Journal Pre-proof

An evacuation model considering the phototactic behavior of panic pedestrians under limited visual field

Chenglin Guo, Feizhou Huo, Chao Li, Yufei Li

PII: S0378-4371(23)00157-7
DOI: https://doi.org/10.1016/j.physa.2023.128602
Reference: PHYSA 128602

To appear in: *Physica A*

Received date : 15 November 2022
Revised date : 18 January 2023

Please cite this article as: C. Guo, F. Huo, C. Li et al., An evacuation model considering the phototactic behavior of panic pedestrians under limited visual field, *Physica A* (2023), doi: https://doi.org/10.1016/j.physa.2023.128602.

Highlights:

A multi-model coupled meta-cellular automata model considering emotional contagion and phototropic behavior is developed.

The effects of individual heterogeneity and environmental differences on emotional contagion are considered.

The way pedestrians move varies depending on the area they are in and their emotional state.

The concept of "phototactic field" is proposed to realize the phototactic movement of the panic pedestrian.

The influences of single light source and multiple light sources on the evacuation process are studied.

An evacuation model considering the phototactic behavior of panic pedestrians under limited visual field

Chenglin Guo[a,b], Feizhou Huo[a,b,*], Chao Li[a,b], Yufei Li[a,b]

[a] *School of Safety Science and Emergency Management, Wuhan University of Technology, China*

[b] *China Research Center for Emergency Management, Wuhan University of Technology, China*

Abstract: In the emergency evacuation process, pedestrians affected by their panic will have evacuation behavior that rushes toward the light. To study the impact of panic pedestrian phototactic behavior on the evacuation process, a multi-model coupled cellular automata model is proposed. First, a heterogeneous model of emotional contagion based on the OCEAN model and the SIS model is established, which considers the influence of individual characteristics such as personality, gender, and age on emotional contagion, and the increase and decay of pedestrian emotion are also correlated with their location. Next, the "guidance field", "orienteering field", "herding field" and "phototactic field" are introduced to build an extended cellular automata model, pedestrians in different areas have different movement modes, and pedestrians with different emotional states in the same area also differ. Finally, the phototactic behavior of pedestrians in evacuation is reproduced by simulation, and the effects of factors such as emotional threshold, information transfer, visual field distance, light source position, and multiple light sources interference on the evacuation process are discussed. The results show that whether phototactic behavior is favorable or unfavorable to evacuation depends on the position of the light source. When the light source is located at the exit can guide pedestrians to escape, while located in other places will trigger local congestion. Increases in the emotional threshold, information transfer, and visual field distance can effectively mitigate the adverse effects of phototactic behavior. Additionally, the light sources in other positions will cause some interference with the light sources at the exit when multiple light sources exist, prolonging the evacuation time. Our research can provide some guidance for designing building structures and developing evacuation strategies in emergency situations.

Keywords: Pedestrian evacuation; Limited visual field; Emotional contagion; Phototactic behavior; Cellular automata

1. Introduction

In recent years, with the deepening of urbanization in the world, many people are gathering in various closed buildings, leading to a massive challenge for pedestrian evacuation during emergencies. After earthquakes, fires, and other emergencies occur in public places, pedestrians often cannot make judgments and decisions based on rational thinking when choosing the escape path due to their panic. The whole evacuation process has a lot of unreasonable evacuation behaviors, such as rushing toward the light, blindly following the crowd, and risking to return, which can easily lead to escape errors and cause casualties [1]. Therefore, to reduce losses and develop effective evacuation strategies, it is of great significance to study the emotional contagion and corresponding evacuation behaviors in the evacuation process under emergencies.

At present, scholars in various countries mainly use experiments [2,3] and simulation models [4,5] to conduct research on pedestrian evacuation. By carrying out pedestrian movement and evacuation experiments, the most realistic experimental phenomena can be observed, and the most original data information can be obtained. This provides scientific basis and data support for the establishment of models and the design of software, and can also be used for the later calibration of parameters and verification of results. However, the experiments are difficult to carry out widely because they require a lot of manpower and material resources and have certain dangers. With the rapid development of computer technology, increasing scholars focus on building simulation models for evacuation. Existing evacuation simulation models can be broadly divided into macroscopic and microscopic models. The macroscopic model treats pedestrians as fluids and analyzes pedestrian motion through the relationship between flow, density, and velocity [6]. It pays more attention to the motion rules that control the behavior of the global crowd while ignoring individual characteristics, so it is difficult to obtain fine results reflecting individual diversity. The microscopic model discusses pedestrian movement from the individual perspective to explore individual behaviors and interactions [7]. It can more realistically present the movement characteristics of pedestrians in groups, mainly including continuous models represented by the social force model [8] and discrete models represented by the cellular automata model [9]. Among them, the cellular automata model is widely used due to its advantages of simple calculation, wide application range, and convenient rule modification [10].

In terms of emotional contagion during evacuation, because emotion is caused by emergencies and acts on the crowd for a short time, with characteristics of suddenness and irreproducibility, so it is difficult to quantitatively define the spread of emotion with experimental methods, and the combination of infectious disease models and microscopic models is often used for research. Fu et al. [11] combined the SIR model with the cellular automata model, arguing that emotional contagion is similar to the spread of disease to simulate the dynamic contagion of emotion in the crowd. Cao et al. [12] combined the OCEAN model and the SIS model to construct the P-SIS emotional contagion model and then added it to the social force model to simulate emotional contagion during evacuation. Xiao et al. [13] considered individual speed changes and direction perception domains, and constructed a dynamic pedestrian evacuation model with emotional contagion based on the SIS model and the cellular automata model. Shang et al. [14] considered that the research on emotional contagion mainly focused on panic and ignored the rationality of pedestrians, so they proposed a game theory-based pedestrian evacuation model incorporating emotional contagion. In addition, the ASCRIBE model proposed by Bosse et al. [15-16] is also a typical emotional contagion model, which is a continuous individual interactive model, and its contagion process is similar to the heat dissipation phenomenon in thermodynamics. Among the many irrational behaviors under panic, phototactic behavior is one of the main ones, usually occurring in situations of limited visual field due to smoke, power failure, and so on. Actual case investigations have shown that people are phototropic when escaping. In the case of lighting system failure or dense smoke, human nature and instinct make people unconsciously take the bright direction as the action target [17]. Wang et al. [18] found through empirical experiments that a fair number of pedestrians will find the exit by following natural light. Lovreglio et al. [19] studied the influencing factors of pedestrian evacuation and showed that light significantly affects the choice of exit during evacuation. Dijkstra et al. [20] measured individuals' egress preference in wayfinding through virtual navigation experiments and showed that individuals tend to choose brighter and wider egress. Taylor et al. [21] conducted experiments with a constructed scenario and demonstrated that the illumination of a channel in pathfinding significantly affects people's choices. Vilar et al. [22,23] obtained similar results in both normal and emergency situations based on virtual reality, and found that the brightness of evacuation channels may have a more significant impact on wayfinding than evacuation signs under certain circumstances [24]. Some studies have also explored the use of flashings [25] or dynamic exit signages [26] that could enhance wayfinding guidance for pedestrians.

It can be seen that although there are some studies on pedestrian phototactic behavior, most of them are observed and analyzed through experiments or virtual reality. This behavior may have yet to receive attention in the current simulation field of pedestrian evacuation, and the research on the specific impact of panic on this behavior is also relatively blank. Therefore, this paper aims to study the emotional contagion and the corresponding phototactic behavior during evacuation based on microscopic simulation, in order to provide some reference and basis for the subsequent research and management of this behavior.

In this paper, a multi-model coupled cellular automata evacuation model is established to study the phototactic behavior of panic pedestrians under limited visual field. The rest of this paper is as follows: Section 2 introduces the coupled cellular automata model, which mainly includes two parts: the emotional contagion model and the pedestrian movement model. Section 3 explores the effects of several critical factors on pedestrian evacuation and discusses the simulation results. Section 4 gives the conclusion.

2. Model

The model in this paper is mainly composed of the emotional contagion model and the pedestrian movement model, and the individual's evacuation strategy is jointly determined by the pedestrian's emotional state and range of vision. Emotional states are classified as "normal state" and "panic state" according to the panic level of pedestrians, and they can be converted to each other when certain conditions are met. The range of vision is the area within the pedestrian's visual field distance R_v, according to which the evacuation space can be divided into three parts: the exit visible area, the wall visible area, and the blind movement area [27], as shown in Fig. 1. Pedestrians located in different areas will have different emotional contagions and movement modes, and there are also differences in the movement modes of pedestrians with different emotional states in the same area.

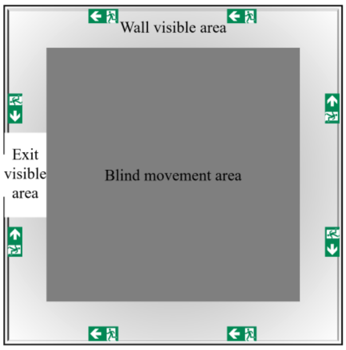


Fig. 1. Division of areas within the evacuation space.

2.1. Emotional contagion model

2.1.1. Heterogeneity of pedestrians

Emotion is a psychological response that accompanies a person's feelings, perceptions, and behaviors. During emergency evacuation, various factors such as age, gender, personality, evacuation experience, physical condition, and cultural differences of the affected population can impact pedestrians' perception of panic and lead to differences in evacuation behavior [28]. However, most of the existing emotional contagion models belong to isomorphic models, which do not consider the influence of individual characteristics. Therefore, this paper develops a heterogeneous emotional contagion model that mainly considers three heterogeneous factors: personality, gender, and age [29], as shown in Fig. 2.

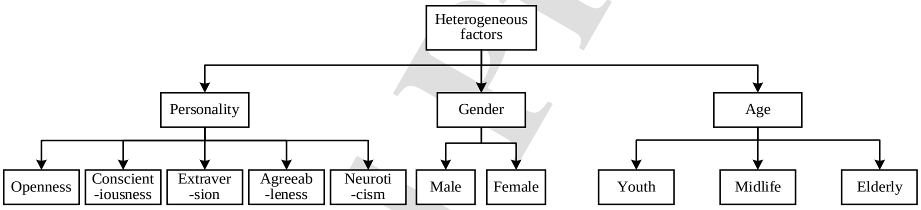


Fig. 2. Heterogeneous factors.

(1) Personality factors

Individuals with different personalities respond differently to emergencies. For example, people who are sensitive to their emotional changes and have a higher emotional response are more susceptible to panic [12]. The OCEAN model [30] is the most widely used personality model today, which describes an individual's personality in five dimensions, including openness, conscientiousness, extraversion, agreeableness, and neuroticism. Therefore, this paper assumes that each pedestrian has five personality factors of $\{p_O, p_C, p_E, p_A, p_N\}$, and the values are between [0,1]. The relationship between an individual's ability to express and perceive emotions and personality is shown in Table 1 [31].

Table 1

Relationship between personality and emotional contagion.

Personality	Expression ability	Perception ability
Openness	No	Positive
Conscientiousness	Positive	Positive
Extraversion	Positive	No
Agreeableness	Positive	Positive
Neuroticism	No	Linear

(2) Gender factors

When faced with the same external stimuli, males and females perceive and express emotions differently.

Compared with males, females are more sensitive to risk during evacuation, more susceptible to the emotions of surrounding individuals, and more likely to influence others [32]. Therefore, this paper defines the gender panic factor p_g to represent the effect of individual gender differences on emotional contagion, $p_g \sim N\left(\mu_g, \sigma_g^2\right)$, the specific division is shown in Table 2.

Table 2

The division of gender panic factors.

Gender	μ_g	σ_g
Male	-0.25	0.3
Female	0.25	0.3

(3) Age factors

In emergencies, individuals of different ages have different perceptions and expressions of emotions. The older the individual is, the more rational the perception of risk due to life experience, the less susceptible to surrounding negative emotions, and the more sensible the performance of their own emotions [33]. Similarly, the age panic factor p_a is defined to indicate the effect of individual age differences on emotional contagion, $p_a \sim N\left(\mu_a, \sigma_a^2\right)$, the details are shown in Table 3.

Table 3

The division of age panic factors.

Age	μ_a	σ_a
Elderly	-0.5	0.2
Midlife	0	0.2
Youth	0.5	0.2

From this, two individual parameters of pedestrians are defined: emotional expression ability q_I, which is the ability of the individual to translate internal panic into external manifestation; emotional perception ability q_S, which is the individual's sensitivity and the degree of vulnerability to panic. The calculations are shown in Eqs. (1)~(2):

$$q_I = k_p\left(p_C + p_E + p_A\right) + k_g p_g + k_a p_a \tag{1}$$

$$q_S = k_p\left(p_O + p_C + p_A\right)p_N + k_g p_g + k_a p_a \tag{2}$$

where k_p, k_g, k_a are the sensitivity coefficients of each factor, and the values are 0.2, 0.5, and 0.5, respectively.

2.1.2. Emotional contagion mechanism and quantification

(1) Emotional contagion mechanism

Pedestrians are prone to panic during emergency evacuation, which has a strong infectious ability and directly affects the evacuation process. The SIS model is one of the most classic infectious disease models, and this paper uses it to simulate the spread of panic. In the model, "S" represents the "normal state" individual, who is the receiver of emotions. "I" represents the "panic state" individual, who is the transmitter of emotions and can also receive panic. Based on the emotional threshold λ_{emo} to achieve dynamic changes in the individual's emotional state. λ_{emo} is the emotional critical value for normal and panic states. If the emotional intensity of the normal state individuals is higher than λ_{emo}, they will turn into the panic state with probability β. If the emotional intensity of panic state individuals is lower than λ_{emo}, they will turn into the normal state with probability γ. β and γ are the infection and calm coefficients, respectively, and both values are 0.5 in this paper [13].

(2) Emotional quantification

The level of panic individuals experience during evacuation is related to the type of emergency, the surrounding environment, their own emotions, and the emotions of others around them [11]. This model uses the emotional parameter $E_m(t)$ to quantify the panic level of pedestrians, $E_m(t) \in [0,1]$, and the calculation is shown in Eq. (3):

$$E_m(t) = E_m(t-1) + E_{inc} + E_{dec} \tag{3}$$

where $E_m(t)$ and $E_m(t-1)$ are the emotional intensity of individual m at times t and t-1, respectively; E_{inc} denotes the increase of emotion; E_{dec} denotes the decay of emotion.

Considering the difference between the limited visual field environment and the ordinary environment, the increase of pedestrian emotion in this paper is not only influenced by the surrounding others but also correlated with the time it stays in the unseen environment. That is, when pedestrians are in the blind movement area, the dark environment and the lack of movement target will lead to the continuous growth of panic, but pedestrians are not affected by this factor when they are in the wall or exit visible area, the calculations are shown in Eqs. (4)~(6):

$$E_{inc} = q_S\left(E_{oth} + E_{env}\right) \tag{4}$$

$$E_{oth} = \sum_{d_{mn}<R_e} q_I E_n(t-1)\left(1 - \frac{1}{1+e^{-d_{mn}}}\right) \tag{5}$$

$$E_{env} = \begin{cases} 1-e^{-\alpha\tau}, & \text{In the blind movement area} \\ 0, & \text{In the wall or exit visible area} \end{cases} \tag{6}$$

where E_{oth} indicates the increment caused by the contagion of surrounding individuals; $E_n(t-1)$ is the emotional intensity of the surrounding panic state individual n at time t-1; d_{mn} is the distance between individuals; R_e is the emotional perception distance, the value is 1.6m [11]; E_{env} indicates the increment caused by the surrounding environment; α is the time correction factor, the value is 0.01; τ is the time that the pedestrian stays in the blind movement area.

The decay of pedestrian emotion is generated by the inner satisfaction that comes from the increased hope of escape [12]. Similarly, it is also related to the location of the pedestrian. When pedestrians are in the blind movement area, the panic will not decay; when they are in the wall visible area, the panic will decay as the hope of escape increases; when they are in the exit visible area, the panic will be significantly attenuated, which is correlated to the distance from the pedestrian to the exit, the expression is shown in Eq. (7):

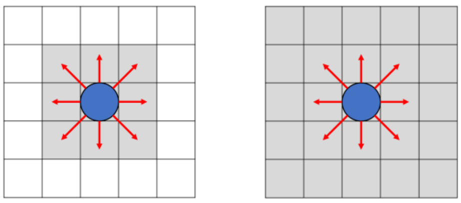
$$E_{dec} = \begin{cases} 0, & \text{In the blind movement area} \\ e^{\delta\text{-}1} E_m(t-1), & \text{In the wall visible area} \\ \left(\delta d_{ij,e}\right)^{-1} E_m(t-1), & \text{In the exit visible area} \end{cases} \tag{7}$$

where δ is the decay rate and the value is 0.1; $d_{ij,e}$ is the length of the shortest path from the cell *(i,j)* to the exit.

2.2. Pedestrian movement model

2.2.1. Extended cellular automata model

The cellular automata model considering the phototactic behavior of panic pedestrians under limited visual field is built in a two-dimensional grid with a cell size of 0.4m×0.4m. Each cell can be empty or occupied by pedestrians and obstacles. Considering the influence of the limited visual field environment on the moving speed of pedestrians, two types of cell neighborhoods are used: Moore neighborhood and extended Moore neighborhood, as shown in Fig. 3. When pedestrians are in the blind movement area, because there is no clear moving target and reference, their speed is slower and move according to the Moore neighborhood. When pedestrians are in the wall or exit visible area, they will move along the wall or directly to the exit, so their speed is faster and move according to the extended Moore neighborhood.



(a) Moore neighborhood (b) Extended Moore neighborhood

Fig. 3. The cell neighborhoods.

Individuals will move to the unoccupied cells in the corresponding neighborhood based on a certain probability when evacuating. P_{ij} is the transfer probability of cell *(i,j)*, which is calculated as shown in Eq. (8):

$$P_{ij} = N\exp\left(k_S S_{ij} + k_G G_{ij} + k_O O_{ij} + k_H H_{ij} + k_L L_{ij}\right)\left(1-\eta_{ij}\right)\varepsilon_{ij} \tag{8}$$

where N is the normalization factor to ensure $\sum P_{ij} = 1$; S_{ij}, G_{ij}, O_{ij}, H_{ij}, L_{ij} are the static field, guidance field, orienteering field, herding field, and phototactic field, respectively; k_S, k_G, k_O, k_H, k_L are the sensitivity coefficients of each field, the values are [0,1], and $k_S + k_G + k_O + k_H + k_L = 1$; η_{ij} indicates whether the target cell *(i,j)* is occupied by obstacles, if the cell is an obstacle, η_{ij} =1, otherwise η_{ij} =0; ε_{ij} indicates whether the target cell *(i,j)* is occupied by pedestrians, if the cell is occupied by a pedestrian, ε_{ij} =0, otherwise ε_{ij} =1.

(1) The static field

The static field represents the attractiveness of the exit to pedestrians, which does not vary with time or pedestrians. The value is inversely proportional to the shortest distance from the cell to the exit. The smaller the distance, the greater the field strength, and vice versa. The expression is shown in Eq. (9):

$$S_{ij} = \max_{(i,j)}\left\{\min_{e_k}\left\{\sqrt{\left(x_{e_k} - x_{ij}\right)^2 + \left(y_{e_k} - y_{ij}\right)^2}\right\}\right\} - \min_{e_k}\left\{\sqrt{\left(x_{e_k} - x_{ij}\right)^2 + \left(y_{e_k} - y_{ij}\right)^2}\right\} \tag{9}$$

where k is the number of exits; e_k means the kth exit; x_{e_k} and y_{e_k} represent coordinate values of the kth exit; x_{ij} and y_{ij} represent coordinate values of the cell *(i, j)*.

(2) The guidance field

In public places, evacuation signs are usually installed on walls to help people evacuate effectively in emergencies. The guidance field represents the guiding effect of evacuation signs on pedestrians [34], and is calculated as Eq. (10). When the pedestrian is in the wall visible area, it will move along the wall in the direction pointed by the evacuation signs, but need not be strictly against the wall, as shown in Fig. 4.

$$G_{ij} = \begin{cases} d_{mw}\cos\theta + 1, & \text{Direction indicated by the evacuation sign} \\ d_{mw}\cos\theta - 1, & \text{Direction opposite to the evacuation sign} \end{cases} \tag{10}$$

where d_{mw} is the straight-line distance from the pedestrian to the wall ahead; θ is the angle at which pedestrians deviate from the wall where the evacuation sign is located.

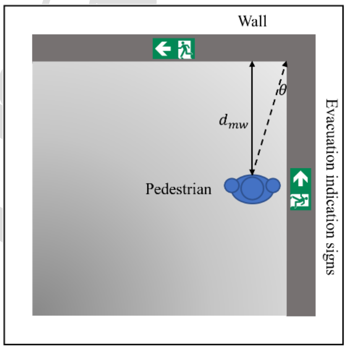


Fig. 4. Schematic diagram of movement along the wall.

(3) The orienteering field

When emergencies such as fires and power outages occur in buildings, it is often difficult for pedestrians to identify the evacuation location and direction at the first time, and they tend to choose a certain direction randomly to move. The orienteering field represents the no backward movement of a pedestrian groping forward in a general direction under limited visual field [35], and the expression is shown in Eq. (11):

$$O_{ij} = \begin{pmatrix} o_1 & M & M \\ o_2 & 0 & M \\ o_3 & M & M \end{pmatrix} \tag{11}$$

where o_k indicates the random field value of the three moving directions ahead, $o_k \in [0,1]$, k=1, 2, 3; M is infinitely negative to ensure no backward motion of the pedestrian.

Considering the memory effect and direction perception of pedestrians in reality, pedestrians still have a subconscious awareness of the evacuation space in their brains under the condition of limited visual field [36], and relying on this subconscious effect can motivate pedestrians to choose a reasonable direction of movement to some extent. Therefore, the probability Q_{rig} of pedestrians choosing the direction pointing to the wall where the exit is located is set to be greater than the other directions, as shown in Eq. (12):

$$Q_{rig} = \omega Q_{wro} \tag{12}$$

where ω takes the value of 2; Q_{wro} indicates the probability of pedestrians choosing a direction other than the direction of the wall where the exit is located.

(4) The herding field

If pedestrians are in an unfamiliar environment and cannot find the exit in time, they often lose their independence. Especially in a state of panic, they prefer to move in the direction with the most pedestrians within their range of vision [37]. The herding field indicates the effect of other pedestrians within the range of vision on evacuated individuals, and the expression is shown in Eqs. (13)~(14). As shown in Fig. 5, the pedestrian's range of vision consists of eight colored regions corresponding to eight directions of motion.

$$H_{ij} = \begin{pmatrix} h_1 & h_2 & h_3 \\ h_4 & 0 & h_5 \\ h_6 & h_7 & h_8 \end{pmatrix} \tag{13}$$

$$h_k = \frac{n_k}{n_{all}} \tag{14}$$

where n_k is the number of pedestrians in direction k within the range of vision, k=1, 2…8; n_{all} is the number of all pedestrians within the range of vision; h_k denotes the ratio of the number of pedestrians in direction k to the number of all pedestrians in the eight directions within the range of vision.

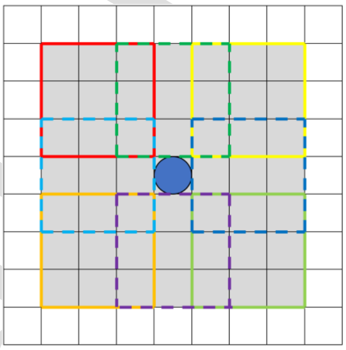


Fig. 5. Schematic diagram of range of vision.

(5) The phototactic field

Pedestrians are phototactic when evacuating in emergencies such as fires and power outages, and light has a significant impact on their choice of escape routes [17]. The phototactic field represents the attraction of the light source to pedestrians under the condition of limited visual field, which varies with the position of the light source and takes a value inversely proportional to the distance from the cell to the light source. The expression is shown in Eq. (15):

$$L_{ij} = -\min_{(x_{l_k}, y_{l_k}) \in \kappa} \sqrt{\left(x_{l_k} - x_{ij}\right)^2 + \left(y_{l_k} - y_{ij}\right)^2} \tag{15}$$

where κ indicates the cell coordinate set of all light sources; k is the number of light sources; l_k means the kth light source; x_{l_k} and y_{l_k} represent coordinate values of the kth light source.

2.2.2. Normal state pedestrian movement rules

Pedestrians in the normal state are the calmer group in the scene and usually adopt rational evacuation strategies. But in the case of limited vision caused by smoke and power failure, it is difficult for most pedestrians to know the location of the safety exit at the first time. Therefore, when a normal state pedestrian is in the blind movement area, it will usually make a no backward movement in a rough direction until it enters the other two areas; when in the wall visible area, it will move along the wall according to the evacuation signs; and when in the exit visible area, it will take the shortest path to the exit to escape. The coefficients of each field for the normal state pedestrians are shown in Eq. (16):

$$\begin{cases} k_G = k_O = k_H = k_L = 0, k_S = 1, & \text{In the exit visible area} \\ k_S = k_O = k_H = k_L = 0, k_G = 1, & \text{In the wall visible area} \\ k_S = k_G = k_H = k_L = 0, k_O = 1, & \text{In the blind movement area} \end{cases} \tag{16}$$

2.2.3. Panic state pedestrian movement rules

Pedestrians in the panic state are individuals who are greatly affected by panic in the scene. It is usually difficult for them to take a rational evacuation strategy, and they will be influenced by the light source and the surrounding pedestrians in the evacuation process. Therefore, when the panic state pedestrian is outside the exit visible area, it will move under the coupling effect of the herding field and the phototactic field until it reaches the vicinity of the light sources or exit. If pedestrians find it impossible to escape or obtain exit information at the light source as they move toward it, they will change the evacuation strategy and then make a no backward movement or walk along the wall, and may pass this information to the surrounding pedestrians through body language, loud shouting, and other methods [38], where the information transmission distance is R_t and the information transmission probability is φ. The coefficients of each field for the panic state pedestrians are shown in Eq. (17):

$$\begin{cases} k_G = k_O = k_H = k_L = 0, k_S = 1, & \text{In the exit visible area} \\ k_S = k_G = k_O = 0, & \\ k_H = \dfrac{k_h e^{-\zeta E_m(t)}}{k_h e^{-\zeta E_m(t)} + k_l e^{\zeta E_m(t)}}, & \text{In the wall visible area or blind movement area} \\ k_L = \dfrac{k_l e^{\zeta E_m(t)}}{k_h e^{-\zeta E_m(t)} + k_l e^{\zeta E_m(t)}}, & \end{cases} \tag{17}$$

where k_h and k_l denote the initial sensitivity coefficients of the herding field and the phototactic field, with values of 0.7 and 0.3, respectively, which affect the corresponding sensitivity coefficients together with $E_m(t)$; ζ is the correction factor and takes the value of 0.5 [10].

2.3. Model assumptions

This paper tries to explore the influence of phototactic behavior on evacuation under limited visual field as realistically as possible, but due to the complexity of the evacuation process, the following assumptions should be made in the simulation:

(1) The light source in the scene mainly refers to the relatively weak light generated by natural light, flash lamps or emergency lighting facilities, which is not enough to illuminate a large area.

(2) Due to factors such as power outages and smoke, pedestrians can only see a certain area within the range of vision. However, light is penetrating and therefore not affected by this factor.

(3) Only when the light source appears in the pedestrian's range of vision, the pedestrian can see whether they can escape or get exit information at the light source.

2.4. Update Rules

The model adopts a synchronous parallel update rule, and people update their positions synchronously in each time step. When multiple pedestrians want to enter a cell simultaneously and compete, a pedestrian is randomly selected to enter, and the other pedestrians wait in place. The specific rules are shown in Fig. 6.

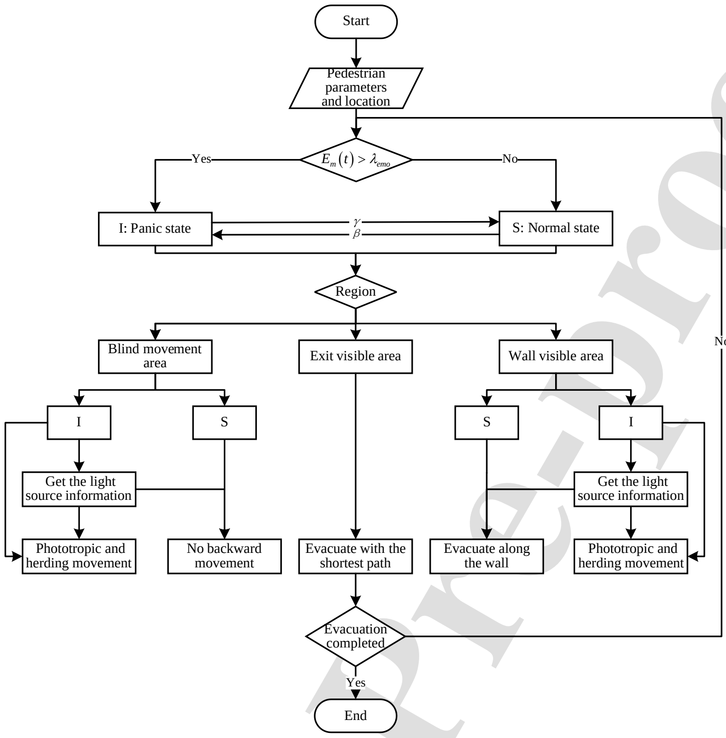


Fig. 6. Update rules.

3. Evacuation simulation and results analysis

The simulated scene is shown in Fig. 7, which is a 24m×24m single-exit room and is discrete into 60×60 cells. In the figure, black, yellow, blue, and red cells represent walls, light sources, pedestrians in the normal state, and pedestrians in the panic state, respectively. The gray background represents the limited visual field environment. In the initial scene, the light source is located in the center but does not occupy the actual space. Pedestrians are randomly distributed within the scene, gender and age are divided equally, and the initial emotional intensity value obeys the normal distribution function $E_m(t=0) \sim N(0.1, 0.4^2)$. In this paper, the evacuation time is represented by time step T. And to reduce errors, all data are the average of 25 simulation results.

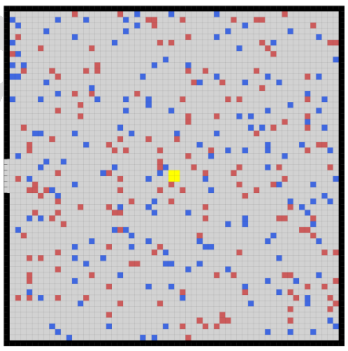
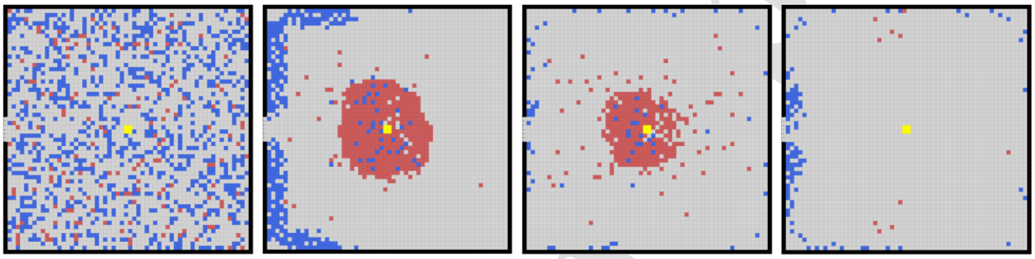


Fig. 7. Simulation scene.

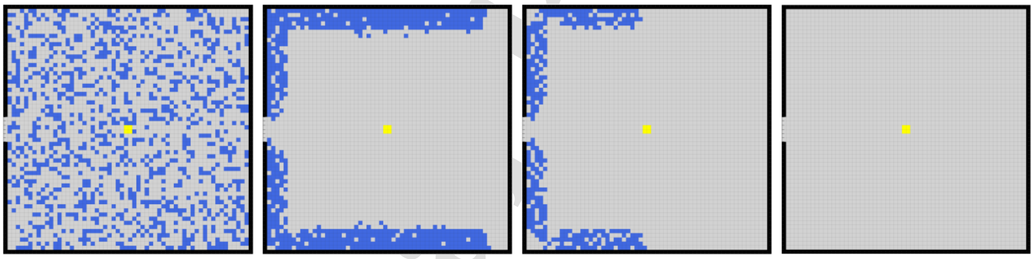
3.1. Effect of panic on the evacuation process

To study the effect of panic on the evacuation process, a comparative simulation with and without emotion is performed. Fig. 8 shows the distribution of people in two situations at different T, where ρ=0.3, R_v =2m, and when panic is considered, λ_{emo} =0.5, R_t =0.4m, and φ=0.01. From Fig.8, there is a significant difference between the evacuation processes in the two cases. When considering emotions, pedestrians in the panic state will be affected by the light source in the scene to produce phototactic behavior, while pedestrians in the normal state will not be affected, resulting in pedestrians being divided into two groups of evacuating along the wall and tending to the light source in the early stage of evacuation. Among them, people who want to leave the light source and tend to the light source will create local congestion near the light source. As information passed between individuals, the congestion only began to dissipate as more pedestrians learned that they could not escape or get exit information at the light source. Dissipated pedestrians evacuate as instructed upon reaching the wall or exit visible area, and become normal state pedestrians as the panic decays. When emotions are not considered, the crowd will not be affected by the light source, and most of the time will evacuate along the wall in the wall visible area. In addition, there is an apparent "edge effect" near the exit in both cases, pedestrians escape mainly through the locations on both sides of the exit, while the central area is less utilized due to the need for detours.



T=0 *T*=80 *T*=160 *T*=240

(a) With considering the influence of emotion



T=0 *T*=80 *T*=160 *T*=237

(b) Without considering the influence of emotion

Fig. 8. Snapshots at different time steps with and without emotion.

3.2. Effect of emotional thresholds

To further analyze the effect of panic on evacuation time, Fig. 9 shows the change of evacuation time with the emotional threshold under different pedestrian densities, where R_v =2m, R_t =0.4m, φ=0.01. As shown in Fig. 9, the evacuation time under different pedestrian densities is negatively correlated with the emotional threshold. As the emotional threshold increases, on the one hand, the emotional contagion among pedestrians will be reduced, on the other hand, it becomes more difficult for pedestrians to transform into the panic state. Thus, more pedestrians will be in the normal state not to produce phototactic behavior, effectively alleviating the congestion near the light source. However, the emotional threshold affects the evacuation time differently under different pedestrian densities. When ρ≥0.3, the evacuation time is obviously affected by λ_{emo} and is always in attenuation; when ρ=0.2, the evacuation time does not change significantly after λ_{emo} >0.5; and when ρ=0.1, the evacuation time is rarely influenced by λ_{emo} throughout. It can be seen that the higher the pedestrian density, the more easily panic spreads in the crowd, and the more significant the impact of pedestrians' phototactic behavior on evacuation time.

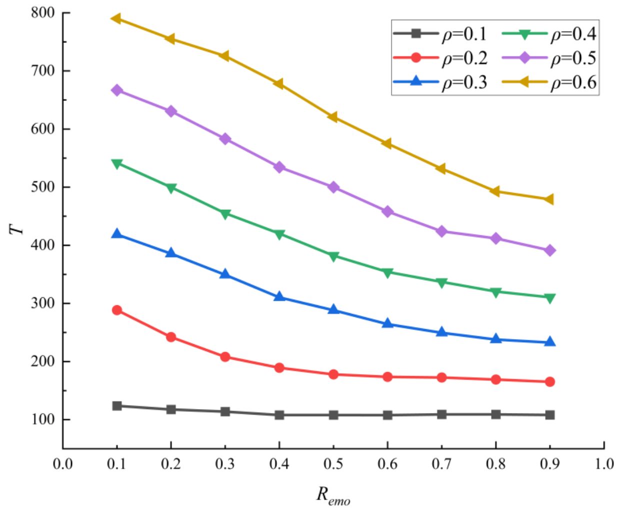


Fig. 9. Variation of evacuation time with the emotional threshold at different pedestrian densities.

3.3. Effect of information transfer

Fig. 8 shows that when panic is considered, the crowd will produce serious local congestion in the vicinity of the light source, and the dissipation speed of the packed crowd is the key to affecting evacuation efficiency at this time. Considering the information transfer between individuals can make pedestrians know the information at the light source in advance and effectively alleviate the congestion. For this purpose, the variation of evacuation time with different information transfer distance and information transfer probability is simulated, and the results are shown in Fig. 10, where ρ=0.3, R_v =2m, and λ_{emo} =0.5. From Fig. 10, the increase in the distance and probability of information transfer can have a positive effect on evacuation. Information transfer can make pedestrians who arrive near the light source spread the information at the light source quickly to the periphery, and pedestrians who are still in the process of tending to the light source can choose in advance whether to continue tending to it after receiving information, thereby reducing the scale of reverse pedestrian flow. Meanwhile, this positive effect is more apparent when R_t increases from 0.4m to 0.8m and φ increases from 0.005 to 0.015. The result is minor after continuing to grow and even has some negative impact, because too many pedestrians changing their moving targets early may lead to congestion at other locations.

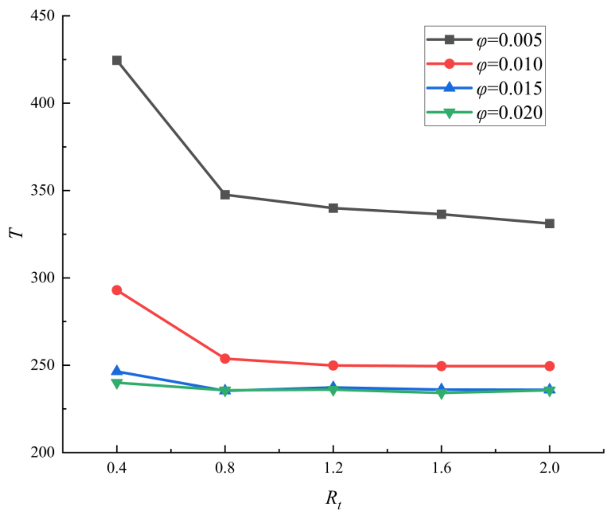


Fig. 10. Evacuation time with different information transfer distance and transfer probability.

3.4. Effect of visual field distance

Visual field distance is the first element for pedestrians to judge evacuation information, the larger it is, the richer the information and the more accurate the pedestrian's choice of evacuation direction and strategy. Therefore, the change of evacuation time at different visual field distances is simulated, and the results are shown in Fig. 11, where λ_{emo} =0.5, R_t =0.4m, and φ=0.01. From Fig. 11, the evacuation time decreases with the increase of the visual field distance at the same pedestrian density. On the one hand, the increased visual field distance allows the wall and exit visible area to be expanded. More people can get exit information to go directly to the exit or evacuate along the wall. On the other hand, it can allow pedestrians to learn about the light source earlier and judge whether to continue tending to the light source. It is worth noting that the R_v has a significant effect on reducing evacuation time in the process of increasing from 1.2m to 2.8m, and the result is no longer evident after continuing to grow, especially at lower pedestrian densities. Because when R_v =2.8m, the impact of the light source on pedestrians has been minimal, most pedestrians have been able to choose a reasonable movement target and direction based on the information seen, continuing to increase may instead lead to congestion near the exit or wall.

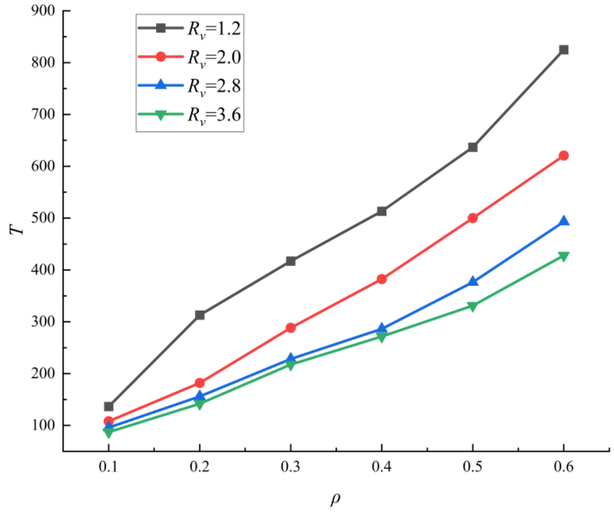
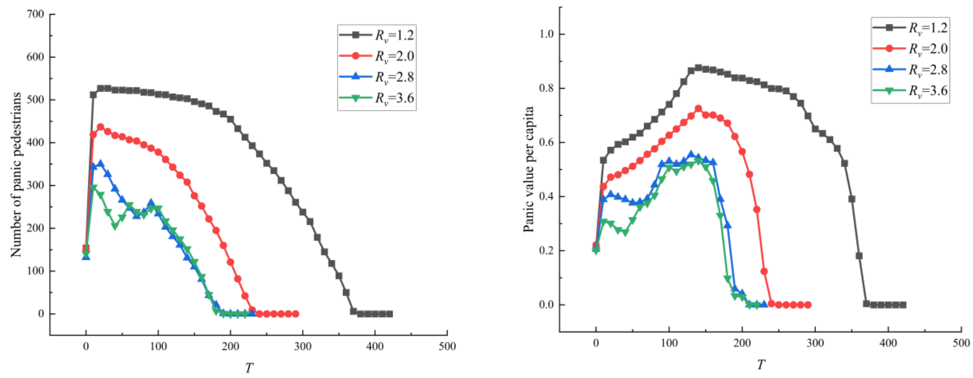


Fig. 11. Variation of evacuation time with pedestrian density at different visual field distances.

To further explore the effect of visual field distance on pedestrian panic, Fig. 12 shows the variation of the number of panic pedestrians and the per capita panic value with evacuation time for different visual field distances, where ρ is set to 0.3. From Fig. 12, the number of panic pedestrians and the panic value per capita are basically negatively correlated with the visual field distance. The reason is that the increased visual field distance will allow pedestrians to see the exit and the wall earlier, reduce the time of blind movement, and then slow the increase of panic and accelerate the decay of panic, so the overall panic degree of pedestrians is effectively alleviated. And this positive effect is more apparent when the R_v increases from 1.2m to 2.8m, and then the effect is small, which is also consistent with the simulation results of the evacuation time in Fig. 11. In addition, they both show a trend of increasing and then decreasing with evacuation time, but there are small fluctuations when R_v =2.8 and R_v =3.6. This is because when the visual field distance is large, pedestrians can get the information at the light source quickly, so the time of local congestion near the light source is shorter. When pedestrians move near the wall after leaving the light source, they will spread panic to the surrounding pedestrians moving along the wall, leading to the increases in the number of panic pedestrians and the panic value per capita.



（a）Number of panic pedestrians （b）Panic value per capita

Fig. 12. Variation of the number of panic pedestrians and the panic value per capita with evacuation time at different visual field distances.

3.5. Effect of light source position

In reality, the position of the light source is random and diverse, so the evacuation situation when the light source is located in other places is simulated, and the influence of phototactic behavior on evacuation results under different light source positions is comparatively studied. Six representative position distribution schemes are selected, where Case 0: Indicates the initial scene (Light source is located in the middle of the scene); Case 1: Light source is located in the middle of the wall away from the exit; Case 2: Light source is located in the corner away from the exit; Case 3: Light source is located in the middle of the wall near the exit; Case 4: Light source is located in the corner near the exit; Case 5: Light source is located at the exit, as shown in Fig. 13.

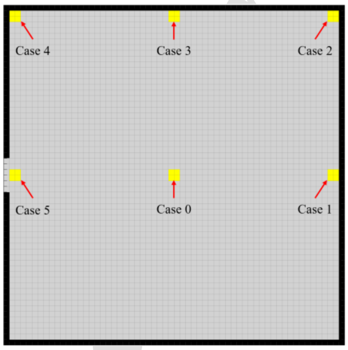


Fig. 13. Light source position distribution.

Fig. 14 shows the statistics of evacuation time under different light source distribution schemes with different pedestrian densities, where R_v =2m, λ_{emo} =0.5, R_t =0.8m, and φ=0.015. From Fig. 14, compared to the no light scene, only case 5 appears a significant reduction in evacuation time, while all other schemes show a certain increase, of which Case 2, Case 3, and Case 4 increased more, and Case 0 and Case 1 increased less. Observing their evacuation process separately. In Case 5, the crowd can quickly gather near the exit to evacuate directly due to the phototactic behavior, and the typical "arching phenomenon" replaces the "edge effect" at the exit, as shown in Fig.15(a), which improves the exit utilization rate and therefore the evacuation time is reduced. In Case 2 and Case 4, pedestrians moving towards the light source and those evacuating along the wall will form the "bi-directional pedestrian flow" with a large angle, as shown in Fig. 15(b), resulting in severe congestion at the intersection. At the same time, too many pedestrians concentrated on one side of the scene can also lead to a decrease in exit utilization and prolong the evacuation time. In Case 3, the angle of "bi-directional pedestrian flow" is smaller, as shown in Fig. 15(c). However, it still leads to a significant reduction in evacuation efficiency and prolongs evacuation time. In Case 1, there is no other pedestrian flow at the light source, and the crowd can evacuate quickly along the wall on both sides according to the evacuation signs after reaching its vicinity, as shown in Fig. 15(d), so the addition in evacuation time is less. It can be concluded that light sources near the exit can reduce evacuation time and improve evacuation efficiency, while light sources located elsewhere may adversely affect the evacuation.

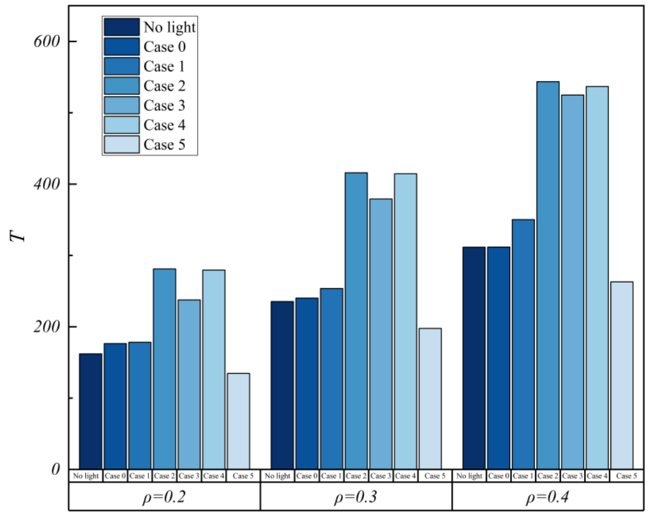


Fig. 14. Evacuation time for different light source distribution schemes with different pedestrian densities.

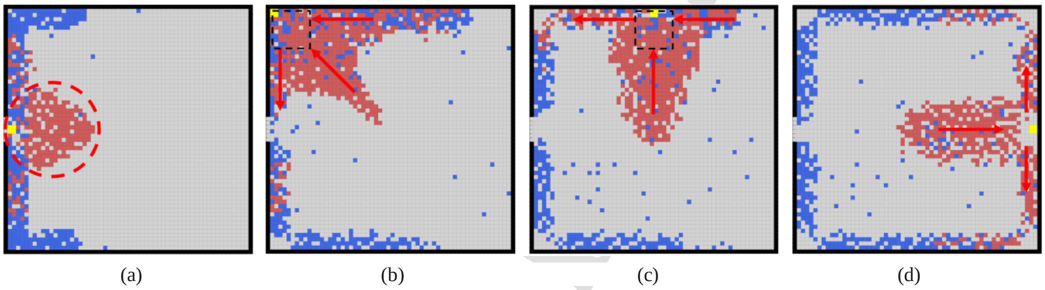


Fig. 15. Schematic diagram of the special phenomenon.

3.6. Effect of multiple light sources interference

From Section 3.5, it can be seen that when the light source is located near the exit is conducive to the evacuation, but considering that there may be multiple light sources in the actual evacuation, so further explore the effect of other light sources on the light source at the exit when multiple light sources exist. Because the number and position of multiple light sources are very complex, only the following three representative schemes are selected here. Scenario A: Indicates that other light sources are in the opposite orientation to the light source at the exit; Scenario B: Indicates that other light sources are in the adjacent orientation to the light source at the exit; Scenario C: Indicates that other light sources are in the same orientation to the light source at the exit, as shown in Fig. 16.

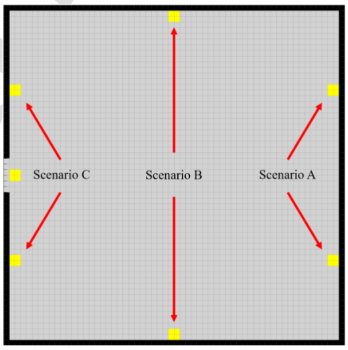


Fig. 16. Multiple light source position distribution.

Fig. 17 shows the variation of evacuation time with pedestrian density for different multiple light source scenarios, where R_v =2m, λ_{emo} =0.5, R_t =0.8m, and φ=0.015. From Fig. 17, the evacuation time in all three scenarios is greater than that when only the exit position has a light source. Among them, Scenario B has the longest evacuation time at the same pedestrian density, followed by Scenario A, and finally Scenario C. The reason is that the interference light source in Scenario B is located in the middle of the scene, so its influence scope is broader, which will cause a large number of pedestrians to move toward it. This leads to the formation of a massive "bi-directional pedestrian flow", and because its location in the middle of the scene will make the congestion time longer, so the evacuation time is the longest in this scenario. In Scenario A, the interference light source is located at the rear of the scene. Although this will increase the pedestrian movement distance to some extent, the evacuation time is shorter than Scenario B because of its smaller impact area and fewer pedestrians in the vicinity. In Scenario C, the interference light source is located near the exit. After pedestrians arrive around it, the distance between them and the exit is shorter. They can quickly escape through the exit, so the evacuation time in this scenario is relatively short. In summary, when there is a light source other than the light source at the exit in the scene, no matter where it is located will have a certain impact on the positive effect of the exit light source, and the higher the density of pedestrians, the greater the interference.

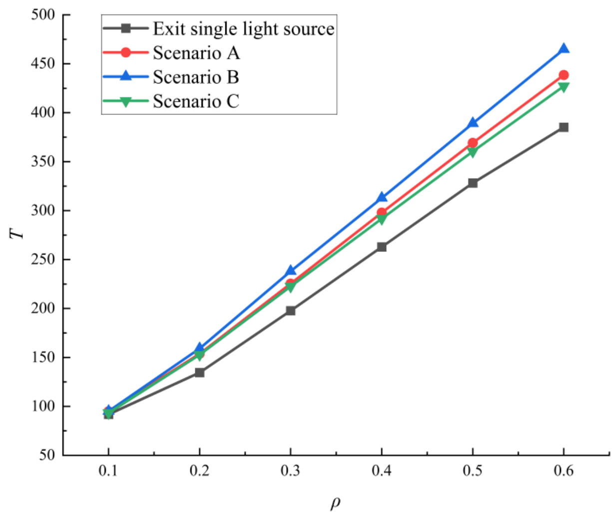


Fig. 17. Variation of evacuation time with pedestrian density under different scenarios.

4. Conclusion

In this paper, a multi-model coupled cellular automata model is constructed to study the emotional contagion and phototactic behavior of pedestrians under limited visual field. Considering the influence of individual characteristics and environmental factors, each individual has independent emotional expression and perception ability, and pedestrians located in different areas will have different emotional contagions and movement modes, and pedestrians with different emotional states in the same area will also have different ways of moving. By analyzing the effects of emotional threshold, information transfer, visual field distance, light source location, and multiple light sources interference on the evacuation process, the main conclusions obtained are as follows:

(1) Emotional threshold is a crucial factor influencing emotional contagion, and the higher the pedestrian density, the more significant its impact. As the emotional threshold increases, the degree of panic among pedestrians and the number of people moving toward the light source decrease.

(2) The information transfer between individuals can effectively alleviate local congestion near the light source and weaken the adverse effects caused by phototropic behavior, but excessive information transmission may play the opposite role.

(3) The increase in visual field distance makes it easier for pedestrians to get useful evacuation information,

reducing evacuation time and the panic degree of pedestrians. The buildings should be designed with reasonable daylighting to protect pedestrians' visual field distance in emergencies such as fires and power outages.

(4) Light sources near the exit can significantly reduce evacuation time, while light sources located in other positions will adversely affect evacuation. Public places can set up light sources at the exit to guide pedestrians to move towards it.

(5) When there are light sources other than the exit light source in other positions, it will cause some interference with the light source at the exit. The existence of interference light sources in the scene should be avoided as far as possible.

Therefore, this paper not only develops a simulation model of pedestrian evacuation, but also has important guiding significance for architectural design and emergency management. In future research, the intensity of the light source should be quantified in as much detail as possible, and the influence of other factors such as the type of light source, the moving light source, and the occlusion of the light source should be considered.

Acknowledgments

This work was supported by the National Natural Science Foundation of China (No. 51808422) and the Fundamental Research Funds for the Central Universities (WUT: 2021III052JC, 2021III053JC).

References

[1] L.J. Zheng, X.L. Peng, L.L. Wang, D.H. Sun, Simulation of pedestrian evacuation considering emergency spread and pedestrian panic, Physica A: Statistical Mechanics and its Applications 522 (2019) 167-181. https://doi.org/10.1016/j.physa.2019.01.128.

[2] S. Heliövaara, J.M. Kuusinen, T. Rinne, T. Korhonen, H. Ehtamo, Pedestrian behavior and exit selection in evacuation of a corridor - An experimental study, Safety Science 50 (2012) 221-227. https://doi.org/10.1016/j.ssci.2011.08.020.

[3] L.B. Fu, Y.X. Liu, H.G. Qin, Q.X. Shi, Y. Zhang, Y.Q. Shi, J.T.Y. Lo, An experimental study on bidirectional pedes trian flow involving individuals with simulated disabilities in a corridor, Safety science 150 (2022) 105723. https://doi.org/10.1016/j.ssci.2022.105723.

[4] Y. Zheng, B. Jia, X.G. Li, R. Jiang, Evacuation dynamics considering pedestrians' movement behavior change with fire and smoke spreading, Safety Science 92 (2017) 180-189. https://doi.org/10.1016/j.ssci.2016.10.009.

[5] R. Alizadeh, A dynamic cellular automaton model for evacuation process with obstacles, Safety Science 49 (2011) 315-323. https://doi.org/10.1016/j.ssci.2010.09.006.

[6] A. Borrmann, A. Kneidl, G. Koster, S. Ruzika, M. Thiemann, Bidirectional coupling of macroscopic and microscopic pedestrian evacuation models, Safety Science 50 (2012) 1695-1703. https://doi.org/10.1016/j.ssci.2011.12.021.

[7] L.B. Fu, Y.X Liu, Y.Q. Shi, Y.X. Zhao, Dynamics of bidirectional pedestrian flow in a corridor including individuals with disabilities, Physica A: Statistical Mechanics and its Applications 580 (2021) 126140. https://doi.org/10.1016/j.physa.2021.126140.

[8] D. Helbing, I. Farkas, T. Vicsek, Simulating dynamical features of escape panic, Nature 407 (2000) 487-490. https://doi.org/10.1038/35035023.

[9] F.Z. Huo, Y.F. Li, C. Li, Y.P. Ma, An extended model describing pedestrian evacuation considering pedestrian crowdi ng and stampede behavior, Physica A: Statistical Mechanics and its Applications 604 (2022) 127907. https://doi.org/10.1016/j.physa.2022.127907.

[10] G.N. Wang, T. Chen, J.W. Chen, K.F. Deng, R.D. Wang, Simulation of crowd dynamics in pedestrian evacuation concerning panic contagion: A cellular automaton approach, Chinese Physics B 31 (2022). https://doi.org/10.1088/1674-1056/ac4a66.

[11] L.B. Fu, W.G. Song, W. Lv, S.M. Lo, Simulation of emotional contagion using modified SIR model: A cellular automaton approach, Physica A: Statistical Mechanics and its Applications 405 (2014) 380-391. https://doi.org/10.1016/j.physa.2014.03.043.

[12] M.X. Cao, G.J. Zhang, M.S. Wang, D.J. Lu, H. Liu, A method of emotion contagion for crowd evacuation, Physica A: Statistical Mechanics and its Applications 483 (2017) 250-258. https://doi.org/10.1016/j.physa.2017.04.137.

[13] Q. Xiao, J.Y. Li, Pedestrian evacuation model considering dynamic emotional update in direction perception domain, Complexity 2021 (2021). https://doi.org/10.1155/2021/5530144.

[14] H.Y. Shang, P.P. Feng, J. Zhang, H.R. Chu, Calm or panic? A game-based method of emotion contagion for crowd evacuation, Transportmetrica A: Transport Science (2022). https://doi.org/10.1080/23249935.2021.1995529.

[15] T. Bosse, M. Hoogendoorn, M.C.A. Klein, J. Treur, C.N. Wal, A. Wissen, Modelling collective decision making in groups and crowds: Integrating social contagion and interacting emotions, beliefs and intentions, Autonomous Agents and Multi-Agent Systems 27 (2013) 52-84. https://doi.org/10.1007/s10458-012-9201-1.

[16] T. Bosse, R. Duell, Z.A. Memon, J. Treur, C.N. Wal, A multi-agent model for mutual absorption of emotions, in: 23rd European Conference on Modelling and Simulation, 2009, pp. 212-218. https://doi.org/10.7148/2009-0212-0218.

[17] D.C. Wang, S. Liang, B.B. Chen, C.L. Wu, Investigation on the impacts of natural lighting on occupants' wayfinding behavior during emergency evacuation in underground space, Energy and Buildings 255 (2022) 111613. https://doi.org/10.1016/j.enbuild.2021.111613.
[18] D.C. Wang, T.J. Zhou, G. Yang, Way-finding strategies and individual influencing factors of fire evacuation in underground commercial buildings, in: 9th International Conference on Fire Science and Fire Protection Engineering, 2019, pp. 1-6. https://doi.org/10.1109/ICFSFPE48751.2019.9055855.
[19] R. Lovreglio, A. Fonzone, L. Dell'Olio, A mixed logit model for predicting exit choice during building evacuations, Transportation Research Part A: Policy and Practice 92 (2016) 59-75. https://doi.org/10.1016/j.tra.2016.06.018.
[20] J. Dijkstra, Q.L. Chen, B. Vries, J. Jessurun, Measuring individual's egress preference in wayfinding through virtual navigation experiments, in: Pedestrian and Evacuation Dynamics 2012, 2012, pp. 371-383. https://doi.org/10.1007/978-3-319-02447-9_31.
[21] L.H. Taylor, E.W. Socov, The movement of people toward lights, Journal of the Illuminating Engineering Society 3 (1974) 237-241. https://doi.org/10.1080/00994480.1974.10732257.
[22] E. Vilar, F. Rebelo, P. Noriega, J. Teles, C. Mayhorn, The influence of environmental features on route selection in an emergency situation, Applied Ergonomics 44 (2013) 618-627. https://doi.org/10.1016/j.apergo.2012.12.002.
[23] E. Vilar, F. Rebelo, P. Noriega, E. Duarte, C.B. Mayhorn, Effects of competing environmental variables and signage on route-choices in simulated everyday and emergency wayfinding situations, Ergonomics 57 (2014) 511-524. https://doi.org/10.1080/00140139.2014.895054.
[24] E. Vilar, F. Rebelo, P. Noriega, J. Teles, C. Mayhorn, Signage versus environmental affordances: Is the explicit information strong enough to guide human behavior during a wayfinding task?, Human Factors and Ergonomics in Manufacturing & Service Industries 25 (2015) 439-452. https://doi.org/10.1002/hfm.20557.
[25] S. Arias, J. Wahlqvist, D. Nilsson, E. Ronchi, S. La Mendola, O. Rios, Virtual reality evacuation experiments on way-finding systems for the future circular collider, Fire Technology 55 (2019) 2319-2340. https://doi.org/10.1007/s10694-019-00868-y.
[26] L. Filippidis, H. Xie, E.R. Galea, P.J. Lawrence, Exploring the potential effectiveness of dynamic and static emergency exit signage in complex spaces through simulation, Fire Safety Journal 125 (2021) 103404. https://doi.org/10.1016/j.firesaf.2021.103404.
[27] F.Z. Huo, C. Li, Y.F. Li, W. Lv, Y.P. Ma, An extended model for describing pedestrian evacuation considering the impact of obstacles on the visual view, Physica A: Statistical Mechanics and its Applications 604 (2022) 127932. https://doi.org/10.1016/j.physa.2022.127932.
[28] J.H. Wang, W.Y. Yan, Y.R. Zhi, J.C. Jiang, Investigation of the panic psychology and behaviors of evacuation crowds in subway emergencies, Procedia Engineering 135 (2016) 128-137. https://doi.org/10.1016/j.proeng.2016.01.091.
[29] M.S. Wang, G.J. Zhang, H. Liu, Heterogeneous emotional contagion model for crowd evacuation simulation, Computer Science, 46 (2019) 287-297, (In Chinese). https://doi.org/10.11896/j.issn.1002-137X.2019.03.043.
[30] Y. Mao, Z.X. Fan, J.W. Zhao, Q.C. Zhang, W. He, An emotional contagion based simulation for emergency evacuation peer behavior decision, Simulation Modelling Practice and Theory 96 (2019) 101936. https://doi.org/10.1016/j.simpat.2019.101936.
[31] X.J. Wu, W.L. Wang, Z.H. Hu, Study on emotion contagion model and intervention strategies of panic in subway stations under emergency, Computer Engineering and Applications 56 (2020) 265-272, (In Chinese). https://doi.org/10.3778/j.issn.1002-8331.1903-0148.
[32] J.A. Hall, D. Matsumoto, Gender differences in judgments of multiple emotions from facial expressions, Emotion 4 (2004) 201-206. https://doi.org/10.1037/1528-3542.4.2.201.
[33] A. Mill, J. Allik, A. Realo, R. Valk, Age-related differences in emotion recognition ability: A cross-sectional study, Emotion 9 (2009) 619-630. https://doi.org/10.1037/a0016562.
[34] Z. Zhang, L.M. Jia, Y. Qin, Optimal number and location planning of evacuation signage in public space, Safety Science 91 (2017) 132-147. https://doi.org/10.1016/j.ssci.2016.07.021.
[35] Y. Tajima, T. Nagatani, Scaling behavior of crowd flow outside a hall, Physica A: Statistical Mechanics and its Applications 292 (2001) 545-554. https://doi.org/10.1016/S0378-4371(00)00630-0.
[36] Z.F. Geng, X.L. Li, H. Kuang, X.C. Bai, Y.H. Fan, Effect of uncertain information on pedestrian dynamics under adverse sight conditions, Physica A: Statistical Mechanics and its Applications 521 (2019) 681-691. https://doi.org/10.1016/j.physa.2019.01.122.
[37] C.K. Chen, H.K. Sun, P. Lei, D.Y. Zhao, C.L. Shi, An extended model for crowd evacuation considering pedestrian panic in artificial attack, Physica A: Statistical Mechanics and its Applications 571 (2021) 125833. https://doi.org/10.1016/j.physa.2021.125833.
[38] Q.L. Zou, S.R. Chen, Simulation of crowd evacuation under toxic gas incident considering emotion contagion and information transmission, Journal of Computing in Civil Engineering 34 (2020) 04020007. https://doi.org/10.1061/(ASCE)CP.1943-5487.0000889.

CRediT authorship contribution statement

Chenglin Guo: Software; Writing - original draft; Methodology; Formal analysis

Feizhou Huo: Conceptualization; Resources; Funding acquisition; Supervision

Chao Li: Investigation; Writing - review & editing

Yufei Li: Data curation; Validation

Declaration of Interest Statement

We declare that we have no financial and personal relationships with other people or organizations that can inappropriately influence our work, there is no professional or other personal interest of any nature or kind in any product, service and/or company that could be construed as influencing the position presented in the manuscript entitled "An evacuation model considering the phototactic behavior of panic pedestrians under limited visual field".