ISSN 1674-1056
http://cpb.iphy.ac.cn
http://iopscience.iop.org/cpb
中国物理 B
Chinese Physics
中国物理 Chinese Physics B

Spatial memory enhances the evacuation efficiency of virtual pedestrians under poor visibility condition

Yi Ma(马毅), Eric Wai Ming Lee(李伟民), Meng Shi(施朦), Richard Kwok Kit Yuen(袁国杰)
Citation: Chin. Phys. B . 2018, 27(3): 038901. **doi:** 10.1088/1674-1056/27/3/038901

Journal homepage: http://cpb.iphy.ac.cn; http://iopscience.iop.org/cpb

What follows is a list of articles you may be interested in

Analysis of dynamic features in intersecting pedestrian flows

Hai-Rong Dong(董海荣), Qi Meng(孟琦), Xiu-Ming Yao(姚秀明), Xiao-Xia Yang(杨晓霞), Qian-Ling Wang(王千龄)
Chin. Phys. B . 2017, 26(9): 098902. **doi:** 10.1088/1674-1056/26/9/098902

Bottleneck effects on the bidirectional crowd dynamics

Xiao-Xia Yang(杨晓霞), Hai-Rong Dong(董海荣), Xiu-Ming Yao(姚秀明), Xu-Bin Sun(孙绪彬)
Chin. Phys. B . 2016, 25(12): 128901. **doi:** 10.1088/1674-1056/25/12/128901

Pedestrians' behavior in emergency evacuation: Modeling and simulation

Lei Wang(汪蕾), Jie-Hui Zheng(郑杰慧), Xiao-Shuang Zhang(张晓爽), Jian-Lin Zhang(张建林), Qiu-Zhen Wang(王求真), Qian Zhang(张茜)
Chin. Phys. B . 2016, 25(11): 118901. **doi:** 10.1088/1674-1056/25/11/118901

Pedestrian evacuation at the subway station under fire

Xiao-Xia Yang(杨晓霞), Hai-Rong Dong(董海荣), Xiu-Ming Yao(姚秀明), Xu-Bin Sun(孙绪彬)
Chin. Phys. B . 2016, 25(4): 048902. **doi:** 10.1088/1674-1056/25/4/048902

Row-column visibility graph approach to two-dimensional landscapes

Xiao Qin, Pan Xue, Li Xin-Li, Mutua Stephen, Yang Hui-Jie, Jiang Yan, Wang Jian-Yong, Zhang Qing-Jun
Chin. Phys. B . 2014, 23(7): 078904. **doi:** 10.1088/1674-1056/23/7/078904

Spatial memory enhances the evacuation efficiency of virtual pedestrians under poor visibility condition*

Yi Ma(马毅)[1,2,†], Eric Wai Ming Lee(李伟民)[2], Meng Shi(施朦)[2], and Richard Kwok Kit Yuen(袁国杰)[2]

[1] *Institute for Disaster Management and Reconstruction, Sichuan University, Chengdu* 610207, *China*
[2] *Department of Architecture and Civil Engineering, City University of Hong Kong, Kowloon, Hong Kong, China*

(Received 1 August 2017; revised manuscript received 17 December 2017; published online 13 February 2018)

Spatial memory is a critical navigation support tool for disoriented evacuees during evacuation under adverse environmental conditions such as dark or smoky conditions. Owing to the complexity of memory, it is challenging to understand the effect of spatial memory on pedestrian evacuation quantitatively. In this study, we propose a simple method to quantitatively represent the evacuee's spatial memory about the emergency exit, model the evacuation of pedestrians under the guidance of the spatial memory, and investigate the effect of the evacuee's spatial memory on the evacuation from theoretical and physical perspectives. The result shows that (i) a good memory can significantly assist the evacuation of pedestrians under poor visibility conditions, and the evacuation can always succeed when the degree of the memory exceeds a threshold ($\varphi > 0.5$); (ii) the effect of memory is superior to that of "follow-the-crowd" under the same environmental conditions; (iii) in the case of multiple exits, the difference in the degree of the memory between evacuees has a significant effect (the greater the difference, the faster the evacuation) for the evacuation under poor visibility conditions. Our study provides a new quantitative insight into the effect of spatial memory on crowd evacuation under poor visibility conditions.

Keywords: crowd evacuation, memory, visibility, social force model

PACS: 89.65.Gh, 89.40.–a, 07.05.Tp, 05.65.+b, **DOI:** 10.1088/1674-1056/27/3/038901

1. Introduction

Crowd evacuation is an intriguing but important issue; previous studies on this issue can be roughly categorized into two types: empirical study and modeling and simulation study. Many empirical studies such as post-accident survey,[1] controlled laboratory experiment,[2–7] and evacuation drill[8] have been carried out to understand individual and collective behaviors, self-organized phenomena, and dynamical features of evacuees during the evacuation. Many mathematical models, such as the social force model,[9,10] cellular automaton model,[11,12] lattice gas model,[13,14] agent-based model,[15] and various hybrid models[16–19] were developed to simulate crowd evacuations in different scenarios.

In recent years, the study of pedestrian evacuation under adverse environmental conditions such as dark or smoky conditions has attracted considerable attention. Helbing *et al.*[10] simulated pedestrian evacuation under the smoky context based on the social force model. Isobe *et al.*[20] studied the evacuation process from a room with a single exit for the case of no visibility through both controlled experiments and simulations. Nagai *et al.*[21] surveyed the effect of the configuration of exits in the dark room on the evacuation process through experiments and simulations. Shi *et al.*[22] developed an agent-based model coupling fire expansion to simulate 6-pedestrian evacuation in large public buildings under fire conditions. Guo *et al.*[23] conducted experimental and simulation studies to investigate the route-choice behavior of pedestrians during an evacuation from a classroom in the cases of good and zero visibility. Guo and Huang[24] presented a theoretical analysis to estimate the moving distance of evacuees for leaving the rooms in the case of no visibility. Xia *et al.*[25] pointed out the importance of memory on the pedestrian flow in an environment with diminished visibility. Furthermore, Nguyen *et al.*,[26] Ma and Wang,[27] and Yue *et al.*[28] developed different simulation models to investigate the crowd evacuation under various adverse environmental conditions. Further, evacuation guidance under the dark or smoky environmental condition has been a popular topic of study.[29–31]

In most of these previous studies, it was assumed that evacuees often become disoriented under the dark or smoky environmental condition. However, this is often not the case; in many cases, evacuees are not fully disoriented. They may discern the approximate exit direction based on their memory, especially when they are very familiar with the building layout. For example, a person who usually patronizes a shopping mall may memorize the location of the emergency exit of the shopping mall, and thus, he/she can promptly find the emergency exit during evacuation even if under dark or smoky environmental conditions. Thus, it is particularly necessary to investigate and understand the effect of spatial memory on pedestrian evacuation under the poor visibility condition.

In this study, we propose a simple method to represent the evacuee's spatial memory about the emergency exit, model

*Project supported by the Research Grants Council of the Hong Kong Special Administrative Region, China (Grant No. 11203615).
†Corresponding author. E-mail: yima23-c@my.cityu.edu.hk
© 2018 Chinese Physical Society and IOP Publishing Ltd

the evacuation of pedestrians under the guidance of the spatial memory, and investigate the effect of the evacuee's spatial memory on the evacuation under poor visibility conditions from the theoretical and the physical perspectives. In particular, we address the following questions: (i) how does the degree of memory affect the evacuation of pedestrians under poor visibility conditions, (ii) which among "memory" and "follow-the-crowd," is a more effective approach for evacuation of pedestrians under poor visibility conditions, (iii) in the case of multiple exits, how does the memory difference between evacuees affect the evacuation of pedestrians under poor visibility conditions?

2. Model and method

2.1. Basic model

In this study, the social force model is used as the basic crowd dynamical model.[9,10] The social force model is a typical continual crowd dynamical model. In the model, the evacuee i is represented as an entity with body radius r_i and mass m_i. The motion of evacuee i is determined by the following acceleration equations:

$$m_i \frac{\mathrm{d}\boldsymbol{v}_i(t)}{\mathrm{d}t} = m_i \frac{v_i^0 \boldsymbol{e}_i^0 - \boldsymbol{v}_i(t)}{\tau} + \sum_{j(\neq i)} \boldsymbol{f}_{ij}(t) + \sum_W \boldsymbol{f}_{iw}(t), \quad (1)$$

$$\frac{\mathrm{d}\boldsymbol{r}_i(t)}{\mathrm{d}t} = \boldsymbol{v}_i(t), \quad (2)$$

where $\boldsymbol{r}_i$ and $\boldsymbol{v}_i$ represent the evacuee's current position and velocity, respectively; v_i^0 and $\boldsymbol{e}_i^0$ represent the evacuee's desired speed and direction, respectively; τ is the characteristic time used for adjusting its current velocity $v_i^0 \boldsymbol{e}_i^0$ to the desired velocity $\boldsymbol{v}_i$; and $\boldsymbol{f}_{ij}$ represents the interaction force between the evacuee i and any of the other evacuees j, which is calculated by

$$\begin{aligned} \boldsymbol{f}_{ij} &= A_i \exp[(r_{ij} - d_{ij})/B_i]\boldsymbol{n}_{ij} + kg(r_{ij} - d_{ij})\boldsymbol{n}_{ij} \\ &\quad + \kappa g(r_{ij} - d_{ij})\Delta v_{ji}^t \boldsymbol{t}_{ij}, \end{aligned} \quad (3)$$

where the term $A_i \exp[(r_{ij} - d_{ij})/B_i]\boldsymbol{n}_{ij}$ represents the psychological repulsive force between evacuee i and j; A_i and B_i are constants; and r_{ij} and d_{ij} represent the sum of the body radii of evacuee i and j and the distance of the centers of mass between evacuee i and j, respectively. $\boldsymbol{n}_{ij} = (n_{ij}^1, n_{ij}^2) = (\boldsymbol{r}_i - \boldsymbol{r}_j)/d_{ij}$ is the normalized vector pointing from evacuee j to i and the terms $kg(r_{ij} - d_{ij})\boldsymbol{n}_{ij}$ and $\kappa g(r_{ij} - d_{ij})\Delta v_{ji}^t t_{ij}$ are respectively referred to as body force and sliding friction force; they are activated when evacuee i and j touch each other (i.e., $d_{ij} < r_{ij}$). The function $g(x)$ equals x only when $d_{ij} < r_{ij}$; otherwise it equals zero; k and κ are large constants; $\boldsymbol{t}_{ij} = (n_{ij}^2, n_{ij}^1)$ represents the tangential direction; and $\Delta v_{ij}^t = (\boldsymbol{v}_j - \boldsymbol{v}_i) \cdot \boldsymbol{t}_{ij}$ represents the tangential velocity difference. It should be noted that the properties of the body force and sliding friction force are different in comparison to the psychological repulsive force. The latter represents the tendency that the pedestrian will avoid the collision with neighbors and move away from the neighbors. The former represents the physical force due to body contact. The more the overlap between two pedestrians, the larger is the body force. Furthermore, the body force and the sliding friction force arise only when body contact arises.

Similarly, the interaction force $\boldsymbol{f}_{iw}$ between evacuee i and wall w can be given by

$$\begin{aligned} \boldsymbol{f}_{iw} &= A_i \exp[(r_i - d_{iw})/B_i]\boldsymbol{n}_{iw} + kg(r_i - d_{iw})\boldsymbol{n}_{iw} \\ &\quad + \kappa g(r_i - d_{iw})(\boldsymbol{v}_i \cdot \boldsymbol{t}_{iw})\boldsymbol{t}_{iw}, \end{aligned} \quad (4)$$

where d_{iw} denotes the distance between the evacuee i and the wall w, $\boldsymbol{n}_{iw}$ denotes the direction perpendicular to the wall, and $\boldsymbol{t}_{iw}$ denotes the tangential direction.

2.2. Evacuees' spatial memory

The memory about the location of the emergency exit is very important for the disoriented evacuees in an evacuation under dark or smoky environmental conditions. However, it is still challenging to represent the degree of memory with a quantitative method, given that human memory is a very complex psychological process. Nonetheless, it is not difficult to represent the best memory with quantitative terms in the social force model.

The best memory corresponds to the one in which the evacuee can accurately remember and know the location of the emergency exit. Therefore, the escaping direction of evacuee and points to the emergency exit (this behavioral rule is also suitable to those evacuees who can directly see the emergency exit) are known. In modeling terms

$$\boldsymbol{e}_i^0 = \mathrm{Norm}[\boldsymbol{r}_\mathrm{e} - \boldsymbol{r}_i(t)], \quad (5)$$

where $\boldsymbol{r}_\mathrm{e}$ represents the location of the emergency exit. Norm $[Z] = Z/||Z||$ represents the normalization of a vector Z.

We introduce memory noise (θ) to represent general memory quantitatively, as shown in Fig. 1(a). The existence of memory noise increases the uncertainty of the exit direction DI ($x_\mathrm{DI} y_\mathrm{DI}$) (DI ($x_\mathrm{DI} y_\mathrm{DI}$) = Norm[$\boldsymbol{r}_\mathrm{e} - \boldsymbol{r}_i(t)$]). The $\theta = 0$ (i.e., no noise, see Fig. 1(b)) is equivalent to the best memory; this means that there is no uncertainty with regard to the exit direction, and the evacuee can accurately distinguish the exit direction and move toward the exit. Otherwise, for $\theta \neq 0$, the noise confuses the memory, and the evacuee cannot distinguish the accurate exit direction; thus, he/she can only perceive that the exit is located in the noise range between the negative maximal deviation ($-$MD) and the positive maximal deviation (+MD). We assume that the evacuee has the same probability to select any of the directions between $-$MD and +MD. In modeling terms

$$\boldsymbol{e}_i^0 = \left(\cos\left(\arctan\left(\frac{y_\mathrm{DI}}{x_\mathrm{DI}} \right) + \lambda\theta \right), \right.$$

$$\sin\left(\arctan\left(\frac{y_{\mathrm{DI}}}{x_{\mathrm{DI}}}\right)+\lambda\theta\right)\Bigg), \tag{6}$$

where λ represents the random number distributed uniformly from -1 to 1.

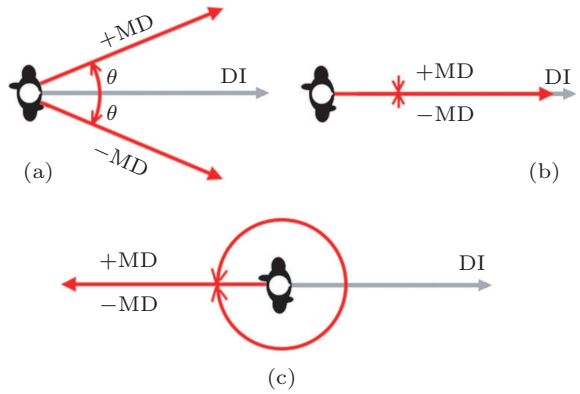


Fig. 1. (color online) (a) Representation of evacuee's memory about the location of the emergency exit. (b) Best memory. (c) Worst memory.

The more the memory noise θ, the larger is the uncertainty of the exit direction. The maximal value of memory noise is π. When $\theta=\pi$, e_i^0 may be in any direction in terms of the value of λ, as shown in Fig. 1(c). This means that the evacuee does not have any memory about the location of the emergency exit, and he/she is fully disoriented under the dark or smoky environmental conditions.

Based on memory noise, we define the evacuee's spatial memory about the emergency exit as

$$\varphi=\frac{\pi-\theta}{\pi}. \tag{7}$$

The degree of the worst memory $\varphi=0$ corresponds to the memory noise $\theta=\pi$ (see Fig. 1(c)), while the degree of the best memory $\varphi=1$ corresponds to the memory noise $\theta=0$ (see Fig. 1(b)).

It is worth noting that, under dark or smoky evacuation conditions, the motion of neighbors within the visual field may exert influence on that of the evacuee. Normally, if the neighbors' direction (ND) is in the memory range, as shown in Fig. 2(a), evacuee will tend to move in the ND (i.e., follow the crowd[32]). In mathematical terms,

$$\boldsymbol{e}_i^0=\mathrm{Norm}\left[\sum_j \boldsymbol{v}_j(t)\right], \tag{8}$$

where $\boldsymbol{v}_j(t)$ represents the moving direction of neighbor j within the visual field.

When the ND is out of the memory range, as shown in Fig. 2(b), we assume that the memory is dominant. The evacuee will trust the memory, and choose the direction closest to the ND (i.e., the closet maximal deviation direction). In mathematical terms,

$$\boldsymbol{e}_i^0=\begin{cases}+\mathrm{MD}, & \text{if}+\mathrm{MD}\cdot\mathrm{ND}>-\mathrm{MD}\cdot\mathrm{ND},\\ -\mathrm{MD} & \text{otherwise.}\end{cases} \tag{9}$$

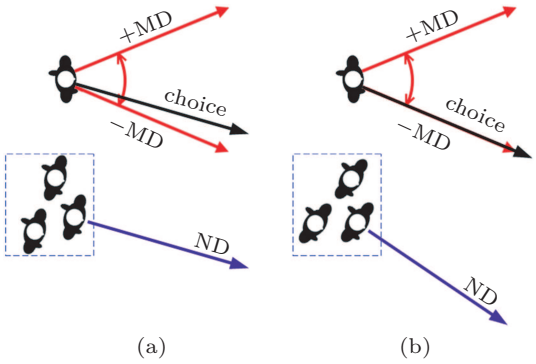


Fig. 2. (color online) (a) Choice of the desired direction e_i^0, when the neighbors' direction (ND) is in the memory range. (b) Choice of the desired direction e_i^0, when the ND is out of the memory range.

The movement rules of evacuees in the model can be generalized by the flow chart shown in Fig. 3.

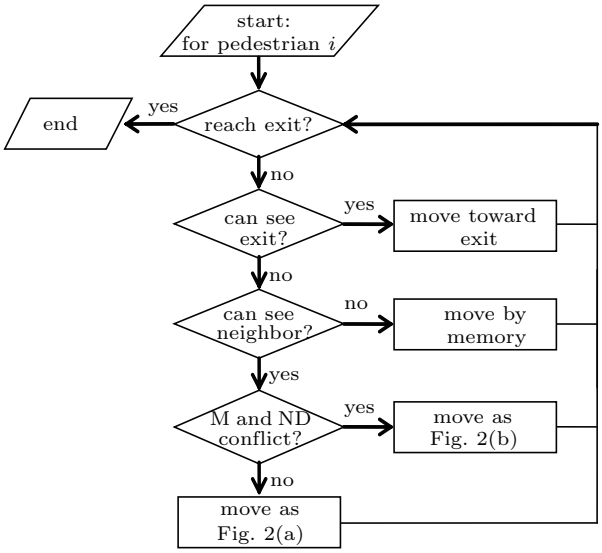


Fig. 3. Movement rules of evacuees in the model, where M represents the memory, and ND represents the neighbors' direction.

2.3. Parameters selection in social force model

Parameters selection is one of the keys of the social force model. Strictly speaking, the parameters should be calibrated; however, the calibration process is very complex and the available calibration data are scarce. Many previous studies reported their choices on the parameter values. By referring to these studies,[10,27,33–35] we specify the parameters values for the social force model as follows: body radius $r=0.3$ m, mass $m=80$ kg, desired speed $v_i^0=1.5$ m/s, characteristic time $\tau=0.2$ s, constants $k=20000$ kg/s^2, $\kappa=30000$ kg/s^2, $A=2000$ N, and $B=0.08$ m. Figure 4 shows the test result under these parameter choices. It can be seen that the virtual evacuees can move reasonably during evacuation. They are capable of moving toward the exit, and they can avoid collisions with walls and neighbors. No obvious oscillation and overlap arise even if at the crowded exit. The clogging and arching phenomena can be observed near the exit.

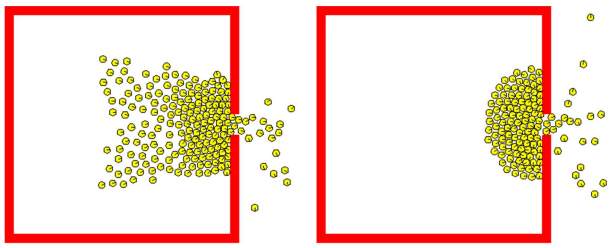


Fig. 4. (color online) Snapshots of the simulation test where the parameters value are set as follows: body radius $r = 0.3$ m, mass $m = 80$ kg, desired speed $v_i^0 = 1.5$ m/s, characteristic time $\tau = 0.2$ s, constants $k = 20000$ kg/s^2, $\kappa = 30000$ kg/s^2, $A = 2000$ N, and $B = 0.08$ m. This simulation represents that 200 evacuees distributed randomly in the 20 m×20 m room without smoke evacuate from the room through the 2-m exit.

3. Simulations and analysis

3.1. Effect of degree of memory on pedestrian evacuation

We simulate the evacuation of a crowd in the scenario shown in Fig. 4 with different crowd sizes, different visibilities, and different degrees of memory to investigate how the degree of memory affects crowd evacuation under poor visibility. In the simulations, the width of the exit is enlarged to 4 m for eliminating the influence of congestion at the exit as much as possible. The manner in which the pedestrians choose the location of the exit (i.e., Eq. (5)) is based on the shortest path principle, rather than the center of the exit, considering the width effect of the exit. Besides, given the body size effect, the actual available width of the exit is 3.4 m, namely, the width of the exit (4 m) deducted by the twobody radius (0.6 m) on the two edges of the exit. The virtual pedestrians only interact with the neighbors within the circular visual field determined by the visibility. For each pedestrian, the parameter λ (in Eq. (6)) is recalculated at each time step. Moreover, the virtual pedestrians evacuated successfully from the scenario are assumed to escape toward a random safe direction out of the scenario, namely the directional range between $-\pi/2$ to $\pi/2$ as suggested in Fig. 4. The time limit of the evacuation is set to 50 s. The evacuation is considered to fail if there is still an evacuee in the room after 50 s. Moreover, for simplicity, two assumptions are made in the simulations: (i) the degree of memory is static and remains constant during the evacuation; (ii) evacuees are homogeneous and have the same degree of memory.

The simulation under each treatment is repeated for 1000 runs, given that the evacuees' initial positions and directions are randomly generated. We record the probability that all evacuees can evacuate from the room successfully within the time limit. Here, the probability is defined as the runs of successful evacuation divided by total runs (1000). Figure 5 shows the plots of the probability H against the degree of memory φ for different visibilities ($\eta = 2$ m, 4 m, 6 m, 8 m, and 10 m) in the cases of different crowd sizes ($N = 50$ and 250).

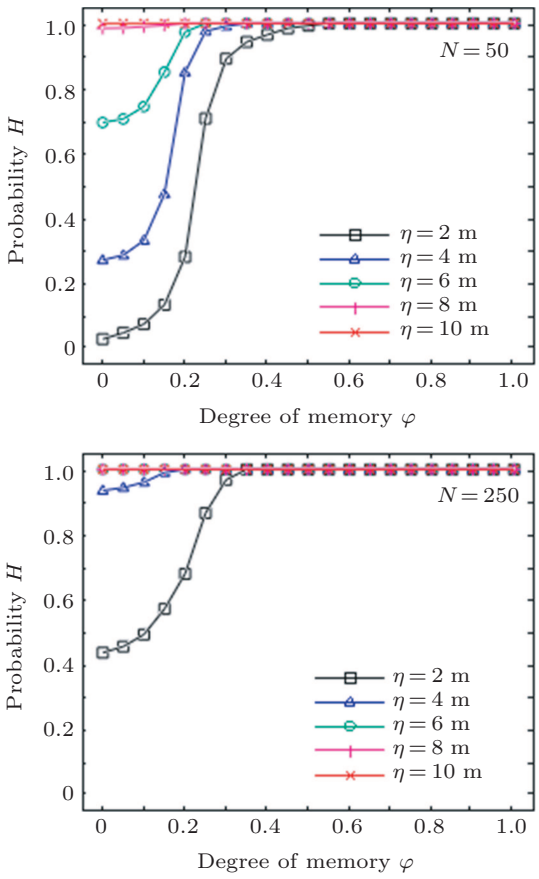


Fig. 5. (color online) Plots of probability H against the degree of memory φ for different visibilities ($\eta = 2$ m, 4 m, 6 m, 8 m, and 10 m) in the cases of different crowd sizes ($N = 50$ and 250).

Figure 5 indicates that although the dependence of the probability on the degree of memory is different in the cases of different visibilities and different crowd sizes, the probability can always reach the maximal value ($H = 1$) when the degree of memory $\varphi > 0.5$. In other words, evacuees can always evacuate from the room regardless of the initial distribution, visibility, and crowd size, if the memory noise $\theta < \pi/2$.

Figure 6 shows the reason for this interesting result. Here, $d_i(t)$ represents the current distance between the evacuee i and the exit, and α represents the deviation between the selected direction by memory and the exit direction. When $\varphi > 0.5$ (i.e., $\theta < \pi/2$), the α will be smaller than $\pi/2$ (see the illustration in Figs. 1 and 2). In addition, when the evacuee i moves from $\boldsymbol{r}_i(t)$ to $\boldsymbol{r}_i(t+1)$ along the selected direction, the distance between the evacuee i and the exit is updated by

$$d_i(t+1) = d_i(t) - ||\boldsymbol{r}_i(t+1) - \boldsymbol{r}_i(t)||\cos(\alpha). \quad (10)$$

Since $\alpha < \pi/2$, $d_i(t+1)$ will be less than $d_i(t)$. In other words, the evacuee i can always move in the direction approaching the exit, rather than away from the exit. Therefore, evacuees can always reach the exit in enough evacuation time when the degree of memory $\varphi > 0.5$.

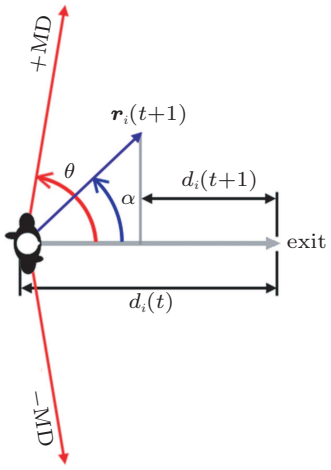


Fig. 6. (color online) Analysis of evacuee's motion, when the degree of memory $\varphi > 0.5$.

3.2. Memory versus "Follow the crowd"

It is possible that an escaping evacuee may meet other escaping evacuees during evacuation. The exit direction in the memory may be conflicted with the escaping direction of these neighbors, as shown in Fig. 2(b). Previously, we assumed that evacuees will trust their memory rather than their neighbors; it is reasonable for the confident evacuees, but not the case for the unconfident evacuees. The unconfident evacuees may trust their neighbors and follow them, rather than their memory, as shown in Fig. 7. Therefore, it is unclear which of the two—memory and "follow the crowd"—is more effective for the evacuation of pedestrians under the poor visibility condition? To address this problem, we conduct simulations to compare their effectiveness. As mentioned above, we record the probability of successful evacuation within the time limit in the simulations when evacuees are set to fully follow the crowd. The results are shown in Fig. 8.

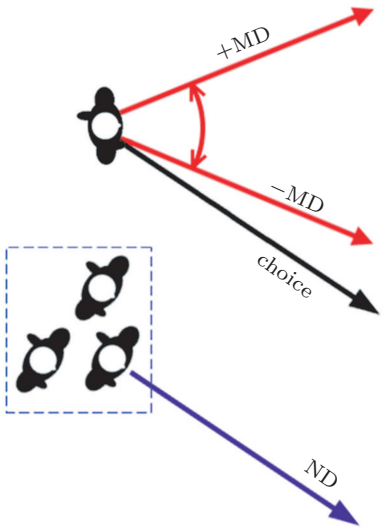


Fig. 7. (color online) Evacuee chooses to trust their neighbors and follow them when the exit direction in memory is conflicted with the neighbors' direction (ND).

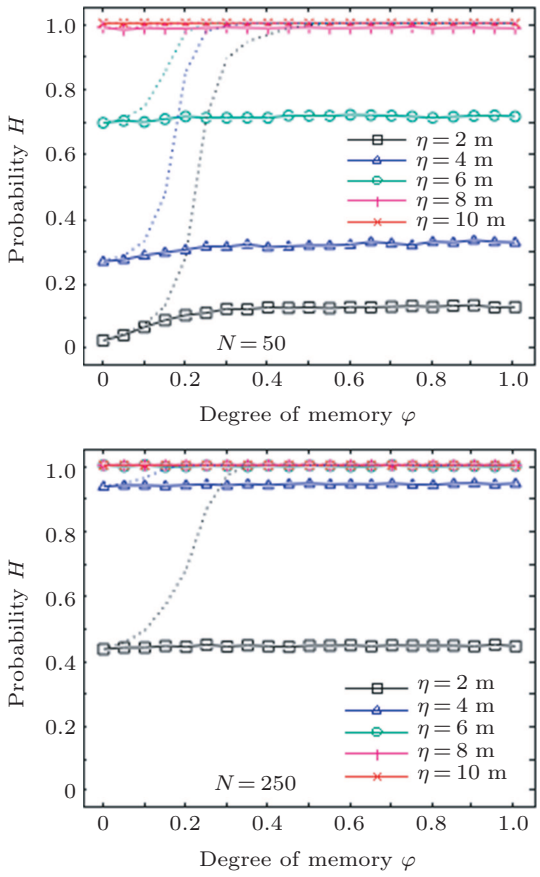


Fig. 8. (color online) Plots of the probability H against the degree of memory φ for different visibilities ($\eta = 2$ m, 4 m, 6 m, 8 m, and 10 m) in the cases of different crowd sizes ($N = 50$ and 250). Evacuees in the simulations are set to fully follow the crowd. For comparison, the data in Fig. 5 is attached in dotted lines with the same colors.

Figure 8 indicates that the probabilities when evacuees choose to follow the crowd (the solid lines) are always no more than that when they choose to trust the memory (the dot lines) in the case of the same degree of memory, visibility and crowd size. In other words, the effect of the memory is superior to that of "follow-the-crowd" under the same environmental conditions. This result gives evacuees a useful suggestion that, in the "blind" evacuation, when the exit direction in memory conflicts with the escaping direction of the neighbors within the visual field, evacuees should better move in the exit direction perceived by memory, rather than follow their neighbors.

The reason for this interesting result is that, when an evacuee chooses to fully trust their memory, the evacuee can constantly approach the exit and not be away from the exit, as we analyzed in the last section. However, when an evacuee chooses to fully trust their neighbors, the evacuee may be away from the exit, because the direction of the neighbors may not be the direction approaching the exit. Further, it is possible that the direction of the neighbors can be very close to and even equal to the direction of the exit when the visibility is good enough. At this time, the selected direction by memory will be equivalent to that by "follow-the-crowd" as illustrated in Fig. 2(a). This is why the effect of the memory is always better than that of "follow-the-crowd".

3.3. Effect of difference in the memory between evacuees in crowd evacuation in the case of multiple exits

In the case of multiple exits, it is possible that an evacuee may only have memory for the exit he/she is familiar with and evacuate from that exit in an emergency. Thus, in the crowd, evacuees' memories may be different from each other and point to different exits. How does the difference in the memory between evacuees affect the evacuation of pedestrians under poor visibility conditions? To address this question, we design a double-exit scenario by adding a symmetrical exit (4 m) on the left in the previous scenario (see Fig. 4). Evacuees are divided into two types: p_r proportion of the right-evacuees having only memory of the right exit, and (1-p_r) proportion of the left-evacuees having only memory of the left exit. The degree of the memory of the right-evacuees and the left-evacuees is assumed to be φ_r and φ_l respectively.

We conduct the simulations in the new scenario with different proportions p_r, different φ_l vs. φ_r, different visibilities η, and different crowd sizes N. Figure 9 gives the plots of the evacuation time T against φ_l vs. φ_r for different p_r ($p_r = 0.5$, 0.7, and 0.9) in the cases of different visibilities ($\eta = 2$ m, 4 m, and 6 m) and crowd sizes ($N = 50$ and 250). Note that it is possible evacuees cannot evacuate from the room successfully within the time limit. In this case, the evacuation time T cannot be quantified and thus be simply replaced by the set evacuation time limit of 50 s.

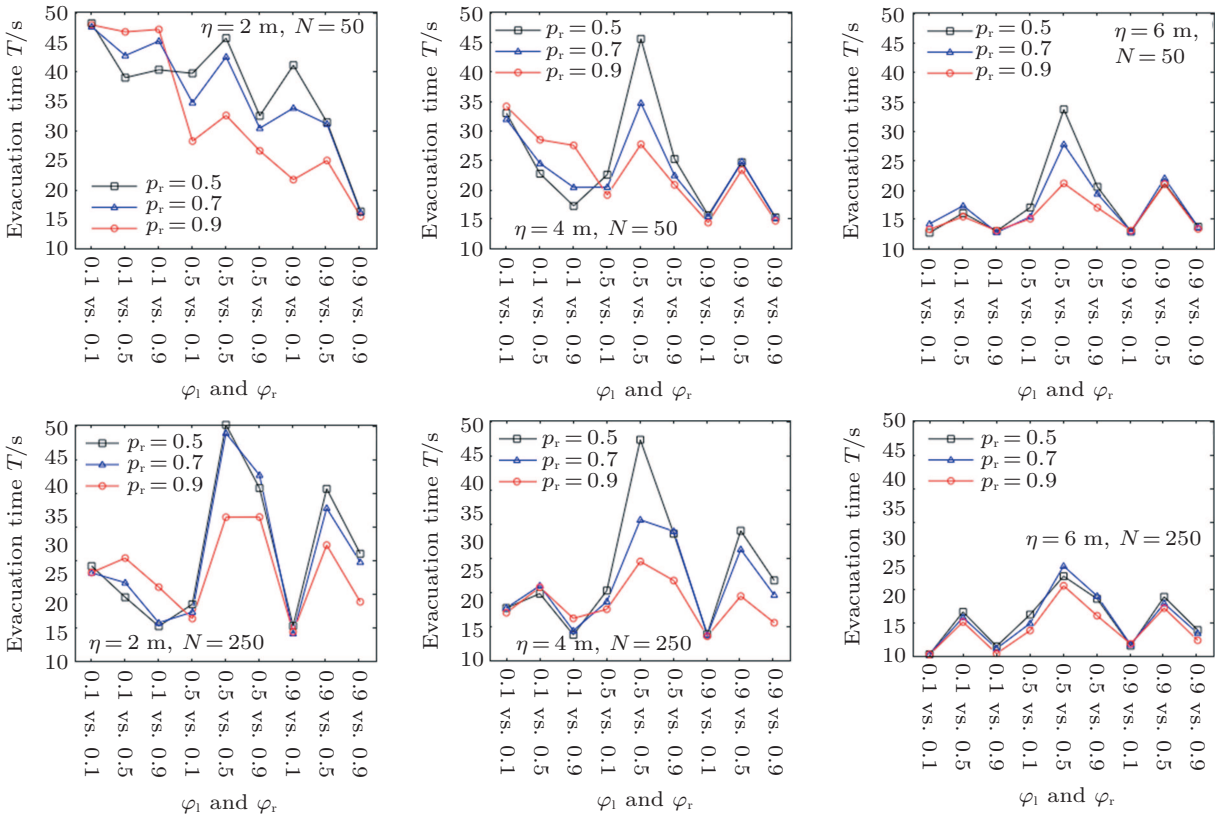


Fig. 9. (color online) Plots of the evacuation time T against φ_l vs. φ_r for different p_r ($p_r = 0.5$, 0.7, and 0.9) in the cases of different visibilities ($\eta = 2$ m, 4 m, and 6 m) and crowd sizes ($N = 50$ and 250).

Figure 9 shows that evacuation time decreases as φ_l vs. φ_r changes from "0.1 vs. 0.1" to "0.9 vs. 0.9," when the visibility and crowd size are both particularly small ($\eta = 2$ m and $N = 50$). This result is similar to that in the case of a single exit (the higher the degree of memory, the better the evacuation performance), because the interaction between the left- and right-evacuees is low in the case of small crowd size and visibility.

The most interesting result is that for most cases (other than $\eta = 2$ m, $N = 50$), the time peak often appears at "0.5 vs. 0.5" while the time bottom often appears at "0.1 vs. 0.9" or "0.9 vs. 0.1" (i.e., the disparity in the degree of memory between the right- and left-evacuees is very high). This result indicates that the higher the disparity in the degree of memory, the faster the evacuation.

The presence of the time peak at "0.5 vs. 0.5" can be ascribed to the interaction between the left- and right-evacuees. Consider the example of a left-evacuee at the middle of the room, under the conditions of large crowd size and visibility. He/she has a high probability of meeting many right-evacuees within the visual field. If the number of right evacuees within the visual field is higher than that of left evacuees, the approximate direction of the neighboring crowd within the visual field will incline to the right exit. At this point, if his/her memory $\varphi_l = 0.5$ (i.e., the memory noise $\theta = \pi/2$), the direction of the neighboring crowd will conflict with the direction of the exit

identified by his/her memory. Given that the memory is dominant, he/she will choose the direction closest to the direction of the neighboring crowd, namely, the +MD ($\cos(\pi/2)$, $\sin(\pi/2)$) or –MD ($\cos(-\pi/2)$, $\sin(-\pi/2)$), as illustrated in Fig. 2(b). Owing to this, he/she will oscillate up or down (i.e., move in the +MD or –MD), as shown in Fig. 10(a).

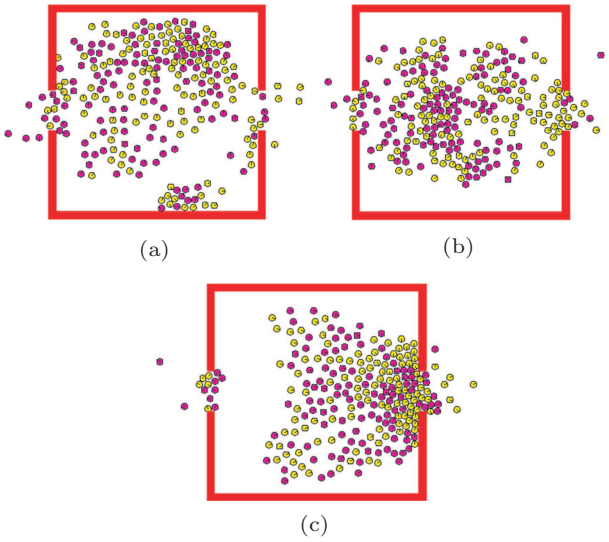


Fig. 10. (color online) Snapshots of simulation in the cases of $N = 250$, $\eta = 2$ m, $p_r = 0.5$, and $\varphi_r = \varphi_l = 0.5$ (a), $N = 250$, $\eta = 2$ m, $p_r = 0.5$, and $\varphi_r = \varphi_l = 0.9$ (b) and $N = 250$, $\eta = 2$ m, $p_r = 0.5$, $\varphi_r = 0.9$ and $\varphi_l = 0.1$ (c). The yellow and purple individuals represent the right- and left-evacuees, respectively.

It is unexpected that the time bottom does not appear at "0.9 vs. 0.9", but at "0.1 vs. 0.9" or "0.9 vs. 0.1" in many cases (e.g., $\eta = 2$ m, $N = 250$). Intuitively, the evacuation time at "0.9 vs. 0.9" should be shorter than that at "0.1 vs. 0.9" or "0.9 vs. 0.1", because "0.9 vs. 0.9" means that nearly all evacuees have full memory and can thus move toward the respective exit directly. The main reason for this unexpected result is that, although both the left- and right-evacuees can move toward the respective exit in the case of "0.9 vs. 0.9", the counter-flow of evacuees (i.e., left-evacuees at the right side of the room escaping toward the left exit, and right-evacuees at the left side of the room escaping toward the right exit, as shown in Fig. 10(b)) will cause many conflicts and collisions. Evacuees need to spend time to solve these conflicts and collisions. However, in the case of "0.1 vs. 0.9" or "0.9 vs. 0.1", although the evacuees with low memory (0.1) cannot get to the exit they memorized, they can reach another exit by following the evacuees with high memory (0.9), as shown in Fig. 10(c). The direction of the entire crowd will converge to the exit memorized by the evacuees with high memory (0.9). Thus, conflicts and collisions between evacuees can be avoided to a considerable extent. Consequently, the evacuation time in this case is shorter than that in the case of "0.9 vs. 0.9".

4. Conclusions

In this study, we have proposed a simple method to quantitatively represent the evacuee's spatial memory about the emergency exit, modeled the evacuation of pedestrians under the guidance of their spatial memory, and investigated the effect of the evacuee's spatial memory on evacuation under poor visibility conditions from the theoretical and the physical perspectives. Specifically, we have found that (i) a good memory can significantly assist the evacuation of pedestrians under poor visibility conditions, and the evacuation always succeeds when the degree of memory exceeds a threshold ($\varphi > 0.5$); (ii) the effect of memory is superior to that of follow-the-crowd under the same environmental conditions; (iii) in the case of multiple exits, differences in the degrees of memory between evacuees may have a significant effect (the higher the difference, the faster the evacuation) on the evacuation under poor visibility conditions.

Our study has provided an extended social force model to simulate the evacuation of pedestrians under the guidance of spatial memory. Compared with the original social force model, the virtual evacuees are given the spatial memory property, representing the evacuees' knowledge about the location of the emergency exit. This new feature enables us to obtain new quantitative insights into the effects of the evacuees' spatial memory on the evacuation under poor visibility conditions. The result of our study also has an important complementary significance for the understanding of the evacuation mechanism of a crowd under dark or smoky environmental conditions.

The following problems will be considered in future work. First, for simplicity, we have not considered the temporal effect of memory (e.g., a pedestrian may forget the exit position as time elapses) in the current model. In future work, we will further consider this important factor and address its effects on the evacuation. Second, in the simulation, we have compared the effectiveness of spatial memory with the behavior of follow-the-crowd. However, we have not considered the compromise between these two effects. Setting a tradeoff or compromise coefficient between these two effects to further analyze the evacuation efficiency will be very meaningful. Third, many important findings can be revealed in the current simulation scenarios. However, these scenarios are relatively simple. More complex scenarios, such as rooms having multiple routes or obstacles should be considered in future work. Fourth, the extended social force model was not calibrated using empirical data, given that available calibration data is scarce. Thus, collecting appropriate empirical data to calibrate the model will be a focus in future works. Finally, it should be noted that the extended social force model was not validated, as it is considerably difficult to measure the memory of actual people and guarantee that it stays static and consistent.

Thus, the results and conclusions are only valid for the current model and suitable to "virtual pedestrians" or agent systems. The model must be carefully examined before applying it to real systems. We will conduct further research to validate the model in future work.

References

[1] Helbing D, Johansson A and Al-Abideen H Z 2007 *Phys. Rev. E* **75** 046109
[2] Zhang J, Song W and Xu X 2008 *Physica A* **387** 5901
[3] Saloma C, Perez G J, Tapang G, Lim M and Palmes-Saloma C 2003 *Proc. Natl. Acad. Sci. USA* **100** 11947
[4] Lin P, Ma J, Liu T, Ran T, Si Y and Li T 2016 *Physica A* **452** 157
[5] Garcimartín A, Pastor J M, Ferrer L M, Ramos J J, Martín-Gómez C and Zuriguel I 2015 *Phys. Rev. E* **91** 022808
[6] Pastor J M, Garcimartín A, Gago P L, Peralta J P, Martín-Gómez C, Ferrer L M, Maza D, Parisi D R, Pugnaloni L A and Zuriguel I 2015 *Phys. Rev. E* **92** 062817
[7] Garcimartín A, Parisi D R, Pastor J M, Martín-Gómez C and Zuriguel I 2016 *J. Stat. Mech.-Theory Exp.* **2016** 043402
[8] Peacock R D, Hoskins B L and Kuligowski E D 2012 *Safety Sci.* **50** 1655
[9] Helbing D and Molnar P 1995 *Phys. Rev. E* **51** 4282
[10] Helbing D, Farkas I and Vicsek T 2000 *Nature* **407** 487
[11] Burstedde C, Klauck K, Schadschneider A and Zittartz J 2001 *Physica A* **295** 507
[12] Kirchner A, Nishinari K and Schadschneider A 2003 *Phys. Rev. E* **67** 056122
[13] Muramatsu M, Irie T and Nagatani T 1999 *Physica A* **267** 487
[14] Kuang H, Li X, Song T and Dai S 2008 *Phys. Rev. E* **78** 066117
[15] Liu S B, Lo S M, Ma J and Wang W L 2014 *IEEE Trans. Intell. Transp. Syst.* **15** 992
[16] Huang H and Guo R 2008 *Phys. Rev. E* **78** 021131
[17] Yue H, Zhang B Y, Shao C F and Xing Y 2014 *Chin. Phys. B* **23** 050512
[18] Kuang H, Song T, Li X L and Dai S Q 2008 *Chin. Phys. Lett.* **25** 1498
[19] Wang L, Zheng J, Zhang X, Zhang J, Wang Q and Zhang Q 2016 *Chin. Phys. B* **25** 685
[20] Isobe M, Helbing D and Nagatani T 2004 *Phys. Rev. E* **69** 066132
[21] Nagai R, Nagatani T, Isobe M and Adachi T 2004 *Physica A* **343** 712
[22] Shi J, Ren A and Chen C 2009 *Automat. Constr.* **18** 338
[23] Guo R Y, Huang H J and Wong S C 2012 *Transport. Res. Part B* **46** 669
[24] Guo R Y and Huang H J 2012 *Simulation* **88** 1138
[25] Xia Y, Wong S C and Shu C W 2009 *Phys. Rev. E* **79** 066113
[26] Nguyen M H, Ho T V and Zucker J D 2013 *Simul. Model. Pract. Th.* **36** 44
[27] Ma P and Wang B 2013 *Physica A* **392** 215
[28] Yue H, Wang S, Jia X, Li J and Shao C 2016 *Simulation* **92** 491
[29] Hou L, Liu J G, Pan X and Wang B H 2014 *Physica A* **400** 93
[30] Cao S, Song W and Lv W 2016 *Phys. Lett. A* **380** 540
[31] Fang J, El-Tawil S and Aguirre B 2016 *Safety Sci.* **83**
[32] Low D J 2000 *Nature* **407** 465
[33] Zeng W, Chen P, Nakamura H and Iryo-Asano M 2014 *Transport. Res. Part C* **40** 143
[34] Zeng W, Chen P, Yu G and Wang Y 2017 *Transport. Res. Part C* **80** 37
[35] Wang L, Zheng J H, Zhang X S, Zhang J L, Wang Q Z and Zhang Q 2016 *Chin. Phys. B* **25** 118901