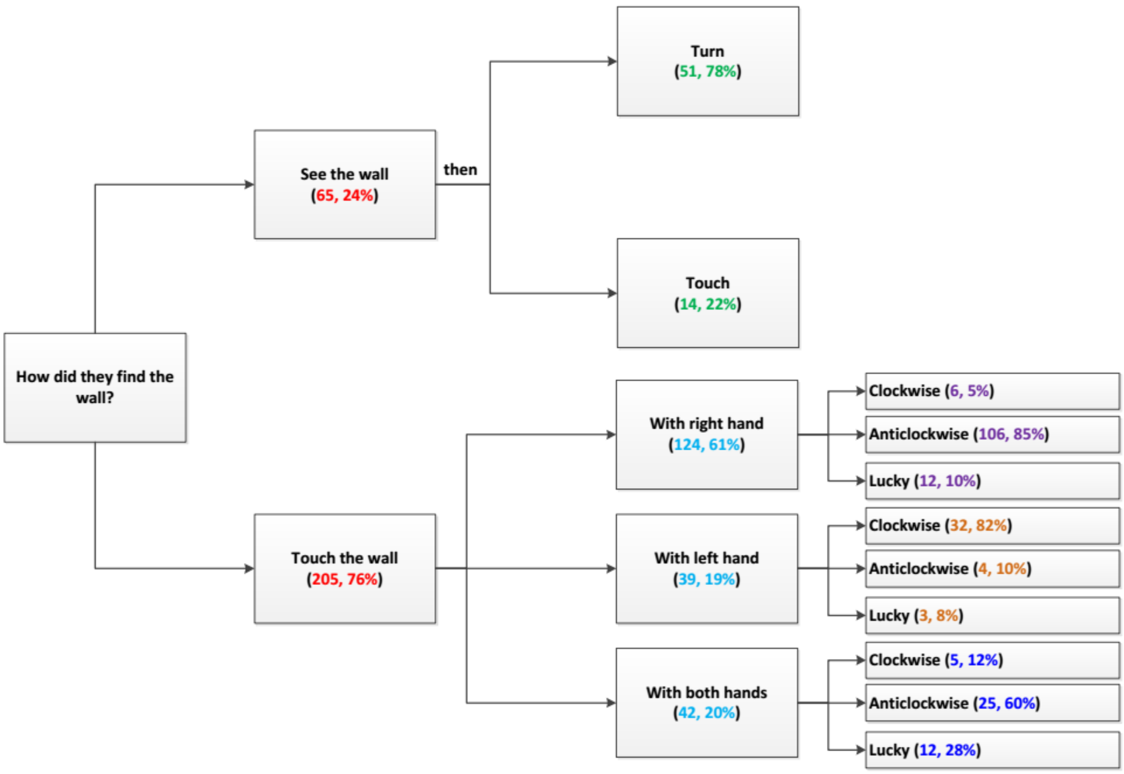


Fig. 3. Summary of the methods participants used to find the wall and determine the wall-following direction.


Fig. 4. Decision on wall-following direction for a participant who has just seen the wall. The red arrow represents the walking direction of the participant who has just seen the wall, and the green arrow represents his/her wall-following direction.

### 4.2 Movement speed before and after participants found the wall

Intuitively, we expected that the participants' movement speed after they touched the wall would be slightly higher than before touching the wall. We sampled and measured the movement speed of each participant from the experimental trials (in total N=231cases) and results are presented in Fig. 5. It was found that participants' movement speed after they touched the wall ($v_i^A$) was usually slight higher than before touching it ($v_i^B$). As given in Table 3, $v^A$ and $v^B$ can be approximated by a normal distribution with means (±standard deviation) of 0.52 m/s (±0.13) and 0.62 m/s (±0.16), respectively.

Table 3. The speeds before and after participants found the wall (N=231cases)

| Velocity | Mean | Standard deviation | Kolmogorov-Smirnov goodness-of-fit |
|---|---|---|---|
| Before | 0.52 | 0.13 | p=1.0 |
| After | 0.62 | 0.16 | p=0.81 |

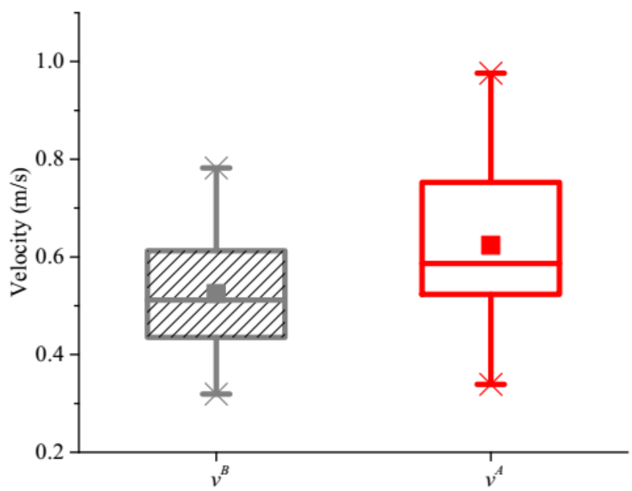


Fig. 5. Speed of participants before and after they found the wall **(N=231cases).**

### 4.3 Interactions in the wall-following process

The results indicate that participants tended to maintain a certain walking direction and were less affected by others before they found the wall, which seems to be an optimal strategy to find the wall. During the wall-following process, conflicts occurred, and most fell into two categories, which can be labelled type A and type B.

Type A: conflicts between a participant who is following the wall and another participant just finding the wall.

Type B: conflicts between two wall-following participants with different wall-following directions.

Fig. 6 summarizes the participants' responses to the two types of conflicts. The frequencies of the two strategies for each type of conflict are summarized in Table 4.

For type-A conflicts, more than 80% (44 of 54 cases) were resolved by the "following" strategy: the participant who had just found the wall followed the direction of the conflicting participant who was already following the wall.

For type-B conflicts, fewer than 20% were resolved by the "following" strategy. Most of these conflicts were resolved by an "insisting" strategy, i.e., the participants who were in conflict insisted on their own wall-following direction. Cooperative behaviour was then observed, in which one participant stopped, and the other went around them by briefly moving away from the wall.

Fig. 7 summarizes the participants' wall-following directions when they first touched or saw the wall and when they eventually exited the room. The findings demonstrate that the changes are much smaller for the two-opposite-exits scenario. Thus, we can conclude that fewer conflicts occurred in the two-opposite-exits scenario than in the other two scenarios.

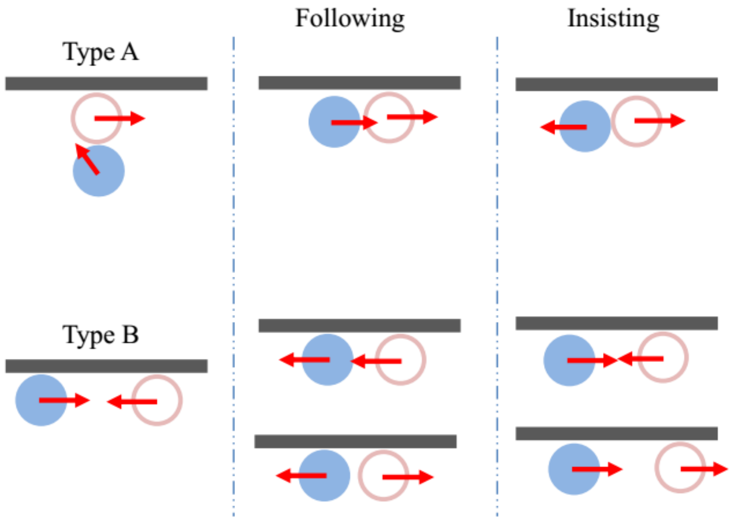


Fig. 6. The possible responses of one participant (represented by the solid blue circle) in the two types of conflict ("following" or "insisting" in response, regardless of the other participant's response)

Table 4. The frequencies of the two strategies used in the two types of conflict.

| Type | Total | Following | Insisting |
|---|---|---|---|
| A | 54 | 44 (81.5%) | 10 (18.5%) |
| B | 90 | 17 (18.9%) | 73 (81.1%) |

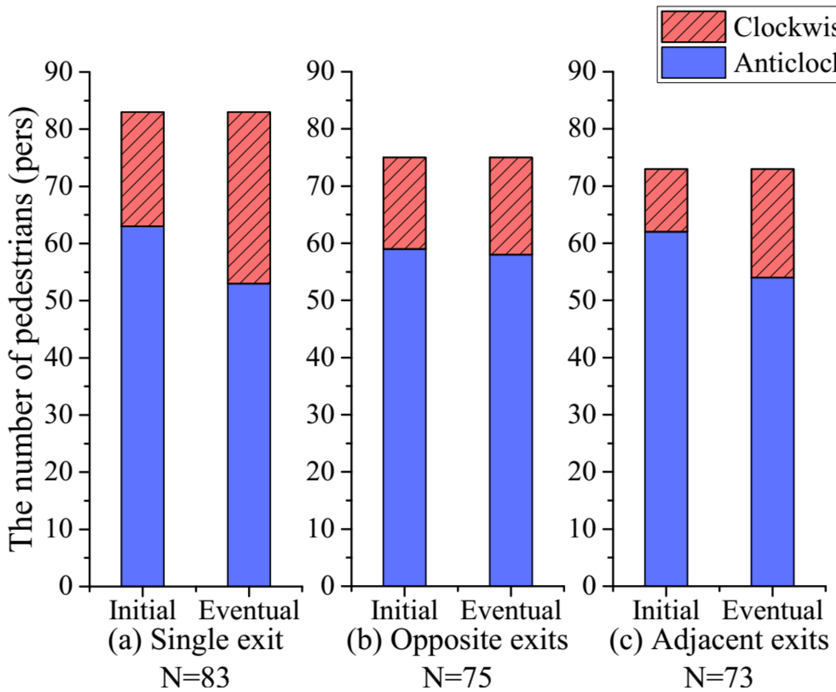


Fig. 7. Summary of the wall-following directions. Initial: the wall-following direction when a participant first touched/observed the wall. Eventual: the wall-following direction when a participant exited the room.

### 4.4 Comparisons of results from different visibility conditions

(1) Comparison with the experiments under normal visibility condition

After the experiment, we repeated the experimental trials listed in Table 2 under the normal visibility condition to provide a direct comparison with the evacuation process in the limited visibility condition. The normal experiment proceeded as follows. First, participants were asked to enter the room with eyes open and position themselves randomly, without wearing the veil. They were then required to close their eyes while the experimenters removed desk(s) from the exit(s). The participants then opened their eyes and were asked to leave the room as quickly as possible. The experimental trial stopped when all participants had left the room.

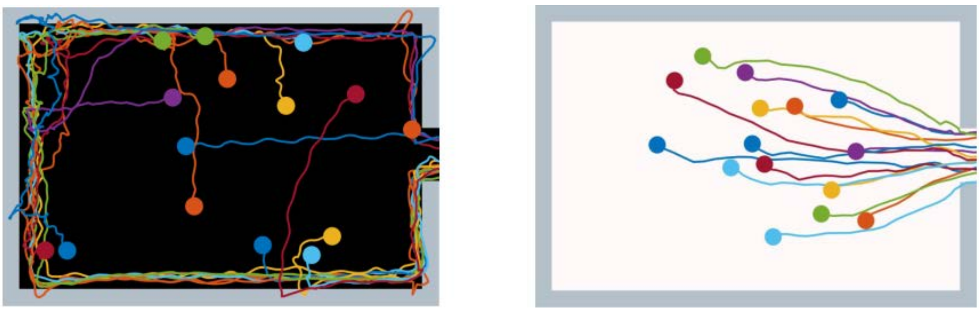

Fig. 8 A comparison of the evacuation trajectories of pedestrians under limited visibility condition (left) and normal visibility condition (right)

Fig. 8 shows distinct differences in the evacuation processes under the two visibility conditions. (i) Under the normal visibility condition, the participants first looked around for the exit when they opened their eyes, and then quickly moved to the exit. Under the limited visibility condition, after the participants finished turning around, they first moved slowly towards the boundaries of the room in the direction they were facing and seldom changed their searching direction before finding a wall. After finding the wall, they would follow it until they had found the exit and left the room. (ii) In the right panel of Fig. 8, one can see that the pedestrian movement trajectories are smooth under normal visibility condition. In the limited visibility condition, however, they involved many fluctuating movements, as shown in the left panel. One reason is that pedestrians had to lower and turn their heads around to look for walls when visibility was seriously reduced. Another difference is that pedestrians conflicted with each other frequently under the limited visibility condition and had to continually adjust their movements. Consequently, the total evacuation time (the time from the start of the evacuation to the time when the last participant left the room) under the limited visibility condition was significantly longer than that under the normal visibility condition, as shown in Table 5.

In addition, when the number of participants was increased from 15 to 30, the total evacuation time increased by only 26% under the limited visibility condition, while in the normal case it increased by 116%. The reason for this discrepancy is that under the limited visibility condition, most participants tried to find the exit by following the walls. The total evacuation time largely depended on the range of the walls rather than the number of participants. Under the normal visibility condition, however, participants would quickly gather around the exit, and congestion would thus form before the exit when the number of participants increased. Thus, the total evacuation time was primarily related to the width of the exit.

Table 5. The total evacuation times for the single-exit scenario under two visibility conditions (in seconds).

| | 15 participants | 30 participants | Rate of relative increase (%) |
|---|---|---|---|
| Limited | 56.32 | 71.10 | 26 |
| Normal | 5.75 | 12.42 | 116 |

The results are averaged over the trials with the same number of pedestrians for each experimental condition.

(2) Comparison with the experiments under zero visibility condition

The similarities and differences between the two previous experiments and our experiments are summarized in Table 6 and are analysed below in more detail.

- **Experimental scenarios.** The scenarios were similar in the three experiments (empty classroom without any internal obstacles), although the sizes of the rooms were different.
- **The visibility conditions**. In Isobe et al. (2004) and Cao et al. (2015), pedestrians had zero visibility for being required to wear opaque eye masks or glasses. Thus, all pedestrians had to stretch their arms to touch the wall, while in our experiment due to the limited visibility condition there was still a fraction of pedestrians who made a visual search for the wall rather than by stretching out their arms.
- **The movement speeds of the participants.** The movement speeds of the pedestrians under the limited visibility condition of our experiment were slightly higher both for the speed before and after finding the wall.
- **The decision process on wall-following directions**. In the work of Isobe et al. (2004), it was suggested that when pedestrians touching the wall they would like to select the anticlockwise or clockwise wall-following direction at random (50%,50%), while the statistical results from the experiment in Cao et al. (2015) and our experiments suggested that pedestrians showed a clear preference of choosing the anticlockwise direction. The proportions of selecting the anticlockwise direction in the experiment of Cao et al. (2015) and our experiment were 62% and 76%, respectively. Moreover, in our experiments we revealed a relationship between the wall-following directions and the hand usages when touching, which was not presented in the works of Isobe et al. (2014) and Cao et al. (2015): For the touching cases with right hand, 85% followed it in an anticlockwise direction and 15% followed in clockwise direction. For left-hand usage cases, 82% followed the wall in a clockwise direction and 18% followed in anticlockwise direction. This was

important to understand the underlying behaviour pattern of pedestrian on the decision of wall-following direction.

Table 6. Comparison with two experiments under zero visibility condition

| | | **Isobe et al. (2004)** | **Cao et al. (2015)** | **This study** |
|---|---|---|---|---|
| **Experimental setup** | Visibility condition | Zero | Zero | Limited |
| | Scenario | W=4.2m and L=5.5m | W=7m and L=8m | W=6.8m and L=10m |
| | Exit layout | Single exit | Single exit | Alterable exit layout |
| | Participants | 10 | 30 | 30 |
| | Repetitions | 10 | 2 | 6 |
| **Movement speed before and after finding the wall** | Before | 0.33* | 0.45 | **0.52** |
| | After | 0.33 | 0.56 | **0.62** |
| **How did pedestrians approach a wall?** | **Touching** | **100%** | **100%** | **76%** |
| | **Visual search** | **0%** | **0%** | **24%** |
| **How did pedestrians decide their wall-following directions in touching cases?** | **Anticlockwise** | **50%**** | **62%** | **76%** |
| | **Clockwise** | **50%** | **38%** | **24%***** |

*It did not distinguish between the speed before and after finding the wall in Isobe et al. (2004).

**The authors suggested that pedestrians would choose the anticlockwise or clockwise direction at random in the work of Isobe et al. (2004).

***27 “lucky” cases were excluded from the total 205 touching cases to make the comparison valid.

## 5. Model description

To reproduce the experimental results, we propose a wall-following model based on the social force model to reproduce the observed wall-following behaviour of pedestrians. The original social force model does not consider pedestrian’s wall-following behaviour and pedestrians are reflected when they hit the wall (Helbing et al., 2000). It was mentioned that the wall-following behaviour was incorporated into the social force model in the work of Isobe et al. (2004). However, to the authors’ best knowledge, such attempt was scarce in the literature. Thus, in this paper, we introduced a simple spring force to mimic the interactions between pedestrians and the walls. The related parameters were calibrated and validated using the experimental data. The simulation results of the pedestrian evacuation process were consistent with the experimental outcomes.

### 5.1 Visual fields

In the model, each pedestrian *i* is represented by a disk of radius $r_i$ and mass $m_i$ ($r_i = m_i / 320$) (Moussaid et al., 2011). Each pedestrian *i*'s position is denoted by the centre of the disk $\boldsymbol{x}_i$, and the pedestrian's walking velocity is denoted by $\boldsymbol{v}_i$.

Due to the limited visibility condition, pedestrians had to obtain information from a limited perceptual field. We have found that pedestrians' visual range was diminished to 50 to 80 cm under these experimental conditions. More specifically, due to the opaque veil, pedestrians had to lower their heads and look down at the floor. Thus, the visual field of the pedestrian can be approximately viewed as a circular field with a diameter of $D_i = d_i + d_i'$, as illustrated in Fig. 9, where $d_i$ is the forward visibility distance of pedestrian *i* (it is assumed to be uniformly distributed at the interval [50 cm, 80 cm] and $d_i'$ is the backward visibility distance). Measurements show that $d_i'$ is approximately 20 cm. In the proposed model, for simplicity, we set $d_i'$ equal to the radius of pedestrian *i*. Therefore, the centre of the visual field for pedestrian *i* can be obtained by formula (1):

$$\boldsymbol{C}_i = \boldsymbol{x}_i + \left(\frac{d_i - r_i}{2}\right)\frac{\boldsymbol{v}_i}{\left\|\boldsymbol{v}_i\right\|} \quad (1)$$

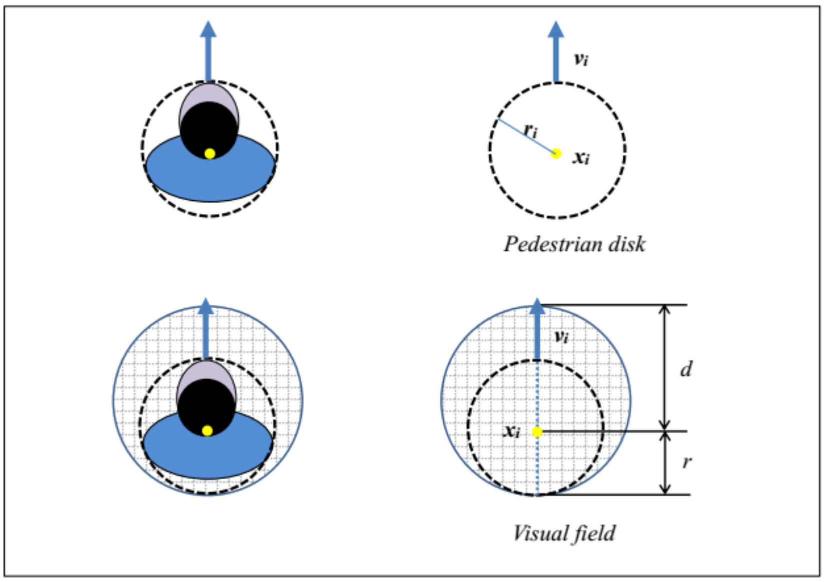


Fig. 9. Representation of the pedestrian and his/her visual field.

### 5.2 Social force model

In the social force model, pedestrian acceleration or deceleration is subjected to a set of social and physical forces $\boldsymbol{f}_i(t)$ (Helbing et al., 1995; Helbing et al., 2000):

$$m_i \frac{d\boldsymbol{v}_i}{dt} = \boldsymbol{f}_i(t) \quad (2)$$

$$\boldsymbol{f}_i(t) = \frac{m_i}{\tau}(v_i^d(t)\boldsymbol{e}_i - \boldsymbol{v}_i(t)) + \sum_{j \in \Omega_i} (\boldsymbol{f}_{ij}^s + \boldsymbol{f}_{ij}^p) + \sum_{W \in W_s} \varepsilon_W \boldsymbol{f}_{iW}^w \quad (3)$$

In Eq. (3), the first term describes the tendency for a pedestrian to approach his/her desired walking speed $v_i^d(t)$ in the desired direction $\boldsymbol{e}_i$, in a relaxation time $\tau$.

We use $\Omega_i$ to denote the set of other pedestrians *j* (*j*≠*i*) in the visual field of pedestrian *i*. The terms $\boldsymbol{f}_{ij}^s$ and $\boldsymbol{f}_{ij}^p$ are used to describe the psychological and physical repulsive effects of pedestrian *j* ( $j \in \Omega_i$ ) on pedestrian *i* and are given by:

$$\boldsymbol{f}_{ij}^s = A_i e^{(r_{ij} - d_{ij})/B_i} \boldsymbol{n}_{ij} \quad (4)$$

$$\boldsymbol{f}_{ij}^p = k_1 g(r_{ij} - d_{ij})\boldsymbol{n}_{ij} + \kappa_1 g(r_{ij} - d_{ij})\Delta v_{ji}^\tau \boldsymbol{t}_{ij} \quad (5)$$

where $r_{ij} = (r_i + r_j)$ is the sum of the radii of the two pedestrians, $A_i$ and $B_i$ are constants that account for the psychological repulsive force, $d_{ij} = \left\| \boldsymbol{x}_i - \boldsymbol{x}_j \right\|$ is the distance between them, $\boldsymbol{n}_{ij} = (\boldsymbol{x}_i - \boldsymbol{x}_j)/d_{ij} = (n_{ij}(1), n_{ij}(2))$ is the normalized vector pointing from pedestrian *j* to *i*, $\boldsymbol{t}_{ij} = (-n_{ij}(2), n_{ij}(1))$ is the normalized tangential vector of the two contacting pedestrians, and $\Delta v_{ji}^\tau = (\boldsymbol{v}_j - \boldsymbol{v}_i) \cdot \boldsymbol{t}_{ij}$ is the difference between their tangential velocities when in contact. $g(x)$ is zero if $x < 0$ and otherwise is equal to *x*.

We use $W_s$ to denote all walls in the scenario, and $\varepsilon_W$ = 1 or 0 to specify whether the wall *W* is in the visual field of pedestrian *i* or not. The term $\boldsymbol{f}_{iW}^w$ is used to model the repulsive effects of wall *W* on pedestrian *i*, and is specified as follows:

$$\boldsymbol{f}_{iW}^w = k_2 g(r_i - d_{iW})\boldsymbol{n}_{iW} + \kappa_2 g(r_i - d_{iW})(\boldsymbol{v}_i \cdot \boldsymbol{t}_{iW})\boldsymbol{t}_{iW} \quad (6)$$

where $d_{iW}$ denotes the closest distance from pedestrian *i* to wall *W*, $\boldsymbol{n}_{iW}$ is the normalized vector perpendicular to the wall, and $\boldsymbol{t}_{iW}$ denotes the normalized vector tangential to the wall. Note that we only considered physical interaction between pedestrians and walls, but did not allow for the psychological element, which will be addressed in the wall-following model outlined in the next section.

## 5.3 Wall-following model

### 5.3.1 Wall-finding patterns

The experimental results show that pedestrians searched for walls using two methods:

i. Pedestrians attempted to touch the wall with their arms outstretched. The total length of each arm is denoted by $l_{i,arm}$ for pedestrian *i*. In Fig. 10, pedestrian *j* illustrates the two arm positions observed during the experiment. : a) before touching the wall, the pedestrian stretched out one or both arm(s) nearly parallel to his or her walking direction; and b) after finding the wall, the pedestrian touched the wall with one hand with the arm perpendicular to the walking direction. In the model, we will calculate and judge whether the arm(s) intersect(s) with the boundaries of the wall by considering the direction and length of the arm(s) at each time step of the simulation. If the arm intersects with the boundary of the wall, the pedestrian will be categorized into those who have touched the wall and their walking direction will be adjusted to follow the wall. In the simulations it is assume that the proportion of pedestrians who attempt to touch the wall is $\alpha_{touch}$. The proportions of pedestrians who use their right/left/both arms to search for the wall are set as $\beta_r, \beta_l, \beta_b$, respectively, and the probabilities of following the wall anticlockwise after touching it are set as $p_{cr}, p_{cl}, p_{cb}$, respectively.

ii. Pedestrians who attempted to catch sight of the wall are illustrated by pedestrian *i* in Fig. 10. The proportion of these pedestrians is $\alpha_{seeing}$. In the model, it is assumed that when a pedestrian sees the wall, he or she will turn to follow the wall in a convenient direction, as illustrated in Fig. 4.

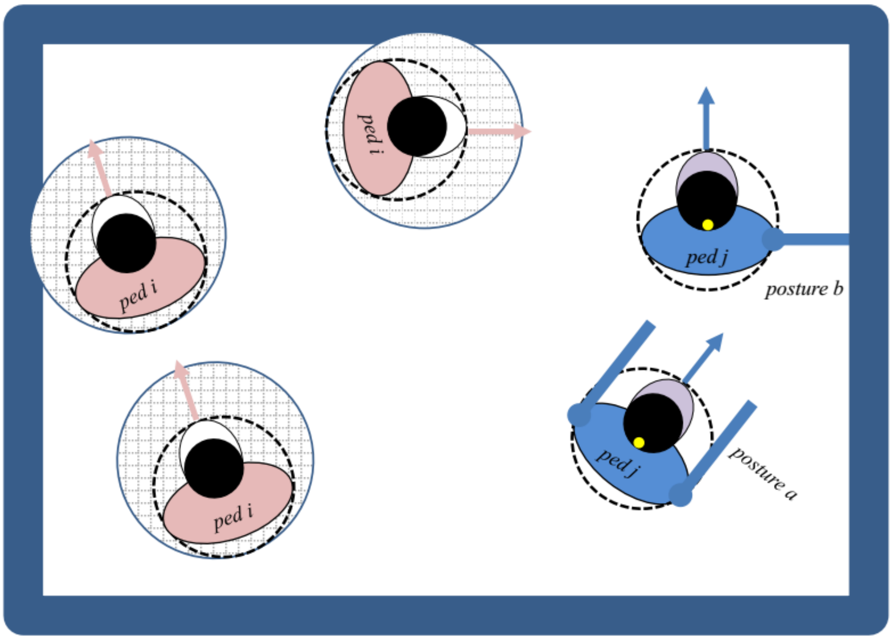


Fig. 10. Illustrations of how pedestrians find the wall. Pedestrian *i* attempts to catch sight of the wall and pedestrian *j* attempts to touch the wall.

#### 5.3.2 Desired distance to the wall

When they start to follow the wall, pedestrians tend to keep a desired distance from the wall to walk comfortably without losing contact with it (by touching or seeing). To model this pattern, we introduce a spring force term to mimic the attractive effect of the wall on a wall-following pedestrian:

$$\boldsymbol{f}_{iW}^{s} = k_s m_i (S_d - d_{iW}) \boldsymbol{n}_{iW} \quad (7)$$

where $S_d$ is the desired distance to the wall and $k_s$ is a constant. In the simulation, we set $S_d$ equal to $r_i$ and added a buffer distance of 0.05 m.

#### 5.3.3 Interaction behaviour

As discussed in section 3, the conflicts in the wall-following process can be divided into two types and are mainly resolved by the “following” or “insisting” strategy.

For type-A conflicts, we assume that the pedestrian will follow his or her neighbour's wall-following direction with a probability of $p_f$.

For type-B conflicts, we simply assume that the pedestrian will insist on his or her wall-following direction with a probability of $p_i$.

In the simulations, the values of $p_f$ and $p_i$ were given in accordance with the experimental results.

5.3.4 Coordination behaviour

(1) Uni-directional interactions

Uni-directional interactions are between a faster wall-following pedestrian and a slower leading wall-following pedestrian. As Fig. 11 shows, in the experiment we observed that the faster pedestrian usually chose to reduce his or her walking speed to follow the leading pedestrian and seldom chose to overtake. This assumption was set in accordance with the observations in the experiment. It was seldom observed that a participant intended to overtake the leading pedestrian even the leading pedestrian walked slower than him (her). The reason behind this might include two aspects: 1) The intention to overtake was not strong because the speeds difference was small when both of them were walking following the wall in the same direction; 2) If the latter overtook the leading pedestrian, he would lose the contact with the wall in touch and might also lose eye contact with the wall. This might put him at a disadvantage.

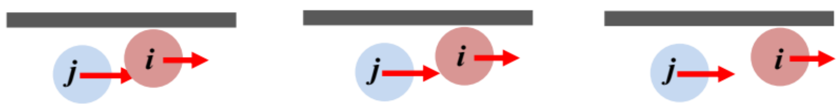


Fig. 11. Uni-directional interactions between faster pedestrian and slower leading pedestrian

(2) Bi-directional interaction

Bi-directional interactions involve two wall-following pedestrians with opposite wall-following directions who both choose the "insisting" strategy.

In the experiment, we observed another coordination behaviour between pedestrians when bi-directional conflicts occurred. As illustrated in Fig. 12, when two wall-following pedestrians *i* and *j* encountered each other (observed or felt each other's), the one nearer to the wall (pedestrian *j*) would slow down and the one farther away from the wall (pedestrian *i*) would move away from the wall and then return to following the wall.

To simulate this phenomenon, we use an evasive force (illustrated in Fig. 13) and a coordination-decision algorithm (Algorithm 1) in the model to mimic the cooperative behaviour of the conflicting pedestrians.

The evasive force exerted on pedestrian

$$f_i^e = m_i a \boldsymbol{e}_{ie} \tag{8}$$

$$a = \frac{s - v_i^{\perp}\Delta t}{0.5\Delta t^2} \tag{9}$$

$$\Delta t = \max(TC, \tau) \tag{10}$$

where $a$ is the desired acceleration, $\boldsymbol{e}_{ie}$ is a unit vector of pedestrian *i*'s evasion direction, $d_{ij} = \left\| \boldsymbol{x}_i - \boldsymbol{x}_j \right\|$, $\boldsymbol{n}_{ij} = (\boldsymbol{x}_i - \boldsymbol{x}_j)/d_{ij}$, $v_i^{\perp}$ is the component of $\boldsymbol{v}_i$ in the evasive direction perpendicular to the wall, $v_i^{-}$ is the component of $\boldsymbol{v}_i$ in the direction tangential to the wall, $s = d_{jW} + r_j - d_{iW} + r_i$ is the minimum distance that pedestrian *i* has to move in the evasive direction within time $\Delta t$, and $\tau$ is the relaxation time. In Eq. (9), we assumed that pedestrian move distance $s$ at a constant acceleration $a$. In Eq. (10), $TC = (d_{ij}\left\| v_j^d \right\| \cos < \boldsymbol{n}_{ij}, \boldsymbol{v}_j > -(r_i + r_j)) \Big/ (\left\| v_j^d \right\| + \left\| v_i^- \right\|)$ is the time to collision between pedestrian *i* and *j* in the direction parallel to the wall, as shown in Fig.13. Therefore, Eqs. (9) and (10) were used to depict that pedestrian *j* tended to move a minimum distance *s* away from the wall before he/she collided with pedestrian *i*.

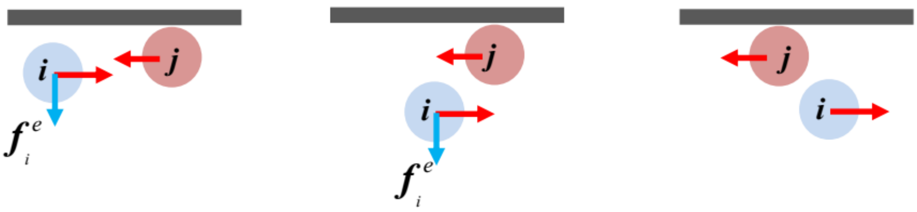


Fig. 12. Coordination behaviour of pedestrians in bi-directional interactions.

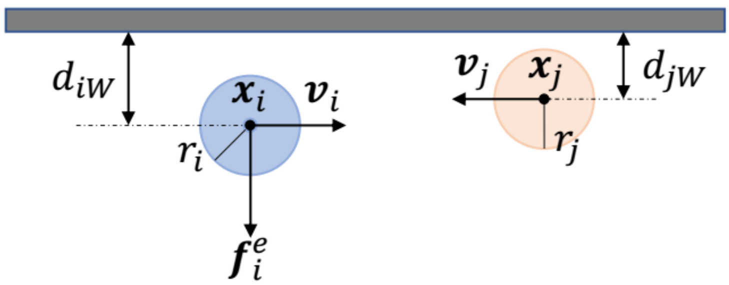


Fig. 13. Illustration of the evasive force.

In Algorithm 1, Line 2 indicates that the two pedestrians will collide and that pedestrian *i* is farther away from the wall than pedestrian *j*; Line 3 indicates that pedestrian *i* tends to slow down in the wall-following direction and will be free of other psychological forces when evading pedestrian *j*; Line 5 indicates that pedestrian *j* will remain still until the evasion process of pedestrian *i* is completed.

In the evading process, we assumed that when a pedestrian was in collision his/her urgent task was to evade, so he/she might not care about the psychological forces at that moment.

Fig. 14 presents an example of the simulated coordination process between two wall-following pedestrians. One can observe that pedestrian 1 first moved away from the wall driven by the evasive force and then returned to following the wall, driven by the wall's attractive force.

**Algorithm 1 Coordination Decisions**

1: **if** *ped i* sees *ped j* is following the wall in front of him in the opposite direction, **then**

2: **if** $d_{iw} + r_i > d_{jw} + r_j > d_{iw} - r_i$, **then**

3: [***ped i* evades**] set $v_i^d(t)$ =0.8 $v_i^A$ and evasive force is exerted according to Eqs.(8)-(10); pedestrian *i* is free of other psychological forces, namely $\sum_{j \in \Omega_i} \boldsymbol{f}_{ij}^s$=0 and $\boldsymbol{f}_{iw}^s$ =0.

4: **if** *ped j* sees *ped i*, and $d_{iw} + r_i > d_{jw} + r_j > d_{iw} - r_i$ **then**

5: [***ped j* slows down**] set $v_j(t)$ =0 at the current time.

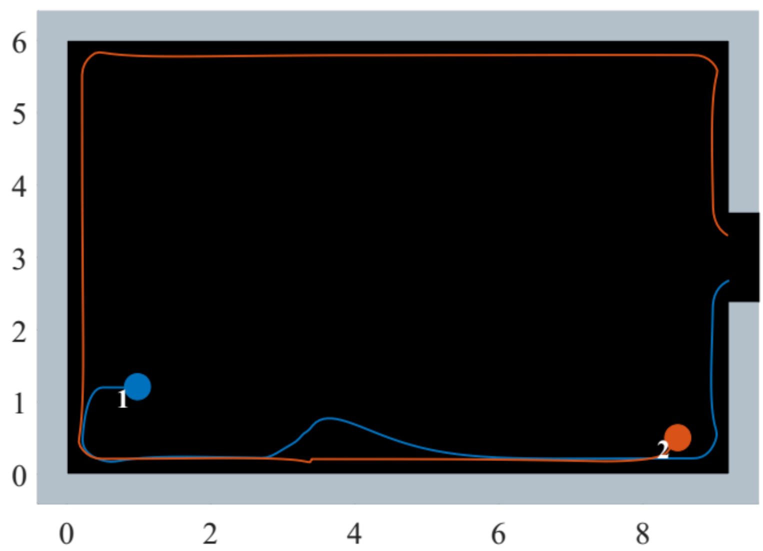


Fig. 14. Simulated coordination process between two wall-following pedestrians.

## 6. Simulation results

To use the proposed model, the parameters were first calibrated and validated based on the experimental data. Next, correlations between the pedestrians' wall-following behaviour and evacuation efficiency were investigated with the calibrated simulation model. Finally, a simple guidance plan was developed and its impact on evacuation efficiency was examined.

### 6.1 Parameters selection

Parameters used in the simulation model can be grouped into two types: measurable and non-measurable. Measurable parameters can be directly measured or estimated from the experimental data, reflecting the basic attributes of a pedestrian or basic characteristic of pedestrian movement, such as the pedestrian's mass, walking speed and visibility. Fourteen such parameters are presented in Table 7. Table 8 summarizes six parameters of the second type that cannot be directly measured or estimated. It is worth noting that parameters $B_i$ and $\tau$ were respectively set as $B_i$=0.08$m$ and $\tau = 0.5s$, which are values that have been widely adopted in previous studies (Helbing et al., 2000; Parisi and Dorso, 2005) and validated by empirical data (Li et al., 2015). The rest of the non-measurable parameters were the strength coefficient of psychological repulsive force $A_i$, strength coefficient of body compression force $k_1$, strength coefficient of sliding force $\kappa_1$, and strength coefficient of the spring force $k_s$. To find an optimum set of these four non-measurable parameters, a genetic algorithm (GA) was used. The goal of GA is to minimize individual evacuation time error between the experiment and the simulation. The fitness function is defined as follows:

Minimize:
$$RMSE = \sqrt{\frac{1}{N}\sum_{\mathrm{i=1}}^{N}(t_i^s - t_i^e)^2} \quad (11)$$

Subject to:
$$0 < A_i < 2000N \quad (12)$$
$$0 < k_1 < 5000kg / s^2 \quad (13)$$
$$0 < \kappa_1 < 5000kg / (m \cdot s) \quad (14)$$
$$0 < k_s < 10N / (\mathrm{kg \cdot m}) \quad (15)$$

In Eq. (11), *RMSE* is the root mean square error between the simulated results and the experimental results, $t_i^s$ is the individual evacuation time of pedestrian *i* in the simulation, $t_i^e$ is the corresponding evacuation time of pedestrian *i* in the experiment, and *N* is the total number of pedestrians. We used trial 3 of the experiment (it has the greatest number of participants and the longest total evacuation time, which means there were plenty of the interactions among pedestrians and interactions between pedestrians and walls to calibrate the model parameters) to calibrate these model parameters and the remainder of the trials to validate them. In calibration and validation, the initial settings of the proposed model were set the same as in the corresponding experimental trail in terms of the scenario, start points of each pedestrian, initial velocities of each individual, and their characteristics in searching the wall and desired walking speed. Other measurable parameters listed in Table 7 were used as input to reproduce the experimental trial as closely as possible.

For the GA settings, the population size was specified as 30 and the maximum number of iterations was set as 100. For other settings, we used the default settings of the Optimization Tool for GA in MATLAB 2016b. The calibrated values of the parameters were $A_i = 478.03N$, $k_1 = 2660.82kg/s^2$, $\kappa_1 = 1534.40kg/(ms)$ and $k_s = 1.43N/(kgm)$, with the minimum of *RMSE* = 6.7 s. In validation, Mean Absolute Percentage Error (MAPE) between the simulated evacuation time and experimental evacuation time were also adopted to assess the calibrated parameters. The results show that the optimal parameters were robust in dealing with different scenarios and different crowd sizes, with the *RMSE* ranging from 1.5 s to 5.8 s and *MAPE* ranging from 0.10 to 0.16.

$$MAPE = \frac{1}{N}\sum_{i=1}^{N}\left|\frac{t_i^e - t_i^s}{t_i^e}\right| \tag{16}$$

Fig. 15 compares the wall-following trajectories in the experimental results and the simulation outputs. Each pedestrian's starting position is marked by a solid coloured circle, and the trajectory is shown by a solid line with the same colour. The results indicate that the trajectories from the experiment show more fluctuations, which might be due to the extraction method. We extracted pedestrian trajectories with a focus on their heads, which might involve many fluctuating movements. In addition, the trajectories of the experiment were extracted half manually and half automatically with Tracker software. Nonetheless, the proposed model can well reproduce the wall-following patterns of pedestrians under the limited visibility condition. The wall-following directions of each pedestrian can also be identified from the trajectories.

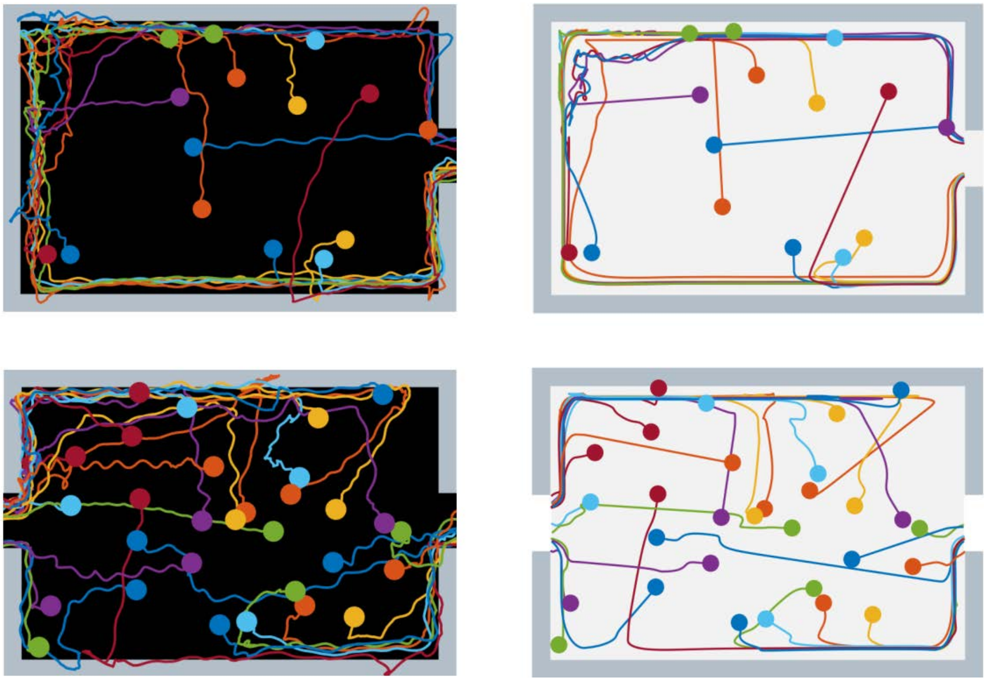

Fig. 15. Wall-following trajectories from the experiment (left) and simulation (right).

Table 7. Parameters for the basic characteristics of pedestrians.

| Parameters | Definition | Value |
|---|---|---|
| $m_{i,1}$ | Mass of a male individual | U (60 *kg*, 80 *kg*) |
| $m_{i,2}$ | Mass of a female individual | U (50 *kg*, 65 *kg*) |
| $v_i^B$ | Moving speed before finding the wall | N (0.52 *m/s*, 0.13 *m/s*) |
| $v_i^A$ | Moving speed after finding the wall | N (0.62 *m/s*, 0.16 *m/s*) |
| $d_i$ | Forward visibility of pedestrian *i* | U (0.5 *m*, 0.8 *m*) |
| $\alpha_t$ | Proportion of pedestrians who tried to touch the wall | 0.76 |
| $\alpha_s$ | Proportion of pedestrians who tried to catch sight of the wall | 0.24 |
| $\beta_l$ | Proportion of LT-pedestrians | 0.23 |
| $\beta_r$ | Proportion of RT-pedestrians | 0.77 |
| $p_{cr}$ | Probability of an RT-pedestrian following the wall anticlockwise | 0.86 |
| $p_{cl}$ | Probability of an LT-pedestrian following the wall clockwise | 0.84 |
| $p_f$ | Probability of "following" in a type-A conflict | 0.815 |
| $p_i$ | Probability of "insisting" in a type-B conflict | 0.811 |
| $l_{i,arm}$ | Length of an arm | U (0.65 *m*, 0.8 *m*) |

U ($x_1$, $x_2$) denotes a uniform distribution between x1 and x2. N (μ, σ) denotes a Gaussian distribution with mean $\mu$ and standard deviation σ. RT-pedestrian and LT-pedestrian are used to indicate pedestrians who tended to find the wall with their right and left hands, respectively. Note that some pedestrians stretched out both of their arms to touch the wall; in most cases they first touched the wall with one hand (left/right) and their wall-following directions were mainly dependent on that hand. Thus, in Table 7 these pedestrians were assigned into the RT/LT-pedestrian categories according to the situation when they first touched the wall.

Table 8. Parameters for the social force model and the wall-following model.

| Parameters | Definition | Method | Value |
|---|---|---|---|
| $B_i$ | Constant that accounts for the psychological repulsive force | Literature | 0.08 *m* |
| $\tau$ | Relaxation/response time | Literature | 0.5 *s* |
| $A_i$ | Strength coefficient of the psychological repulsive force | GA | 478.03 *N* |
| $k_1$ | Strength coefficient of the body compression force | GA | 2660.82 $kg/s^2$ |
| $\kappa_1$ | Strength coefficient of the sliding force | GA | 1534.40 *kg/(ms)* |
| $k_s$ | Strength coefficient of the spring force | GA | 1.43 N/*(kgm)* |

### 6.2 Wall-following behaviour and evacuation efficiency

***Simulation* i)**: The proportion of LT (RT)-pedestrians *vs* evacuation efficiency

To investigate the impact of the proportion of LT (RT)-pedestrians on evacuation efficiency, the following settings were adopted:

（1） The crowd sizes were 30 and 60 pedestrians.

（2） The single-exit scenario was used.

（3） Initially, pedestrians were distributed evenly in the room with random desired walking directions and speed.

（4） All the pedestrians stretched out their arms to find the wall, namely $\alpha_t$=1, $\alpha_s = 0$.

（5） Probability of an RT-pedestrian following the wall anticlockwise was set to 1, namely $p_{cr}$=1.

（6） Probability of an LT-pedestrian following the wall clockwise was set to 1, namely $p_{cl}$=1.

（7） Proportions of LT-pedestrians were set to 0.1, 0.3, 0.5, 0.7, and 0.9.

（8） The simulations were repeated 20 times for each parameter set and the average individual evacuation time (the average of all individual's evacuation times) was used as an indicator of the evacuation efficiency.

（9） Other parameters were set according to Table 7 and Table 8.

***Conclusion* i)**: As shown in Fig. 16, when the crowd size was 30, the proportion of LT (RT)-pedestrians had little effect on the evacuation efficiency. The evacuation time first increased with the proportion of LT-pedestrians and then decreased when the proportion exceeded 0.5 in the case of 60 pedestrians.

When the crowd size was small, conflicts among pedestrians were limited and thus the pedestrians' evacuation time depended largely on their initial positions and walking speeds, whereas when the crowd size was large, conflicts among pedestrians increased and had an impact on evacuation efficiency. In theory, the number of conflicts was more likely to reach its maximum when the proportion of RT-pedestrian and LT-pedestrians was equal. Consequently, as shown in Fig. 16, the evacuation time first increased with the proportion of LT-pedestrians and then decreased when the proportion exceeded 0.5.

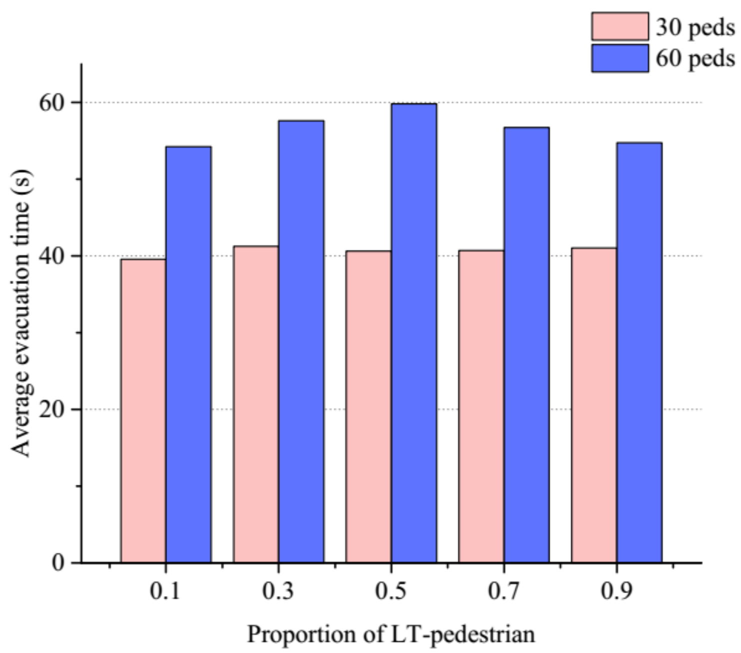


Fig. 16. The proportion of LT-pedestrians *vs* evacuation efficiency

***Simulation*** ii): Conflict resolution strategies *vs* evacuation efficiency

(1) The probability of “following” in a type-A conflict is kept at 0.815. Probability of “insisting” in a type-B conflict is set to 0, 0.2, 0.4, 0.6, 0.8, and 1.0, respectively.

(2) The probability of “insisting” in a type-B conflict is kept at 0.811. Probability of “following” in a type-A conflict is set to 0, 0.2, 0.4, 0.6, 0.8, and 1.0, respectively.

(3) The proportion of LT-pedestrians is set to 0.23.

(4) Other settings remain the same as in Simulation i).

***Conclusion*** ii): As shown in Figs. 17 and 18, when the crowd size was 30, neither the “following” strategy nor the “insisting” strategy had an obvious effect on the evacuation efficiency. When crowd size was 60, in general, the average individual evacuation time slightly reduced as the probability of using the “following” strategy increased, as shown in Fig. 17, whereas the evacuation time had no obvious correlation with the probability of using the “insisting” strategy, as shown in Fig. 18.

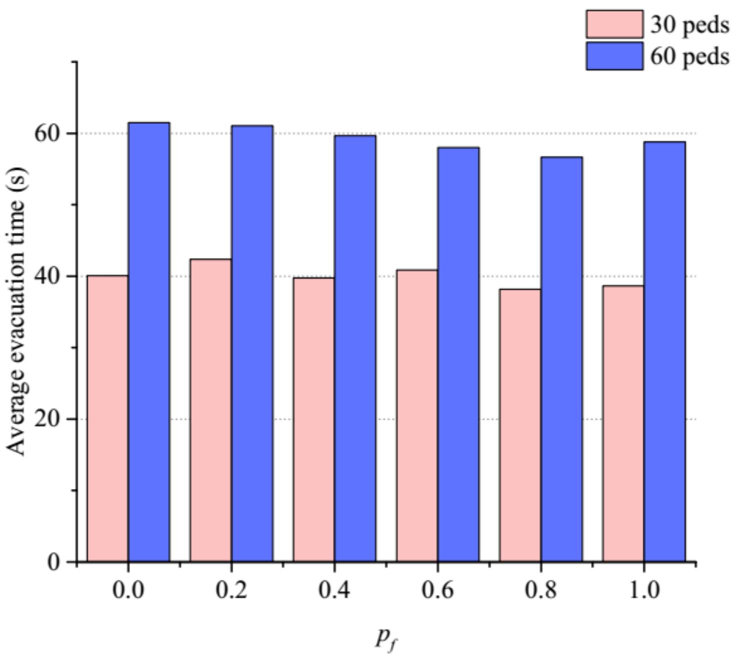


Fig. 17. Probability of using the “following” strategy *vs* evacuation efficiency

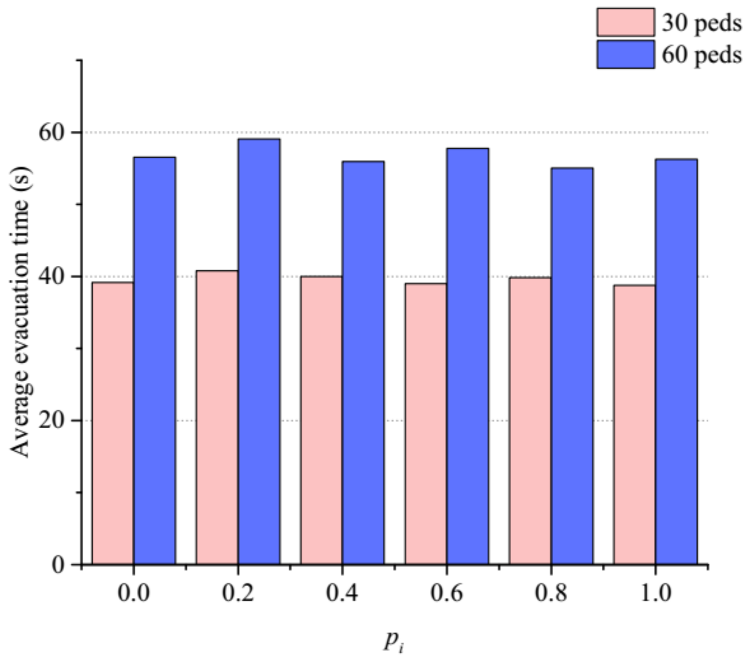


Fig. 18. Probability of using the "insisting" strategy *vs* evacuation efficiency

### 6.3 Evacuation management with a simple guidance plan

In the experiment, nearly all pedestrians tended to find the wall first and then follow it to get out of the room under such a limited visibility condition. We extracted the basic characteristics of pedestrian movement and identified the behavioural rules that pedestrians adopted to find the wall, decide their wall-following directions, and resolve conflicts in the wall-following process. Finally, these basic characteristics of movement and behavioural patterns are considered in the proposed wall-following model. In this part, we explore the possibility of managing the evacuation with a simple guidance plan, thus regulating pedestrians' wall-following directions to improve evacuation efficiency under the limited visibility condition (Chu et al., 2017; Guo, 2018).

Figs. 19 and 20 respectively present the designed guidance plans for the single-exit and two-opposite-exits scenarios. In the single-exit scenario, the walls were divided into region I and region II. For the walls in each region, signage was placed on the wall to instruct pedestrians with the optimal wall-following directions. Here it was supposed that pedestrians would fully follow the instructions when they found the wall. For example, if a pedestrian touched the wall in region I, then he or she would follow the wall clockwise, whereas if he or she touched the wall in region II, he or she would follow it anticlockwise. In Fig. 20, the guidance plan for the two-opposite-exits scenario was presented. The walls in the room were divided into four regions, and the signage specified corresponding wall-following directions for pedestrians who found the walls in different regions. With such a simple guidance plan, we could effectively reduce conflicts among wall-following pedestrians.

Figs. 21a (2) and b (2) present evacuation trajectories with the guidance plan. By comparing them to the cases without the guidance plan, as shown in Figs. 21a (1) and b (1), one can observe that conflicts were remarkably reduced and that the utilization rates of each exit were more balanced in the two-opposite-exits scenario.

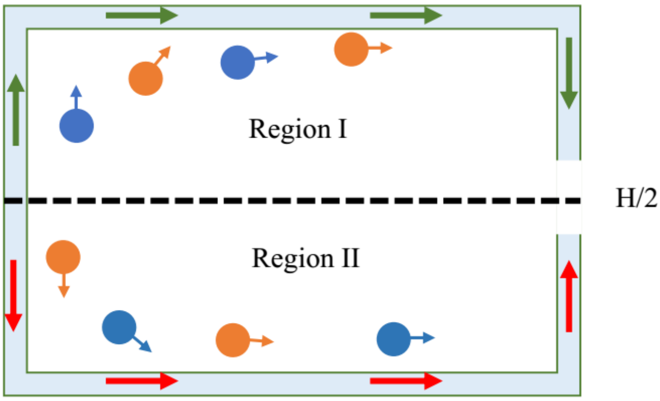


Fig. 19. Designed guidance plan for the single-exit scenario.

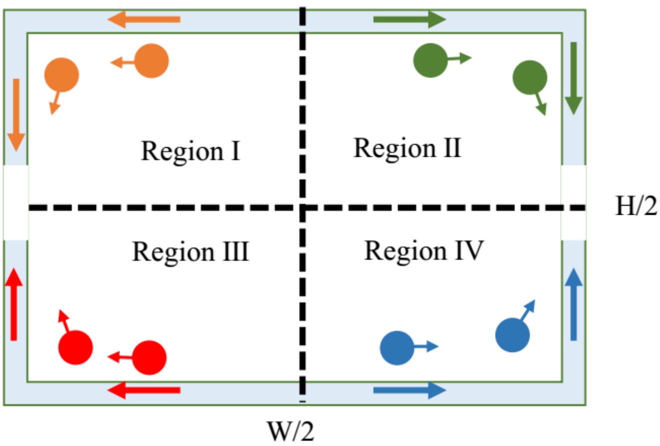


Fig. 20. Designed guidance plan for the two-opposite-exits scenario.

We investigated the effects of the guidance plan on evacuation efficiency under different scenarios (the proportion of LT-pedestrians was set to 0.3). As presented in Table 9, the average individual evacuation time was reduced by about 40% in the single-exit scenario, whereas in the two-opposite-exits scenario, the average individual evacuation time decreased by about 30%.

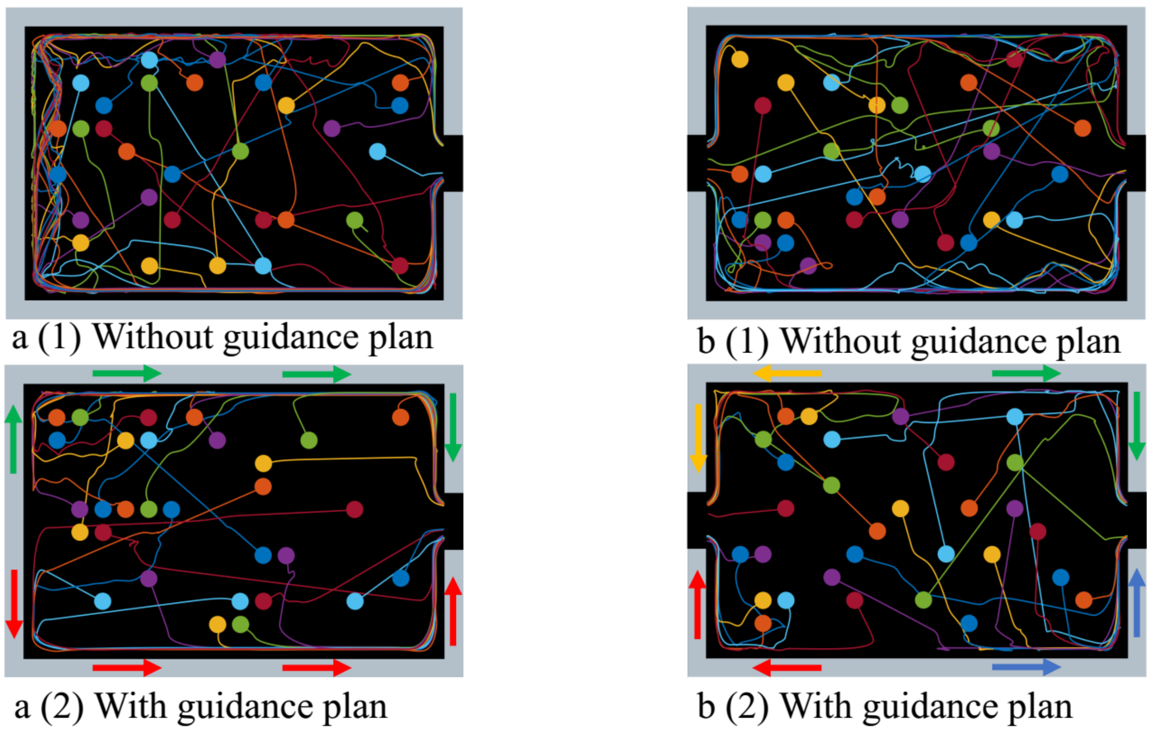


Fig. 21. The simulated evacuation trajectories of pedestrians with and without the guidance plan.

Table 9. The impact of the guidance plan on evacuation efficiency

| Single-exit scenario | | | | | | Two opposite exits scenario | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 30 pedestrians | | | 60 pedestrians | | | 30 pedestrians | | | 60 pedestrians | | |
| O | I | R(↓) | O | I | R(↓) | O | I | R(↓) | O | I | R(↓) |
| 41.24 | 24.64 | 40% | 57.62 | 34.40 | 40% | 21.75 | 15.61 | 28% | 28.10 | 19.31 | 31% |

O and I represent the original evacuation without a guidance plan and the improved evacuation with the guidance plan, respectively. R(↓) is the reduction rate of the evacuation time.

## 7. Conclusions

Understanding pedestrian behaviours under adverse sight and view conditions are important for design of evacuation strategies during emergency. In this study, pedestrians' behaviours under limited visibility conditions were investigated through laboratory experiments and simulation models. Experiments results showed that 76% pedestrians would stretch their arms to find the wall, and among these people, 61%, 19%, and 20% of them stretched out their right, left, and both arms, respectively. The mean walking speed was slightly higher after pedestrians touch the wall (0.1 m/s higher). Pedestrians also behaved different conflict resolving strategies in terms of "following the crowds' directions" or "insisting on their directions" towards two types of conflicts. A modified social force model was proposed incorporating the correlations between the wall-following behaviour and evacuation efficiency. And a simple guidance plan was developed based on the proposed model and the simulation results showed it was effective in enhancing the evacuation efficiency.

However, it still has several limitations of this study, where further research are needed:

(1) The method we adopted to create a limited visibility condition is characterized by peculiarities that was slightly different from those produced by little light or by wearing special glasses. The limited visibility condition can be created by illumination control or special glasses, in which pedestrian sees things hazily, while due to experimental settings in our study, the limited visibility refer to the situation in which participants could only see their surroundings clearly in a restricted distance. But influences of this difference might be limited, thus we think the findings in our experiment can still provide some insight into understanding pedestrian wall-following behaviour under limited visibility condition;

(2) The number of repetitions of our experiments was limited for each exit-layout scenario, and thus lacking some statistical results on the effect of exit layout on the evacuation efficiency. To draw a reliable conclusion on this issue, more experimental trials are needed in future research;

(3) As for the model, it only reflected the experimental situation in this research, which limits its generality. In the future, we need to continue to conduct further experiments to explore and investigate pedestrian wall-following behaviour in depth and continue to improve the model;

(4) In the experimental results, it was found that the hand with which pedestrians first touched the wall largely determined their wall-following direction. We surveyed 30 participants in the experiment and the results showed that 28 of them were right-handed and two of them wrote with the right hand but used chopsticks to eat with the left hand. Thus, it is indeed an interesting question how people's handedness affects their wall-following direction. We need to perform more experiments with left-handed participants. However, it is a tough problem to find a considerable number of left-handed individuals in China to participate our experiments. We call for our peer researchers to perform similar experiments that can provide valuable data on this issue.

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## References

Cao, S., Fu, L., Wang, P., Zeng, G., Song, W., 2018. Experimental and modeling study on evacuation under good and limited visibility in a supermarket. Fire Safety Journal.

102, 27-36.

Cao S., Song W., Lv W., Fang Z., 2015. A multi-grid model for pedestrian evacuation in a room without visibility. Physica A: Statistical Mechanics and Its Applications. 436, 45-61.

Chen, J., Wang, J., Wang, B., Liu, R., Wang, Q., 2018. An experimental study of visibility effect on evacuation speed on stairs. Fire safety journal. 96, 189-202.

Chu, J., Chen A., Lin Y., 2017. Variable guidance for pedestrian evacuation considering congestion, hazard, and compliance behaviour. Transportation Research Part C: Emerging Technologies. 85, 664-683.

Cowan, N. J., Lee J., Full R. J., 2006. Task-level control of rapid wall following in the American cockroach. Journal of Experimental Biology. 209(15), 3043.

Dussutour, A., Deneubourg J. L., Fourcassie V., 2005. Amplification of individual preferences in a social context: the case of wall-following in ants. Proceedings of the Royal Society B: Biological Sciences. 272(1564), 705-714.

Fridolf, K., Ronchi E., Nilsson D., Frantzich H., 2013. Movement speed and exit choice in smoke-filled rail tunnels. Fire Safety Journal. 59, 8-21.

Guo, N., Hao Q., Jiang R., Hu M., Jia B., 2016. Uni- and bi-directional pedestrian flow in the view-limited condition: Experiments and modeling. Transportation Research Part C: Emerging Technologies. 71, 63-85.

Guo, R., Huang H., Wong S. C., 2012. Route choice in pedestrian evacuation under conditions of good and zero visibility: Experimental and simulation results. Transportation Research Part B: Methodological. 46(6), 669-686.

Guo, R., 2018. Potential-based dynamic pedestrian flow assignment. Transportation Research Part C: Emerging Technologies. 91, 263-275.Helbing, D., Farkas I., Vicsek T., 2000. Simulating dynamical features of escape panic. Nature. 407(6803), 487-490.

Helbing, D., Molnar P., 1995. Social force model for pedestrian dynamics. Physical Review E. 51(5), 4282-4286.

Helbing, D., Buzna L., Johansson A., 2005. Self-organized pedestrian crowd dynamics: Experiments, simulations, and design solutions. Transportation Science. 39(1), 1-24.

Hirai K., Tarui K., 1977. A Simulation of the Behaviour of a Crowd in Panic Systems and Control.

Huang, H., Guo R., 2008. Static floor field and exit choice for pedestrian evacuation in rooms with internal obstacles and multiple exits. Physical Review E. 78, 21131.

Hussein, M., Sayed, T., 2017. A bi-directional agent-based pedestrian microscopic model. Transportmetrica A: Transport Science. 13(4), 326-355.

Isobe, M., Helbing D., Nagatani T., 2004. Experiment, theory, and simulation of the evacuation of a room without visibility. Physical Review E. 69(6 Pt 2), 66132.

Jeon, G., Kim J., Hong W., Augenbroe G., 2011. Evacuation performance of individuals in different visibility conditions. Building and Environment. 46(5), 1094-1103.

Jin, T., Yamada T., 1985. Irritating effects of fire smoke on visibility. Fire Science and Technology. 5(1), 79-90.

Kirchner, A., Schadschneider A., 2002. Simulation of evacuation processes using a bionics-inspired cellular automaton model for pedestrian dynamics. Physica A: Statistical Mechanics and Its Applications. 312, 260-276.

Kobes, M., Helsloot I., de Vries B., Post J. G., Oberijé N., Groenewegen K., 2010. Way finding during fire evacuation: An analysis of unannounced fire drills in a hotel at night. Building and Environment. 45(3), 537-548.

Li, M., Zhao Y., He, L., Chen, W., Xu, X., 2015. The parameter calibration and optimization of social force model for the real-life 2013 Ya’an earthquake evacuation in China. Safety Science. 79, 243-253.

Liu, R., Fu, Z., Schadschneider, A., Wen, Q., Chen, J., & Liu, S. (2019). Modeling the effect of visibility on upstairs crowd evacuation by a stochastic FFCA model with finer discretization. Physica A: Statistical Mechanics and its Applications, 121723

Moussaid, M., Helbing D., Theraulaz G., 2011. How simple rules determine pedestrian behaviour and crowd disasters. Proceedings of the National Academy of Sciences. 108(17), 6884-6888.

Nagai, R., Nagatani, T., Isobe, M., Adachi, T., 2004. Effect of exit configuration on evacuation of a room without visibility. Physica A. 343, 712-724.

Nagatani, T., Nagai R., 2004. Statistical characteristics of evacuation without visibility in random walk model. Physica A. 341, 638-648.

Okazaki S., 1979. A study of pedestrian movement in architectural space, part 1: Pedestrian movement by the application on of magnetic models. Trans. AIJ. 1979, 283,111-119.

Parisi, D.R., Dorso, C.O., 2005. Microscopic dynamics of pedestrian evacuation. Physica A: Statistical Mechanics and Its Applications. 354(1), 606-618.

Porter, E., Hamdar, S. H., Daamen, W., 2018. Pedestrian dynamics at transit stations: An integrated pedestrian flow modeling approach. Transportmetrica A: transport science. 14(5-6), 468-483.

Shen, Y., Wang, Q. S., Yan, W. G., Sun, J. H., Zhu, K., 2014. Evacuation processes of different genders in different visibility conditions–an experimental study. Procedia engineering. 71, 65-74.

Shi, X., Ye, Z., Shiwakoti, N., & Grembek, O. (2018). A State-of-the-Art Review on Empirical Data Collection for External Governed Pedestrians Complex Movement. Journal of Advanced Transportation, 2018, 1–42.

Shi, X., Ye, Z., Shiwakoti, N., Tang, D., & Lin, J. (2019). Examining effect of architectural adjustment on pedestrian crowd flow at bottleneck. Physica A: Statistical Mechanics and Its Applications, 522, 350–364.

Shiwakoti, N., Gong Y., Shi X., Ye Z., 2015. Examining influence of merging architectural features on pedestrian crowd movement. Safety Science. 75, 15-22.

Shiwakoti, N., Shi, X., & Ye, Z. (2019). A review on the performance of an obstacle near an exit on pedestrian crowd evacuation. Safety Science, 113, 54–67.

Tak, S., Kim, S., & Yeo, H., 2018. Agent-based pedestrian cell transmission model for evacuation. Transportmetrica A: transport science. 14(5-6), 484-502.

Tavana H., Aghabayk K., 2019 Insights toward efficient angle design of pedestrian crowd egress point bottlenecks, Transportmetrica A: Transport Science.15(2), 1569-1586.

Wolf, P.R., Dewitt, B.A., 2000. Elements of Photogrammetry with Applications in GIS, third ed. McGraw Hill.

Xue, S., Jia B., Jiang R., Shan J., 2016. Pedestrian evacuation in view and hearing limited condition: The impact of communication and memory. Physics Letters A. 380(38), 3029-3035.

Zeng, Y., Song, W., Huo, F., Fang, Z., Cao, S., Vizzari, G., 2018. Effects of initial distribution ratio and illumination on merging behaviours during high-rise stair descent process. Fire technology. 54(5), 1095-1112.