Model considering panic emotion and personality traits for crowd evacuation

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Panic is a common emotion when pedestrians are in danger during the actual evacuation, which can affect pedestrians a lot and may lead to fatalities as people are crushed or trampled. However, the systematic studies and quantitative analysis of evacuation panic, such as panic behaviors, panic evolution, and the stress responses of pedestrians with different personality traits to panic emotion are still rare. Here, combined with the theories of OCEAN (openness, conscientiousness, extroversion, agreeableness, neuroticism) model and SIS (susceptible, infected, susceptible) model, an extended cellular automata model is established by the floor field method in order to investigate the dynamics of panic emotion in the crowd and dynamics of pedestrians affected by emotion. In the model, pedestrians are divided into stable pedestrians and sensitive pedestrians according to their different personality traits in response to emotion, and their emotional state can be normal or panic. Besides, emotion contagion, emotion decay, and the influence of emotion on pedestrian movement decision-making are also considered. The simulation results show that evacuation efficiency will be reduced, for panic pedestrians may act maladaptive behaviors, thereby making the crowd more chaotic. The results further suggest that improving pedestrian psychological ability and raising the standard of management can effectively increase evacuation efficiency. And it is necessary to reduce the panic level of group as soon as possible at the beginning of evacuation. We hope this research could provide a new method to analyze crowd evacuation in panic situations.

Keywords: panic emotion, CA-SIS model, crowd evacuation, personality trait

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1. Introduction

With the continuous development of modern society and rapid expansion of cities, it is a common phenomenon all over the world that large scale of population gathers together for events. However, people are in potential danger in these overcrowded conditions, when a sudden natural or man-made disaster, like fire, earthquake, flood or terrorist attack occurs, it is likely to cause crowd to congest or stampede, which may result in grave casualties and property losses if there are no effective evacuation strategies. Therefore, it is of great significance to study the evacuation psychological and behavioral characteristics of pedestrians in emergence for ensuring the people's safety.

In recent years, modeling approach is one of the hottest research methods to investigate the dynamic properties of pedestrian evacuation, which has attracted considerable attention and received great success. Generally speaking, the currently existing evacuation model can be divided into two categories: macroscopic model and microscopic model.[1] In macroscopic model, pedestrians are treated as a homogeneous mass like gas or fluid, and some hydrodynamic equations are used to calculate the speed, flow, and other physical attributes of the crowd. However, this model overemphasizes the integrity of the crowd, which ignores the differences and interactions between pedestrians, so it is not suitable to describe the details of individual behavior. Unlike macroscopic model, microscopic model regards each pedestrian as an independent unit, so the characteristics of pedestrian dynamics, such as the movement state and the interaction of the individual pedestrian, can be described in detail. Besides, microscopic model can also be subdivided into continuous model and discrete model. The most representative continuous model is social force model, which was proposed by Helbing and Molnar,[2] and successfully reproduces some self-organized phenomena, *e.g.*, "faster-is-slower", "lane formation", and "oscillatory flows at bottlenecks". The typical discrete model includes the cellular automata model,[3–5] the lattice gas model,[6–8] and the agent-based model.[9–11] Compared with other models, the cellular automata model has the advantages of high computational efficiency and simplicity, and has been successfully used to describe pedestrian dynamics in complex circumstances.[12,13] In addition, it is worth noting that the combination of cellular automata model with the floor field method gives the cellular automata model more powerful simulation ability, so it has been widely used to model the evacuation behavior and self-organized phenomenon encountered in pedestrian dynamics, such as congestion,[14] unorganized movement,[15] exit choice,[16] and group behavior.[17]

During emergency evacuation, if pedestrians cannot get rid of or adapt to the current dangerous environment in time, individuals are prone to panic.[18–20] Panic is a stressful emotion produced by people when they try to stay safe

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but feel powerless. The influence of panic emotion will greatly affect the decision-making of the pedestrians and may cause pedestrians to show some maladaptive movements and behaviors.[21,22] Many scholars have made lots of efforts to study pedestrian panic behavior. Helbing *et al.*[18] summarized the dynamical features of escape panics and proposed the social force model to investigate the mechanisms of panic. Shiwakoti *et al.*[23] were inspired by animal collective patterns and proposed a mathematical model for the study of crowd panic. Wang *et al.*[10] proposed a multi-agent model incorporating panic behavior and found that panic will increase casualties. Zou *et al.*[8] used a modified lattice-gas model to capture an underlying mechanism of collective panic in pedestrian evacuations. Shen *et al.*[24] introduced a model to study the collective behaviors in the condition of fire with dense smoke. The simulation results show that moderate panic can reduce the escape time. Zheng *et al.*[25] put forward a panic coefficient to depict the influence of pedestrian panic psychology on evacuation process. Chen *et al.*[22] proposed a floor field cellular automata model considering pedestrian panic to investigate pedestrian dynamics under the threat of artificial attack, which successfully reproduces some real characteristic features of escape panics.

The above researches have made a profound analysis of the connotation of panic and helped people better understand the influence of panic on pedestrian evacuation behavior. Furthermore, panic emotion will not only affect the behavior of individuals, but also can spread among the crowd due to interaction among pedestrians.[26–28] Various examples proved that small incidents eventually evolve into serious crowd accidents because of the contagion of panic emotion. For instance, on April 20, 2015, a female passenger fainted on the platform of Shenzhen Metro Line 5, at first it caused a small number of nearby passengers to flee, and then more passengers ran in panic, which caused crowd riots and resulted in massive trampling. Therefore, it is very necessary to understand the dynamics mechanism of panic emotion in the crowd. Recently, increasing efforts have been made to study emotional models. Hill *et al.*[29] introduced a novel form of the classical mathematical infectious disease SIS model, the model provides a theoretical framework for studying the spread of emotions. Bosse *et al.*[30] proposed a computational model for the interplay of emotions, namely ASCRIBE, the simulation results show that considering the contagion of belief, emotion and intention states of agents are closer to the real-life incident. Tsai *et al.*[31] designed a multi-agent evacuation system ESCAPES, where agents will receive the highest level of emotion from their surrounding persons. Fu *et al.*[26] modified the epidemiological SIR model into a cellular automata approach and proposed a "CA-SIRS" model to integrate emotional contagion with individual movement. Neto *et al.*[32] presented an emotional contagion model adapting for crowd simulation context, the model describes the strength of contagion is influenced by distance and agents can change goals as they change emotional state. In particular, the emotion contagion models usually consider the effect of personality traits to represent individual psychological differences. Durupinar *et al.*[33] introduced an emotion contagion model based on the approach proposed by Dodds and Watta,[34] which is a threshold model that integrates the OCEAN personality model, the OCC emotion model, and the PAD model together to simulate the emotional interaction between different groups in the crowd. Liu *et al.*[35] used the personality model OCEAN to represent the personality of the agent and proposed an emotion contagion model to simulate the crowd evacuation behaviors in a fire scenario. Mao *et al.*[36] put forward an evacuation model incorporating personality traits and emotion contagion, which considers four kinds of agents with specific personalities and three different emotion contagion ways. Zhou *et al.*[37] presented an improved CA-SIRS model combined with personality and emotional contagion, the model takes into account the factors like the accident experience, panic level, environmental familiarity and nearby flow.

In general, to our knowledge at present, although the researches on pedestrian behavior and emotion in emergency evacuation have made great progress, the existing studies on the evolution rules of panic emotion in the crowd, the influence of panic emotion on pedestrian evacuation decision-making, and the stress responses of pedestrians with different personality traits to panic emotion, *etc.* are still rare. The reasons are as follows. On the one hand, the relevant empirical data and quantitative theories under panic conditions are scarce. On the other hand, the emotional or psychological state of people is quite complex to explore. Hence, in this work, an extended cellular automata model combined with the theories of psychological OCEAN personality model[38] and epidemical SIS model[34] is established to investigate the influence of panic emotion on crowd evacuation. And pedestrian personality traits, emotion contagion and decay rules, and the movement of pedestrian are involved. The goal of this work is to present a method to better understand the mechanism of panic emotion on crowd evacuation so as to improve evacuation efficiency and make effective evacuation strategies.

The rest of this paper is organized as follows. In Section 2 the extended CA evacuation model considering emotion and personality traits is introduced. In Section 3 the simulation results and analysis are given. Finally, in Section 4 some conclusions are drawn from the present study.

2. Model description

In this section, an extended cellular automata evacuation model with floor field method is proposed, which combines the

relevant theories of psychological OCEAN personality model and epidemiological SIS model. In the model, two different personality traits in response to emotion are considered. Besides, the model also focuses on the dynamic characteristics of emotion, such as emotion contagion and emotion decay, as well as the influence of emotion on pedestrian decision-making. Next, the emotion contagion and decay rules will be defined and described in detail in Subsection 2.1, and in Subsection 2.2 the pedestrian movement rules driven by emotion will be introduced. In Subsection 2.3, the meanings of the parameters in the model will be summarized and the value ranges of some parameters are determined. Then the update rules of the model are presented in Subsection 2.4.

2.1. Emotion model

Panic is a common emotion when pedestrians are in danger during the actual evacuation. To some degree, emotion contagion is similar to disease spread,[1,26,39] a normal pedestrian who is infected by panic pedestrians may turn into panic, and a panic pedestrian can turn into normal through emotion decay. It is just like a susceptible person becomes infected after coming into contact with infected people, and an infected person becomes susceptible after being cured. Therefore, the SIS model is modified with a cellular automaton approach to simulate the dynamics of pedestrian panic emotion among crowd. Besides, in real evacuation scenarios, some people have a steady personality and more rational thinking: these people are weak in response to external stimuli and have less emotional fluctuation, which means that such a group is weak in receiving and spreading emotion. In addition to the people mentioned above, some people have a neurotic personality and more perceptual thinking: these people are sensitive to external stimuli and their mood swings lot, that is to say, such a group is strong in receiving and spreading emotion. Hence, inspired by the OCEAN personality model in Refs. [38,40], pedestrians are divided into emotion stable pedestrians and emotion sensitive pedestrians in this model, which corresponds to negative pole and positive pole of the neuroticism (N) factor in OCEAN model. This group classification not only conforms to the distribution law of personality traits but also shows the diversity of panic emotion in different groups more truly. For the sake of description, emotion stable pedestrian is called stable pedestrian, and emotion sensitive pedestrian is named sensitive pedestrian in the following. It should be noted that due to the complexity and uncertainty of personality traits of pedestrians in response to emotion, it is very difficult to model all personality traits in detail, so we make it simplified and focus on the above two personality traits in this model.

In this emotion model, the pedestrian emotional states are divided into normal and panic, which correspond to the susceptible state and infected state in the SIS model. Normal pedestrians cannot spread emotion to others and only accept emotion from panic pedestrians in a certain range, and notice that normal pedestrians will become panic if their panic level exceeds their tolerance to panic emotion. As for panic pedestrians, they will spread emotion to normal pedestrians to make more people panic and accept emotion from panic pedestrians at a higher panic level in a certain range, so the emotion contagion here is similar to the transfer of heat from a high-temperature object to a low-temperature object. Moreover, the dynamic characteristics of emotion indicate that emotion can not only propagate but also decay. For example, pedestrians will reduce their panic level after a period of self-regulation and environmental adaptation.[41] Besides, pedestrian emotion will change significantly with the change of position, for example, panic level will be greatly attenuated when pedestrians approach to the exit. Therefore, panic pedestrians may become normal through emotion decay. During the evacuation, stable pedestrians and sensitive pedestrians will change their emotional states dynamically as the emotion spreads and decays in the crowd, so the complex emotional interaction among pedestrians can be well modeled.

In reality, panic is intangible and abstract, so people often evaluate panic in a qualitative way. However, it is very difficult to further study the deep connotation of panic in a qualitative way. Hence, in order to quantify the panic level of pedestrian, a panic parameter p is defined and its theoretical range is assumed to be from 0 to 1. That is to say, the larger the panic parameter, the higher the pedestrian panic level is. In addition, the initial panic parameter $p_{t=0}$ of each pedestrian is determined by the normal distribution function, so the initial panic parameter $p_{t=0}$ of stable pedestrians is calculated from Eq. (1) and the initial panic parameter $p_{t=0}$ of sensitive pedestrians is shown by Eq. (2). Note that in order to ensure that the value range of panic parameter falls in the [0, 1] interval, the model specifies that if the panic parameter is less than 0, it is taken as 0, and if the panic parameter is greater than 1, it is taken as 1, otherwise the panic parameter is taken as the original value.

$$p_{t=0} \sim N\left(\mu_{\mathrm{st}}, \sigma_{\mathrm{st}}^2\right) \tag{1}$$

for stable pedestrian,

$$p_{t=0} \sim N\left(\mu_{\mathrm{se}}, \sigma_{\mathrm{se}}^2\right) \tag{2}$$

for sensitive pedestrian, where, t is the time step. μ_{st} is the mean of stable pedestrian initial panic parameter $p_{t=0}$, σ_{st}^2 is the variance of stable pedestrian initial panic parameter $p_{t=0}$, μ_{se} is the mean of sensitive pedestrian initial panic parameter $p_{t=0}$, and σ_{se}^2 is the variance of sensitive pedestrian initial panic parameter $p_{t=0}$. Hence, the panic level range of pedestrians at the beginning of evacuation can be controlled by adjusting parameters μ_{st}, σ_{st}^2, μ_{se} and σ_{se}^2 in this model. Next, the panic threshold of stable pedestrian λ_{st} and the panic

threshold of sensitive pedestrian λ_{se} are introduced, which indirectly denotes the tolerance of two types of pedestrians to panic emotion. If pedestrian panic parameter is larger than panic threshold, the current pedestrian will be panic. Thus, according to the comparison between pedestrian initial panic parameter $p_{t=0}$ and panic thresholds λ_{st} and λ_{se}, all the pedestrians can be classified as stable normal pedestrians, stable panic pedestrians, sensitive normal pedestrians, and sensitive panic pedestrians at $t = 0$.

2.1.1. Emotion contagion

In the model, pedestrians with different personality traits and emotional states have different emotion contagion processes.[26,42] For instance, if the current pedestrian is a stable normal pedestrian, then he/she will accept the emotion from panic pedestrians within the perception radius, and the panic parameter of the current pedestrian will update after that, as presented in Eqs. (3)–(5). The schematic diagram of emotion contagion can be seen in Fig. 1(a).

$$p(i,t+1) = p(i,t) + \sum_{d_{ij}<r_{st}} \Delta p(j,t) + \sum_{d_{ik}<r_{st}} \Delta p(k,t), \quad (3)$$

$$\Delta p(j,t) = \left(1 - \frac{1}{1+\mathrm{e}^{-d_{ij}}}\right) \cdot \delta_{st} \cdot \xi_{st} \cdot p(j,t), \quad (4)$$

$$\Delta p(k,t) = \left(1 - \frac{1}{1+\mathrm{e}^{-d_{ik}}}\right) \cdot \delta_{se} \cdot \xi_{st} \cdot p(k,t), \quad (5)$$

where t is the current time step, i the stable normal pedestrian, j the stable panic pedestrian, k the sensitive panic pedestrian, $p(i,t)$ and $p(i,t+1)$ denote the panic parameter of individual i at the current time step and the next time step, respectively, $p(j,t)$ and $p(k,t)$ the panic parameter of individual j and individual k at the current time step, respectively, $\Delta p(j,t)$ the emotion sent from sender j to receiver i, $\Delta p(k,t)$ the emotion sent from sender k to receiver i, d_{ij} the distance between individual i and individual j, d_{ik} the distance between individual i and individual k, and r_{st} the emotion perceived radius for stable pedestrian. The larger the emotion perceived radius, the wider the range that the current pedestrian can feel the emotion of nearby panic pedestrians. δ_{st} represents the emotion transfer strength attribute of stable pedestrian, ξ_{st} the emotion receive strength attribute of stable pedestrian, and δ_{se} the emotion transfer strength attribute of sensitive pedestrian. Note that equation (3) indicates that if the current time step does not meet the condition of triggering emotion decay, the stable normal pedestrians will increase their panic level by accepting emotion from the panic pedestrians within the perceived radius. As for the rules of emotion decay, which will be detailed described in Subsubsection 2.1.2. Furthermore, equations (4) and (5) mean that the spread intensity of emotion is positively related to the receive strength attribute of receiver, and the transfer strength attribute of sender, and which is negatively correlated with the distance between emotional receiver and sender.

Similarly, if the current pedestrian is a sensitive normal pedestrian, then he/she will accept the emotion from panic pedestrians within the perception radius, and the panic parameter is updated as shown in Eqs. (6)–(8). The schematic diagram of emotion contagion can be seen in Fig. 1(b).

$$p(i,t+1) = p(i,t) + \sum_{d_{ij}<r_{se}} \Delta p(j,t) + \sum_{d_{ik}<r_{se}} \Delta p(k,t), \quad (6)$$

$$\Delta p(j,t) = \left(1 - \frac{1}{1+\mathrm{e}^{-d_{ij}}}\right) \cdot \delta_{st} \cdot \xi_{se} \cdot p(j,t), \quad (7)$$

$$\Delta p(k,t) = \left(1 - \frac{1}{1+\mathrm{e}^{-d_{ik}}}\right) \cdot \delta_{se} \cdot \xi_{se} \cdot p(k,t), \quad (8)$$

where i represents the sensitive normal pedestrian, j the stable panic pedestrian, k the sensitive panic pedestrian, r_{se} the emotion perceived radius for sensitive pedestrian, and ξ_{se} the emotion receive strength attribute of sensitive pedestrian.

If the current pedestrian is a stable panic pedestrian, then he/she will accept the emotion from the panic pedestrians with higher panic level within the perceived radius, and the panic parameter is updated as expressed in Eq. (9). The schematic diagram of emotion contagion can be seen in Fig. 1(c).

$$p(i,t+1) = p(i,t) + \sum_{\substack{d_{ij}<r_{st} \\ p(j,t)>p(i,t)}} \Delta p(j,t) + \sum_{\substack{d_{ik}<r_{st} \\ p(k,t)>p(i,t)}} \Delta p(k,t), \quad (9)$$

where i represents the stable panic pedestrian, j the stable panic pedestrian whose panic parameter is larger than that of the individual i, and k the sensitive panic pedestrian whose panic parameter is larger than that of the individual i. The calculation methods of $\Delta p(j,t)$ and $\Delta p(k,t)$ are consistent with that of Eqs. (4) and (5), respectively.

Likewise, if the current pedestrian is a sensitive panic pedestrian, then he/she will accept the emotion from the panic pedestrians with higher panic level within the perceived radius, and then the panic parameter is updated as expressed in Eq. (10). The schematic diagram of emotion contagion can be seen in Fig. 1(d).

$$p(i,t+1) = p(i,t) + \sum_{\substack{d_{ij}<r_{se} \\ p(j,t)>p(i,t)}} \Delta p(j,t) + \sum_{\substack{d_{ik}<r_{se} \\ p(k,t)>p(i,t)}} \Delta p(k,t), \quad (10)$$

where i represents the sensitive panic pedestrian, j the stable panic pedestrian whose panic parameter is larger than that of the individual i, and k the sensitive panic pedestrian whose panic parameter is larger than that of the individual i. The calculation methods of $\Delta p(j,t)$ and $\Delta p(k,t)$ are consistent with that of Eqs. (7) and (8), respectively.

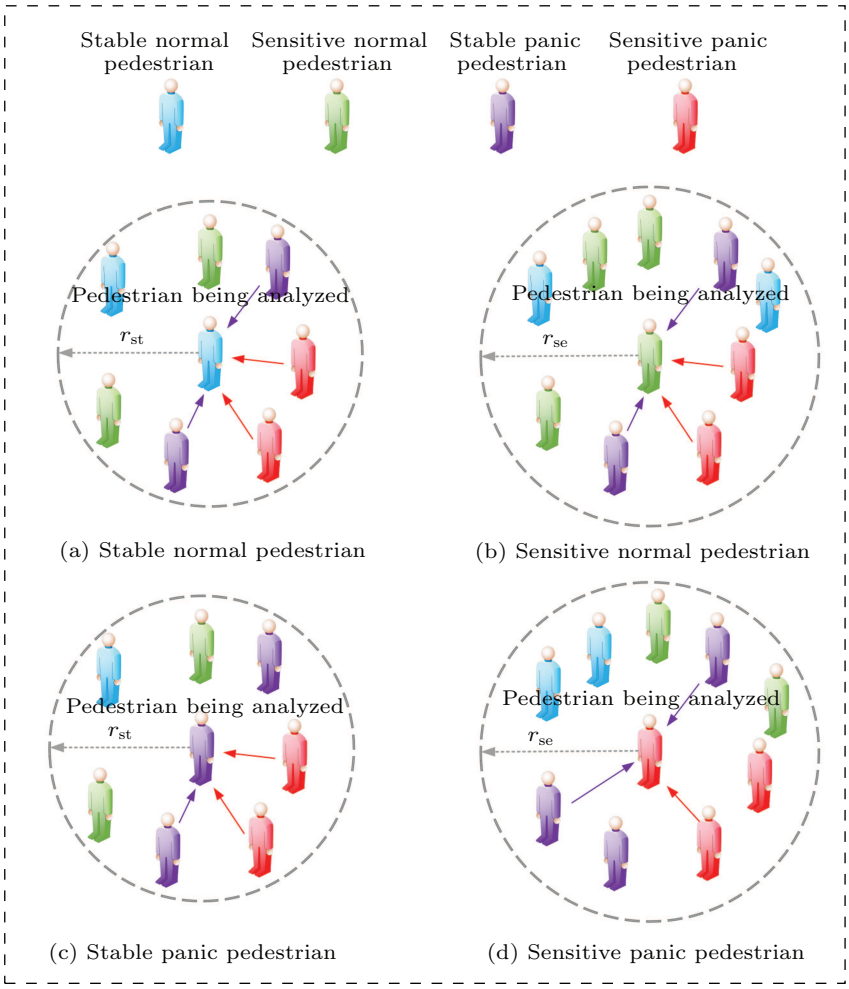


Fig. 1. Schematic diagram of emotion contagion. Note that a normal pedestrian will accept emotion from panic pedestrians within the perception radius and a panic pedestrian will accept emotion from panic pedestrians with higher panic level within the perceived radius.

2.1.2. Emotion decay

In the evacuation process, panic emotion will decay after a period of time as pedestrians adapt to the environment and self-regulation. In addition, panic emotion also will significantly decay when pedestrians move near the exit. Based on the above reasons, considered in this model are two emotion decay ways: emotion self-decay and exit emotion decay.

If the current pedestrian is a stable normal pedestrian, the emotion self-decay way can be expressed as

$$\begin{aligned} &p(i,t+1)\\ &= (1-\beta_{st})\left(p(i,t)+\sum_{d_{ij}<r_{st}}\Delta p(j,t)+\sum_{d_{ik}<r_{st}}\Delta p(k,t)\right),\\ &d_{ie}>r_{exit} \ \text{ and } \ t=m\tau,\ m=1,2,\ldots,n. \end{aligned} \tag{11}$$

Here, β_{st} is the emotion self-decay coefficient of stable pedestrian, which controls the intensity of each emotion self-decay; τ is the emotion self-decay interval, which controls the length of time to trigger off emotion self-decay; d_{ie} is the distance between the individual i and the exit; r_{exit} represents the exit emotion decay radius, which is the radius of the circle with the exit coordinates as the center; the meanings of other parameters in Eq. (11) are the same as those in Eq. (3). Equation (11) implies that if the distance between pedestrian and the exit is larger than the exit emotion decay radius, and the current time step is a multiple of the emotion self-decay interval, then the pedestrian will experience emotion self-decay.

If the current pedestrian is a stable panic pedestrian, the emotion self-decay way can be expressed as

$$\begin{aligned} &p(i,t+1)\\ &= (1-\beta_{st})\left(p(i,t)+\sum_{\substack{d_{ij}<r_{st}\\ p(j,t)>p(i,t)}}\Delta p(j,t)+\sum_{\substack{d_{ik}<r_{st}\\ p(k,t)>p(i,t)}}\Delta p(k,t)\right),\\ &d_{ie}>r_{exit} \ \text{ and } \ t=m\tau,\ m=1,2,\ldots,n. \end{aligned} \tag{12}$$

Here, the meaning of $p(i,t)$, $p(i,t+1)$, $p(j,t)$, $p(k,t)$, $\Delta p(j,t)$, and $\Delta p(k,t)$ are the same as those in Eq. (9).

If the current pedestrian is a sensitive normal pedestrian, the emotion self-decay way can be expressed as

$$\begin{aligned} &p(i,t+1)\\ &= (1-\beta_{se})\left(p(i,t)+\sum_{d_{ij}<r_{se}}\Delta p(j,t)+\sum_{d_{ik}<r_{se}}\Delta p(k,t)\right),\\ &d_{ie}>r_{exit} \ \text{ and } \ t=m\tau,\ m=1,2,\ldots,n, \end{aligned} \tag{13}$$

where β_{se} is the emotion self-decay coefficient of sensitive

pedestrian. The meaning of $p(i,t)$, $p(i,t+1)$, $\Delta p(j,t)$, and $\Delta p(k,t)$ are the same as those in Eq. (6).

If the current pedestrian is a sensitive panic pedestrian, the emotion self-decay way can be expressed as

$$p(i,t+1) = (1-\beta_{\rm se})\left(p(i,t) + \sum_{p(j,t)>p(i,t)}^{d_{ij}<r_{\rm se}} \Delta p(j,t) + \sum_{p(k,t)>p(i,t)}^{d_{ik}<r_{\rm se}} \Delta p(k,t)\right),$$
$$d_{ie} > r_{\rm exit} \ \text{ and } \ t = m\tau,\ m = 1,2,\ldots,n. \tag{14}$$

Here, the meaning of $p(i,t)$, $p(i,t+1)$, $p(j,t)$, $p(k,t)$, $\Delta p(j,t)$, and $\Delta p(k,t)$ are the same as those in Eq. (10).

The exit emotion decay condition will be triggered when the pedestrian enters into the exit emotion decay radius area. Driven by the strong desire to survive, the exit has a strong attraction to evacuees, so the exit emotion decay way plays a major role when pedestrians are near the exit. Thus, the exit emotion decay way of stable pedestrian and sensitive pedestrian can be calculated from the following equations, respectively:

$$p(i,t+1) = (1-\alpha_{\rm st})\,p(i,t),\ d_{ie} \le r_{\rm exit}, \tag{15}$$

for stable pedestrian,

$$p(i,t+1) = (1-\alpha_{\rm se})\,p(i,t),\ d_{ie} \le r_{\rm exit}. \tag{16}$$

for sensitive pedestrian.

In Eq. (15), $\alpha_{\rm st}$ is the exit emotion decay coefficient of stable pedestrian, which controls the intensity of exit emotion decay, and i represents the stable pedestrian. In Eq. (16), $\alpha_{\rm se}$ is the exit emotion decay coefficient of sensitive pedestrian and i represents the sensitive pedestrian.

2.2. Pedestrian movement

To a certain extent, panic emotion has a great influence on pedestrian evacuation decision-making.[18] Therefore, the model incorporates panic emotion with pedestrian movement decision-making and determines the pedestrian movement rules which are driven by emotion. When the panic parameter does not exceed the panic threshold, *i.e.*, the pedestrian emotional state has not changed from normal to panic, the individual is able to make the optimal movement decision-making. However, pedestrians may act maladaptive behaviors when they become panic, for example, because of excessive tension, they tend to escape along any possible path without deep consideration, so they may move to any position in the building that they think is safe, and the greater the panic level of pedestrians, the more likely they are to act maladaptive behavior. Hence, there is a great uncertainty in the direction of panic pedestrian movement.

Based on the above analysis, an extended cellular automata evacuation model with floor field method is established. In the model, the space is divided into two-dimensional uniform four-square cells. Each cell is a typical area of 0.4 m×0.4 m occupied by a person[43] and can be either empty or occupied by an obstacle or a pedestrian. Just as we mentioned above, a normal pedestrian can make the optimal movement decision-making and find the exit quickly, so the static floor field in floor field model[3] is used to specify the regions of space which are more attractive. Besides, Moore neighborhood, which is composed of a central cell and its eight surrounding cells, is employed as the pedestrian moving method. Therefore, a 3×3 matrix of preferences P_{ij} as shown in Fig. 2, is constructed which contains the transition probabilities of its neighbors for cell(i,j). Thus, pedestrian will choose the next position at each time step according to transition probabilities P_{ij}. And the transition probabilities P_{ij} can be computed from Eqs. (17) and (18). That is to say, normal pedestrians can find the optimal evacuation routes to the exit according to transition probabilities P_{ij}.

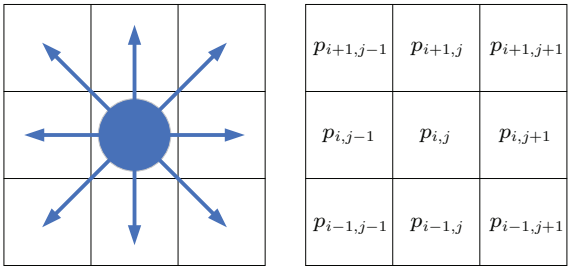


Fig. 2. Possible movement directions of the pedestrian and the transition probabilities P_{ij}.

$$S_{ij} = \max_{(i,j)\in{\rm region}}\left\{\sqrt{(x_{\rm e}-x_{ij})^2+(y_{\rm e}-y_{ij})^2}\right\} - \sqrt{(x_{\rm e}-x_{ij})^2+(y_{\rm e}-y_{ij})^2}, \tag{17}$$
$$P_{ij} = N\exp(k_{\rm s}S_{ij})\varepsilon_{ij}(1-\eta_{ij}). \tag{18}$$

Here, N is the normalization factor to ensure that the result falls in the [0, 1] interval; S_{ij} denotes the static floor field; $k_{\rm s}$ is its sensitivity coefficient; ε_{ij} represents the pedestrian occupation number of cell(i,j), and $\varepsilon_{ij}=0$ if the target cell is occupied by a pedestrian, otherwise $\varepsilon_{ij}=1$; η_{ij} represents the obstacle occupation number of cell(i,j) and $\eta_{ij}=1$ if the target cell is occupied by the obstacle, otherwise $\eta_{ij}=0$. Therefore, transitions to occupied cells are forbidden. $x_{\rm e}$ and $y_{\rm e}$ represent the coordinate values of the exit, x_{ij} and y_{ij} denote the coordinate values of cell(i,j), respectively.

Additionally, panic pedestrians may have some blindness when choosing escape routes, they may follow the footsteps of others[22] or move randomly,[24,26] and the movement decision-making mechanism of panic pedestrians has not been fully understood yet. Therefore, in order to better explore this issue and for the sake of discussion, we assume that panic

pedestrians have two strategies to escape on the basis of the researches in Refs. [22,24]: optimal movement decision-making or random moving. And the probability of random moving is positively related to the panic level. Hence, in order to model the maladaptive behavior of panic pedestrians flustering escape, the model assumes that panic pedestrians move randomly with a certain probability p_{rand}, which is given by Eq. (19), *i.e.*, panic pedestrians randomly choose one of the 8 movable directions in the Moore neighborhood or stay in place as the next position with a certain probability p_{rand}, or panic pedestrians will make the optimal movement decision-making with the probability $1-p_{\text{rand}}$, that is to say, panic pedestrians will choose the next position according to transition probabilities P_{ij} with the probability $1-p_{\text{rand}}$.

$$p_{\text{rand}} = \frac{p(i,t)}{\max(p(i,t))}, \quad p_{\text{rand}} \in [0,1], \tag{19}$$

where $p(i,t)$ represents the panic parameter of panic individual being analyzed at the current time step, $\max(p(i,t))$ denotes the largest panic parameter of all panic pedestrians at the current time step. Equation (19) indicates that the more panicked pedestrians are, the more likely they are to move randomly.

2.3. Determination of parameter

There are many parameters in this model, and for the convenience of reading and understanding, Most of the important parameters within the model are summarized in Table 1.

Table 1. Meanings of the parameters in the model.

Parameter	Meaning
p	Panic parameter
t	Time step
n_{st}	Initial number of stable pedestrian
n_{se}	Initial number of sensitive pedestrian
μ_{st}	Mean of stable pedestrian initial panic parameter
σ_{st}^2	Variance of stable pedestrian initial panic parameter
μ_{se}	Mean of sensitive pedestrian initial panic parameter
σ_{se}^2	Variance of sensitive pedestrian initial panic parameter
r_{st}	Emotion perceived radius for stable pedestrian
r_{se}	Emotion perceived radius for sensitive pedestrian
λ_{st}	Panic threshold of stable pedestrian
λ_{se}	Panic threshold of sensitive pedestrian
τ	Emotion self-decay interval
β_{st}	Emotion self-decay coefficient of stable pedestrian
β_{se}	Emotion self-decay coefficient of sensitive pedestrian
r_{exit}	Exit emotion decay radius
α_{st}	Exit emotion decay coefficient of stable pedestrian
α_{se}	Exit emotion decay coefficient of sensitive pedestrian
δ_{st}	Emotion transfer strength attribute of stable pedestrian
ξ_{st}	Emotion receive strength attribute of stable pedestrian
δ_{se}	Emotion transfer strength attribute of sensitive pedestrian
ξ_{se}	Emotion receive strength attribute of sensitive pedestrian
d_{ij}	Distance between individual i and individual j
d_{ie}	Distance between individual i and the exit

In the proposed model, pedestrians are divided into stable pedestrians and sensitive pedestrians according to their personality traits. Therefore, the value ranges of parameters that reflect the difference between the two types of pedestrians in response to emotion should be determined first before the simulation. Note that these parameters only depend on the personality traits of pedestrians and will not change with individual emotional state changing. As discussed before, sensitive pedestrians are sensitive to external stimuli and their mood swings lot, which means that they are prone to be affected by emotion, so such a group is strong in receiving and spreading emotion. Hence, compared with stable pedestrians, sensitive pedestrians can perceive the emotion in a larger area and are more likely to fall into a panic state. Besides, sensitive pedestrians are more capable of emotion contagion and decay than stable pedestrians. In summary, the parameters can be selected as follows:

$$0 \le \lambda_{\text{se}} < \lambda_{\text{st}} \le 1, \tag{20}$$

$$0 < r_{\text{st}} < r_{\text{se}}, \tag{21}$$

$$0 \le \beta_{\text{st}} < \beta_{\text{se}} \le 1, \tag{22}$$

$$0 \le \alpha_{\text{st}} < \alpha_{\text{se}} \le 1, \tag{23}$$

$$0 \le \delta_{\text{st}} < \delta_{\text{se}} \le 1, \tag{24}$$

$$0 \le \xi_{\text{st}} < \xi_{\text{se}} \le 1. \tag{25}$$

2.4. Update rules

The specific simulation update rules of this model are structured as follows.

Step 1 Set simulation time $t=0$. Initialize and set parameters n_{st}, n_{se}, μ_{st}, σ_{st}^2, μ_{se}, σ_{se}^2, ….

Step 2 Generate stable pedestrians and sensitive pedestrians, then populate them randomly into the cells inside the room. For each pedestrian, the initial panic parameter $p_{t=0}$ can be calculated from Eq. (1) or Eq. (2). Thus, according to the comparison between pedestrian initial panic parameter and pedestrian panic threshold, all the pedestrians can be classified as stable normal pedestrians, stable panic pedestrians, sensitive normal pedestrians, and sensitive panic pedestrians.

Step 3 Calculate the static floor field S_{ij} from Eq. (17).

Step 4 Update the panic parameter of each pedestrian according to Subsection 2.1. Next, update the pedestrian emotional state according to the comparative result of panic parameter and panic threshold.

Step 5 If the emotional state of pedestrian is normal, he/she can make the optimal movement decision-making according to transition probabilities P_{ij}, which is calculated from Eq. (18). If the emotional state of pedestrian is panic, he/she moves randomly with a certain probability p_{rand}, which is computed from Eq. (19), or make the optimal movement decision-making with the probability $1-p_{\text{rand}}$. Update the position of all the pedestrians.

Step 6 For each pedestrian, repeat Steps 4 and 5 until the pedestrian evacuates from the exit, then the pedestrian is removed from the system.

Step 7 When all the pedestrians have been evacuated, the simulation process ends.

To make the simulation process much clearer, the flow chart of the simulation process is shown in Fig. 3.

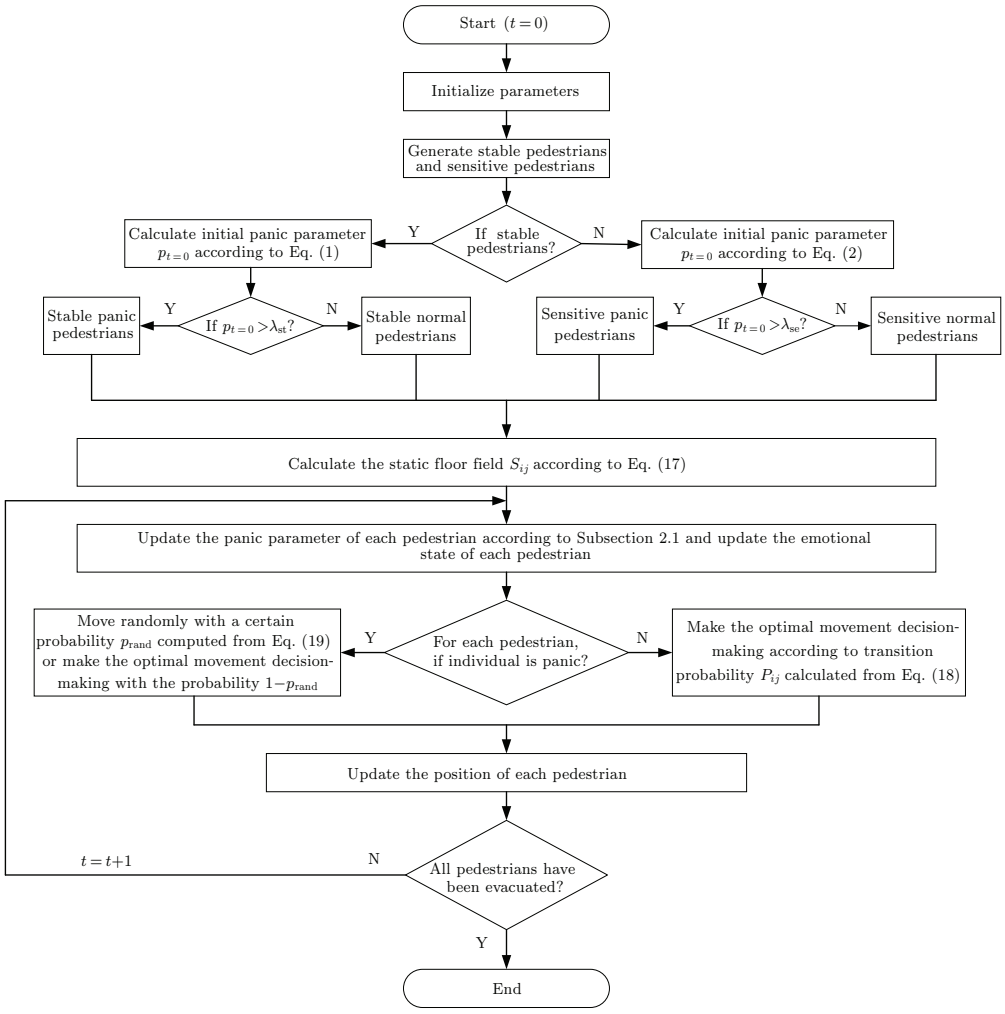


Fig. 3. Flow chart of simulation process.

3. Simulation results and discussion

As shown in Fig. 4, the proposed model is tested in a cellular space of 45×45 cells and the pedestrians are initially distributed randomly and attempt to escape from the room with one exit. The value range of pedestrian initial panic parameter is determined according to the normal distribution function. Moreover, owing to differences in personality traits and emotional states, all pedestrians can be classified as stable normal pedestrians, stable panic pedestrians, sensitive normal pedestrians, and sensitive panic pedestrians. It is worth noting that stable pedestrians and sensitive pedestrians have different reactions to emotion, so their emotion changes are also different, and the detailed description can be seen in Subsection 2.1. When the simulation starts, normal pedestrians will accept the emotion from panic pedestrians within the perceived radius, and panic pedestrians will accept the emotion from the panic pedestrians at higher panic level within the perceived radius, so pedestrian panic parameter increases after emotion contagion. As a result, normal pedestrians will become panic if their panic parameter exceeds the panic threshold.

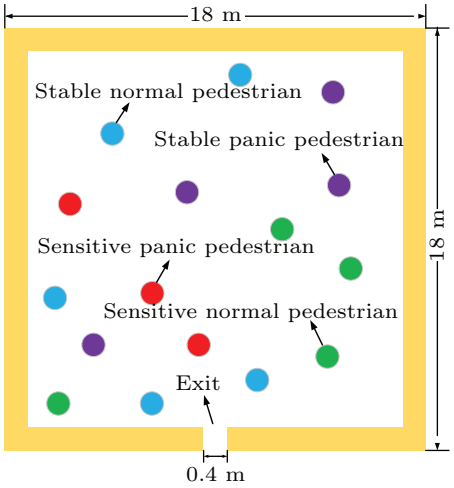


Fig. 4. Schematic illustration of the room. Each cell is an identical square area of 0.4 m×0.4 m.

In addition to emotion contagion, pedestrians will also experience emotion decay during the evacuation, so the emotion self-decay and the exit emotion decay are focused on in the work. Consequently, panic pedestrians may become normal through emotion decay. Normal pedestrians can make the optimal movement decision-making and find the exit quickly ac-

cording to transition probabilities P_{ij}. Panic pedestrians move randomly with a certain probability p_{rand} or make the optimal movement decision-making with the probability $1-p_{\text{rand}}$. In the following, emotional interaction among pedestrians and the effects of some key parameters on pedestrian flow are studied. Results for each scenario are averaged over 20 independent simulations.

3.1. Effect of initial number of pedestrians

In reality, pedestrians will respond differently to emotion due to the diversity of personality traits, so this model divides the crowd into emotion stable pedestrians and emotion sensitive pedestrians. In this subsection, the influence of the initial number of these two groups on evacuation is studied by changing parameters n_{st} and n_{se}. And the other parameters are set to the following values: $\mu_{\text{st}}=\mu_{\text{se}}=0.5$, $\sigma_{\text{st}}^2=\sigma_{\text{se}}^2=0.01$, $\lambda_{\text{st}}=0.5$, $\lambda_{\text{se}}=0.4$, $r_{\text{st}}=2$ m, $r_{\text{se}}=3.2$ m, $r_{\text{exit}}=3.2$ m, $\delta_{\text{st}}=0.3$, $\delta_{\text{se}}=0.5$, $\xi_{\text{st}}=0.3$, $\xi_{\text{se}}=0.5$, $\beta_{\text{st}}=0.1$, $\beta_{\text{se}}=0.2$, $\alpha_{\text{st}}=0.8$, $\alpha_{\text{se}}=0.9$, $\tau=5$ time steps.

We first consider the case where the two types of pedestrian groups are not mixed, *i.e.*, the pedestrians in the crowd are all stable pedestrians or all sensitive pedestrians. Figure 5 reveals that the evacuation time increases significantly as the number of individuals rises. It can be seen that the curve of stable pedestrian without emotion and the curve of sensitive pedestrian without emotion almost coincide, because the difference in personality trait will not work without considering the influence of emotion. Figure 5 also indicates that the evacuation time for the crowd with emotion is more than that without emotion, because pedestrians who are affected by panic emotion may act maladaptive behaviors. On the one hand, panic pedestrians move randomly will increase the confusion of the crowd and accelerate the spread of emotion. On the other hand, panic pedestrians may occupy the optimal evacuation path for other pedestrians. Hence, the evacuation efficiency decreases and the evacuation time prolongs. Besides, it can be found that when the number of people is the same, the evacuation time for a crowd composed of all stable pedestrians is less than that of all composed of sensitive pedestrians, the explanation for this phenomenon is stated as follows. As mentioned in Subsection 2.1, compared with sensitive pedestrians, stable pedestrians are weaker in receiving and spreading emotion, which means that emotion is harder to sweep and intensify among stable pedestrians than sensitive pedestrians. Furthermore, stable pedestrians have higher panic thresholds, that is to say, they are more difficult to get into a panic. Although sensitive pedestrians have a greater emotion decay intensity, their emotion will rise rapidly after each decay due to strong emotional interactions. Therefore, the crowd composed of all sensitive pedestrians will have higher panic level so that they are more likely to move randomly and need more time to evacuate.

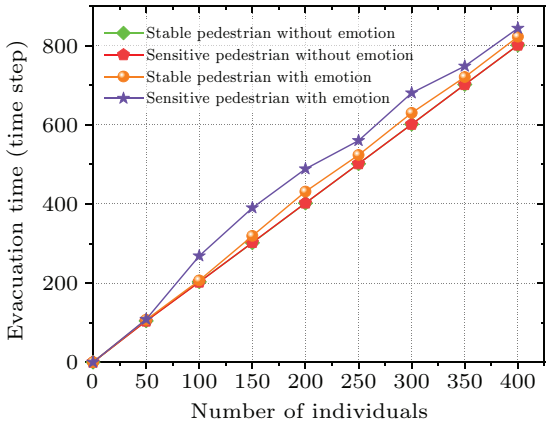


Fig. 5. Evacuation time against the number of individuals with or without panic emotion.

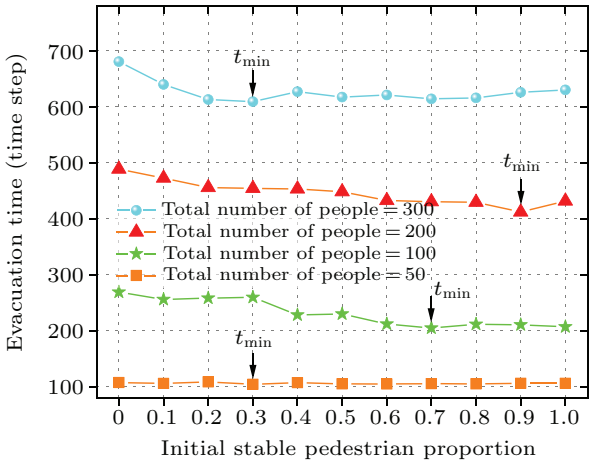


Fig. 6. Evacuation time *versus* initial stable pedestrian proportion for different total numbers of people.

Next, the case where the two types of pedestrians are mixed is studied. The evacuation time when two types of pedestrians are mixed in different proportions under different total numbers of people as shown in Fig. 6. There is no doubt that the evacuation time will rise as the total number of people increases. Furthermore, we can find an interesting phenomenon in Fig. 6. When stable pedestrians and sensitive pedestrians are mixed in different proportions, it seems that an appropriate proportion can minimize the evacuation time and the proportion varies with the total number of people (see black arrow in Fig. 6). The possible reason for this is that, on the one hand, stable pedestrians can slow down the spread speed of emotion in the crowd and prevent the overall panic level from rising too fast. On the other hand, sensitive pedestrians will help the crowd decay emotion faster and reduce the overall panic level availably. Consequently, if the two types of pedestrians are mixed in an appropriate proportion, the evacuation entropy of the crowd will reduce to the minimum so that the evacuation time reaches the local optimum. In addition, the emotional interaction among crowds would become more frequent and complex as the total number of people, *i.e.*, pedestrian density, increases, which may

change the appropriate mixed proportion. In sum, one can understand that either stable pedestrians or sensitive pedestrians will play a positive role to some degree during the evacuation when they are mixed, and the coupling positive effects will be maximal if they are mixed in an appropriate proportion, thus the evacuation time reaches a local minimum value. However, the pedestrian density affects the emotional dynamics,[26] so the appropriate proportion may vary as the pedestrian density changes.

3.2. Effect of emotion decay

Emotion can not only spread in the crowd with the movement of pedestrians, but also decay with the changes in time and space. Hence, there are two emotion decay ways, namely emotion self-decay and exit emotion decay, which are considered in the established model. We assume that $n_{st} = n_{se} = 150$ and the values of other parameters are the same as those in Subsection 3.1.

First, the influence of emotion self-decay way on pedestrian evacuation is studied, which can be realized by adjusting the parameters β_{st}, β_{se}, and τ in this model. Figure 7 shows the pedestrian average panic parameter at each time step under different emotion self-decay coefficients. It can be seen that sensitive pedestrians have more intense emotional fluctuations than stable pedestrians, which is consistent with the personality traits of these two types of pedestrians. In addition, the changing trend of pedestrian average panic parameter in Fig. 7 can be roughly divided into three stages as the emotion self-decay coefficient changes.

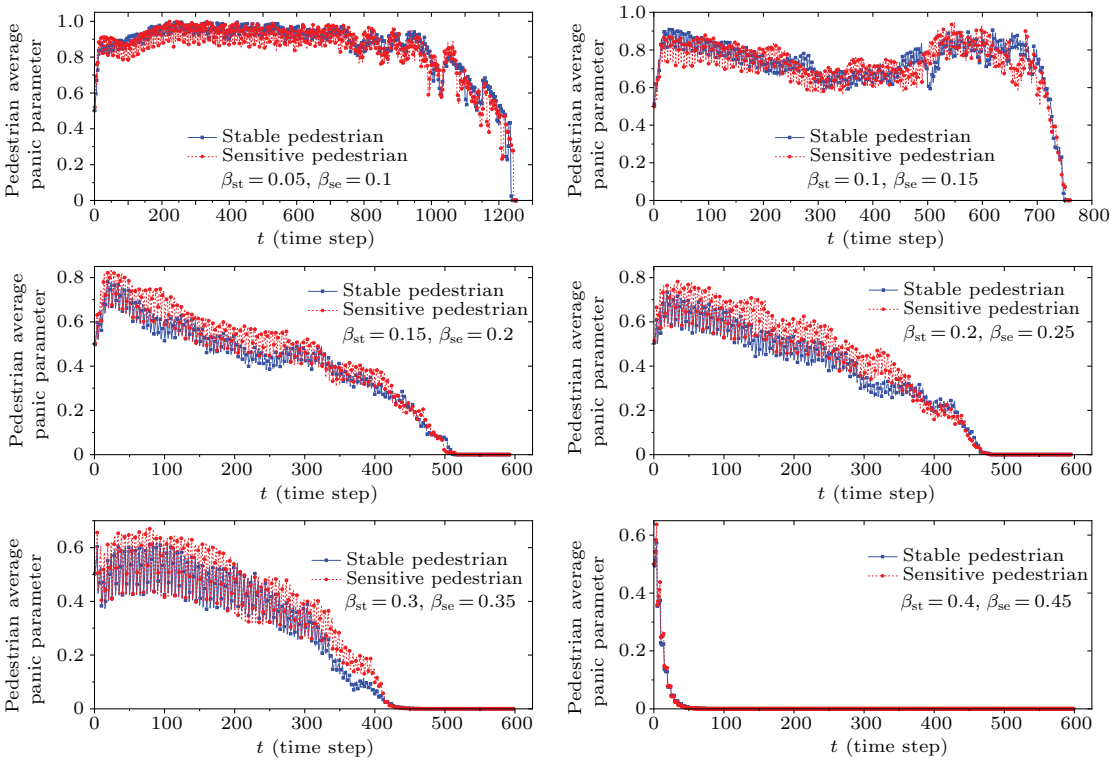


Fig. 7. Curves of pedestrian average panic parameter *versus* time step for different emotion self-decay coefficients, with $\tau = 5$ time steps. Note that pedestrian average panic parameter is calculated by dividing the sum of panic parameters of corresponding pedestrians by the number of these pedestrians.

In the first stage, where the emotion self-decay coefficient is small, *e.g.*, $\beta_{st} = 0.05$, $\beta_{se} = 0.1$, and $\beta_{st} = 0.1, \beta_{se} = 0.15$, it can be seen pedestrian average panic parameter rises quickly and remains high until most pedestrians leave the room, because the speed of emotion contagion is faster than the speed of emotion decay in this case. Figure 8 illustrates snapshots at different time steps when $\beta_{st} = 0.05$ and $\beta_{se} = 0.1$. It is observed that most pedestrians become panic in a short time after the evacuation starts, because emotion spreads rapidly among the crowd with the movement of pedestrians. Furthermore, it is difficult for panic pedestrians to recover from panic into normal, for the emotion self-decay coefficient is small, so most of pedestrians will keep panic for a long time. And only the pedestrians near the exit who are affected by the exit emotion decay can stay normal and then leave from the exit. As a result, pedestrians need to spend lots of time on evacuating from the room, because high panic level not only reduces the rationality of pedestrians, but also would further increase the confusion of the crowd, thus the overall evacuation efficiency decreases.

When the emotion self-decay coefficient continues to increase to, *e.g.*, $\beta_{st} = 0.15$, $\beta_{se} = 0.2$; $\beta_{st} = 0.2, \beta_{se} = 0.25$ and $\beta_{st} = 0.3$, $\beta_{se} = 0.35$, the changing trend of pedestrian average panic parameter in Fig. 7 enters into the second stage.

In this case, the speed of emotion decay is faster than the speed of emotion contagion, so the curve of pedestrian average panic parameter gradually decreases after a peak, and the larger the emotion self-decay coefficient is, the faster the curve goes down. Figure 9 illustrates snapshots at different time steps when $\beta_{st} = 0.2$ and $\beta_{se} = 0.25$. It can be seen that most of pedestrians will become panic under the influence of emotion contagion before the first emotion self-decay. However, pedestrian panic parameter will decrease a lot after each emotion self-decay so that panic pedestrians are more likely to return to normal and have a greater probability of making the optimal movement decision-making to move toward the exit. When panic pedestrians enter into the exit emotion decay radius area, their panic level can be well alleviated and will become normal. Hence, arching and clogging are observed near the exit when a mass of pedestrians reach the exit.

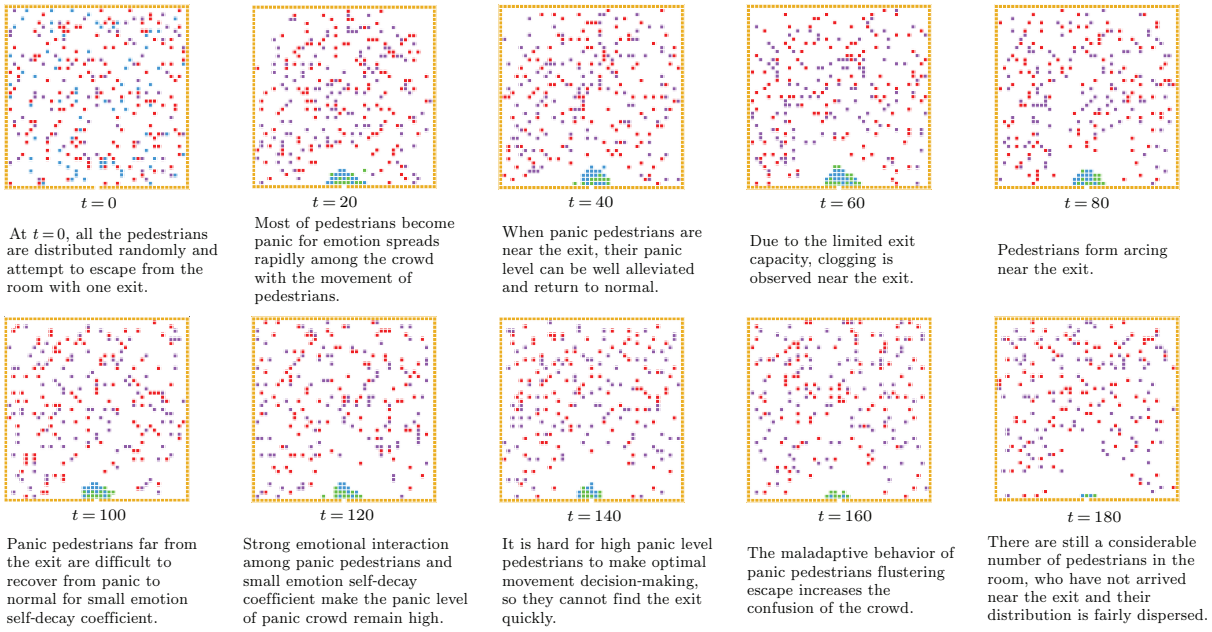


Fig. 8. Snapshots at different time steps, with blue square representing the stable normal pedestrian, the green the sensitive normal pedestrian, the purple the stable panic pedestrian, the red the sensitive panic pedestrian, and the brown the wall, with $\beta_{st} = 0.05$, $\beta_{se} = 0.1$, $\tau = 5$ time steps.

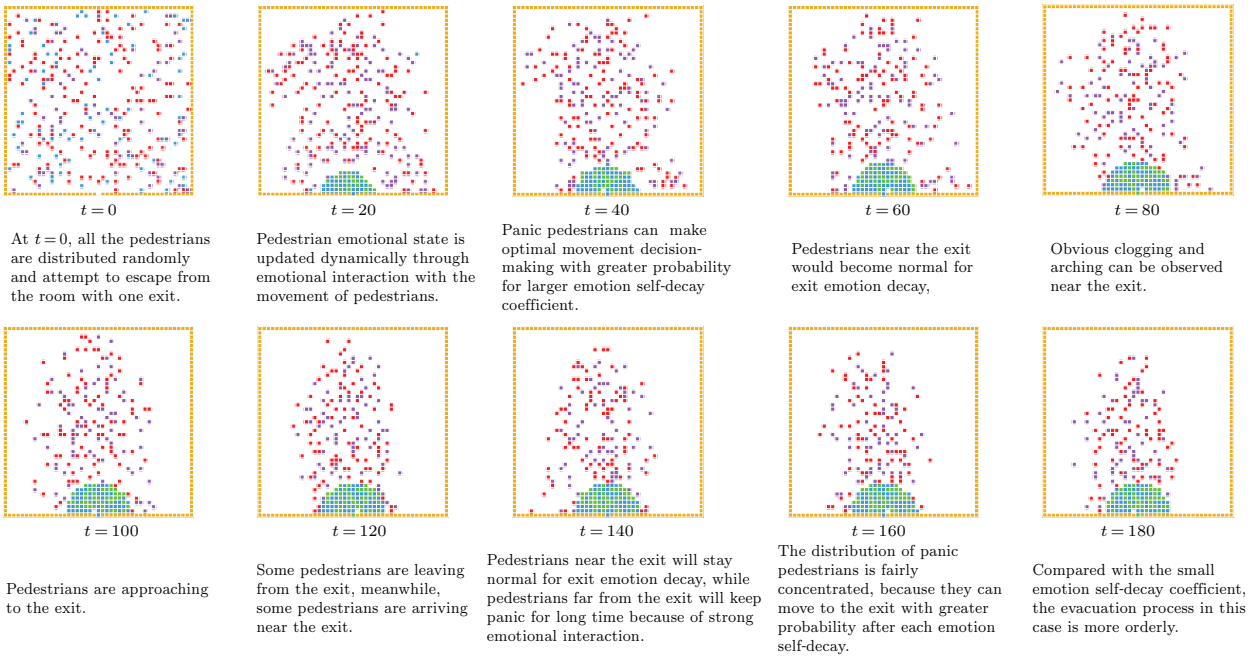


Fig. 9. Snapshots at different time steps, with $\beta_{st} = 0.2$, $\beta_{se} = 0.25$, $\tau = 5$ time steps.

If the emotion self-decay coefficient is large enough, *e.g.*, $\beta_{st} = 0.4$, $\beta_{se} = 0.45$ or more, the changing trend of pedestrian average panic parameter in Fig. 7 enters into the third stage. Under this circumstances, the curve of pedestrian average panic parameter drops quickly close to 0 and stays near 0. The reason is that the emotion self-decay degree is very large each time in this case, which means that pedestrians are easy to recover from panic to normal, so the speed of panic emotion contagion slows

down and all the pedestrians will become normal after experiencing several emotion self-decays. That is to say, emotion stops spreading and only decays, so pedestrian average panic parameter decreases rapidly. As shown in Fig. 10, it can be seen that all the pedestrians become normal in a short time, and then they will make the optimal movement decision-making to find the exit, so normal pedestrians will gather near the exit and leave the room orderly.

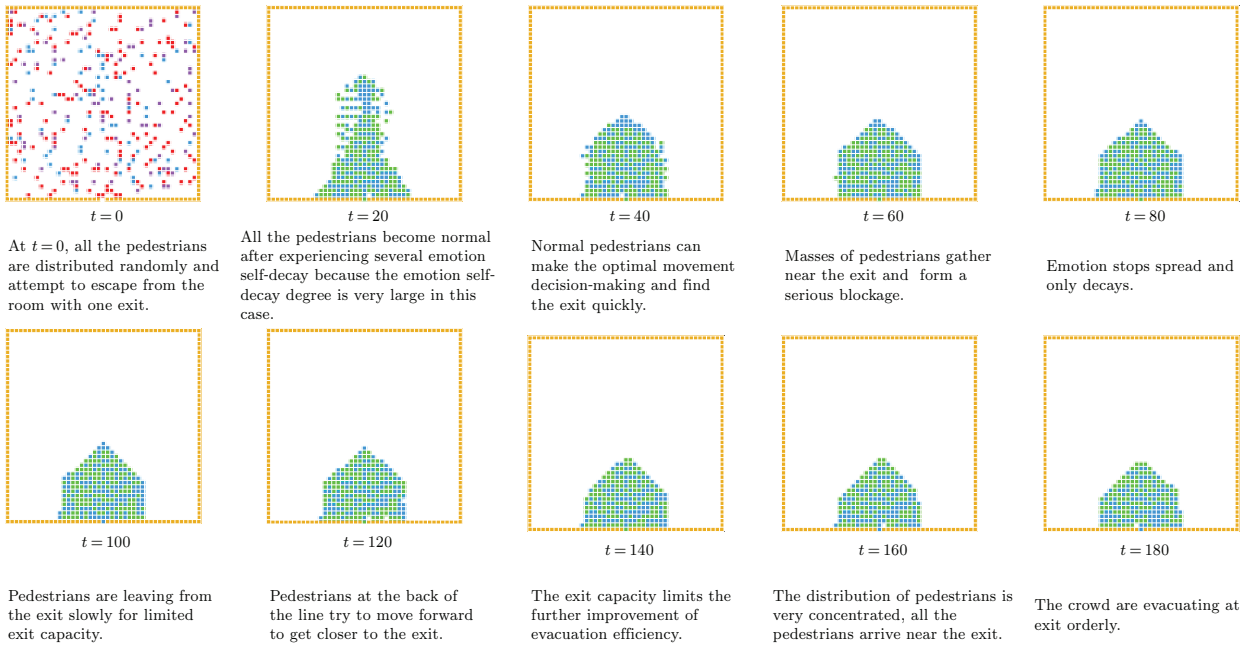


Fig. 10. Snapshots at different time steps, with $\beta_{st}=0.4$, $\beta_{se}=0.45$, $\tau=5$ time steps.

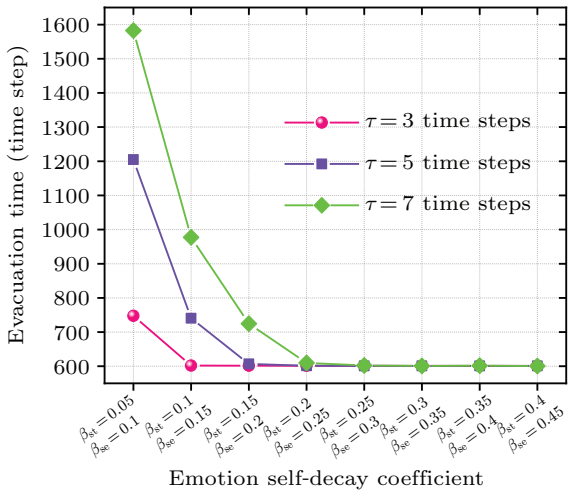


Fig. 11. Curves of evacuation time against emotion self-decay coefficient for different emotion self-decay intervals.

Figure 11 presents how the emotion self-decay coefficients β_{st}, β_{se}, and the emotion self-decay interval τ affect evacuation time. In Fig. 11, either increasing the emotion self-decay coefficient or shortening the emotion self-decay interval can reduce the evacuation time. Nevertheless, when the evacuation time decreases to a certain value, it will no longer continue to decrease with the change of emotion self-decay coefficient and emotion self-decay interval. Generally speaking, increasing the emotion self-decay coefficient means that the pedestrian panic level can be well alleviated after each emotion self-decay, and shortening the emotion self-decay interval means that the pedestrian can experience more emotion self-decay in the same amount of time, so both of them are beneficial to panic pedestrians to get rid of panic and stay normal. Consequently, panic pedestrians can make the optimal movement decision-making with a greater probability so that evacuation efficiency improves. However, owing to the limited exit capacity, the crowd will form blockages near the exit. In such condition, the exit capacity limits the further improvement of evacuation efficiency, so the evacuation time no longer decreases and tends to a stable value.

Next, the influence of the exit emotion decay way on the pedestrian evacuation is investigated, which can be implemented by adjusting the parameters exit emotion decay radius r_{exit} and the exit emotion decay coefficients α_{st} and α_{se} in the model. The pedestrian average panic parameter in each time step under different exit emotion decay radii and exit emotion decay coefficients are shown in the following Fig. 12. It can be found that both the increment of the exit emotion decay radius and the exit emotion decay coefficient can accelerate the reduction of the pedestrian emotion. But it is noted that in comparison with the trend of the change exit emotion decay coefficient, the trend of the pedestrian average emotion parameter changes more obviously by changing exit emotion decay radius. In fact, one can understand the exit emotion decay radius as the exit influence range, that is to say, when pedestrians move into the exit influence range, they can feel exactly that they are near the exit by vision or hearing. Knowing that the

exit location is not far away is great comfort for pedestrians, and it is also the prerequisite for triggering off the exit emotion decay. Furthermore, the exit emotion decay coefficient can be explained as the exit influence intensity. When pedestrians know that they are not far from the exit, increasing the exit influence intensity will help them allay the panic level faster. Therefore, as the exit emotion radius gets larger, more pedestrians can feel the influence of exit earlier and reduce their panic level, so the pedestrian average panic parameter will decay faster. Hence, based on the above analyses, the earlier the exit emotion decay is triggered off, the better it is for pedestrians to reduce the panic level, so changing the exit emotion decay radius has a greater influence on the pedestrian average panic parameter.

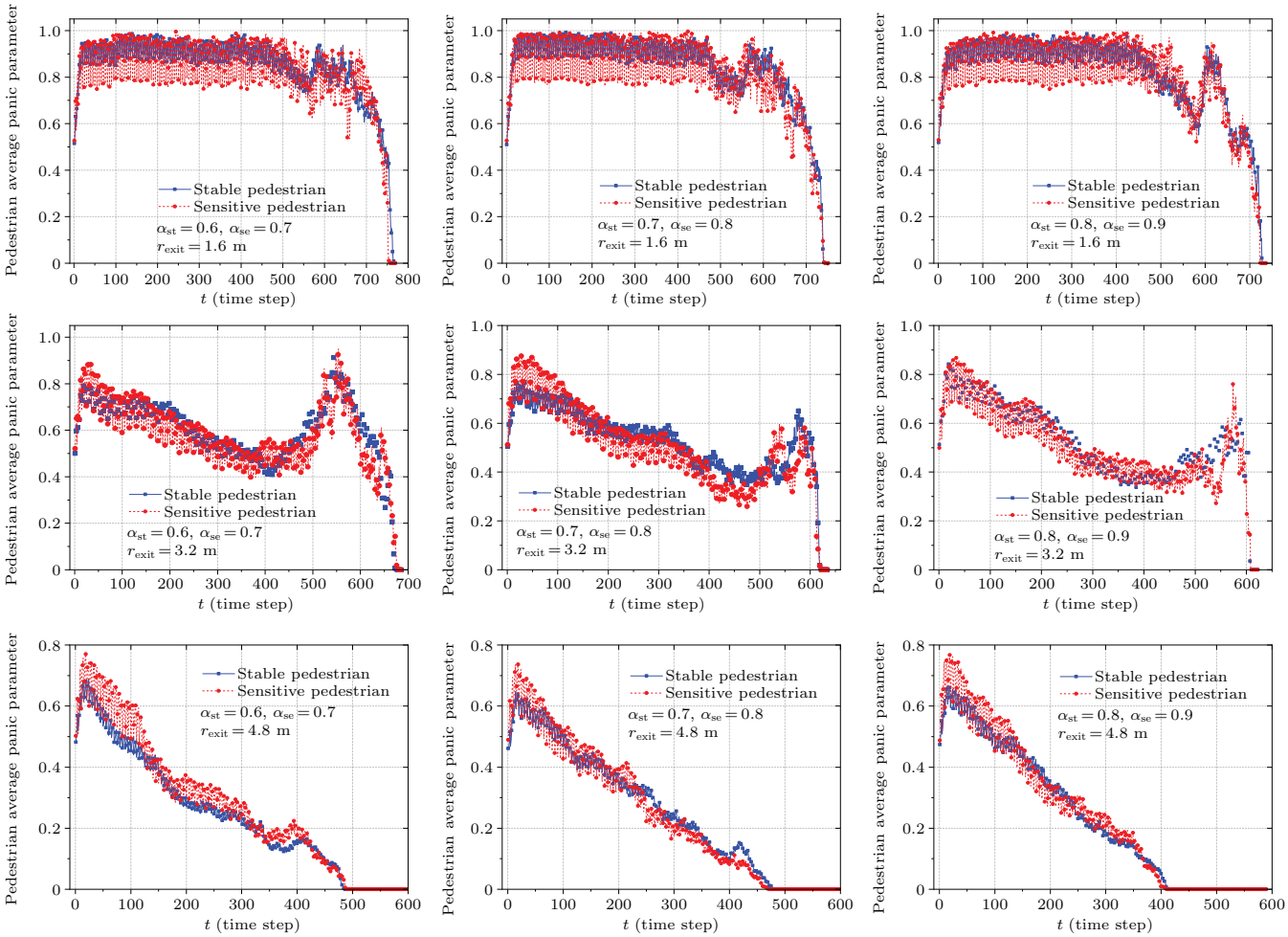


Fig. 12. Curves of pedestrian average panic parameter *versus* time step for different exit emotion decay radii and exit emotion decay coefficients.

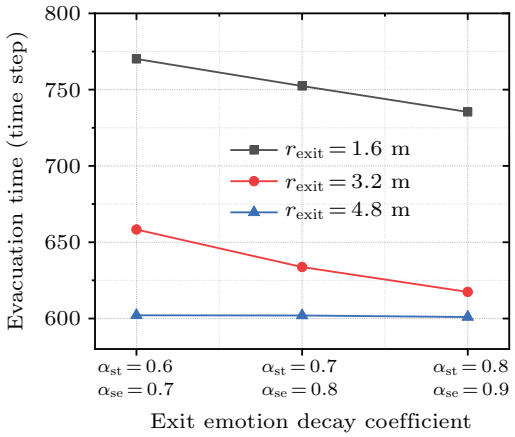


Fig. 13. Variations of evacuation time with exit emotion decay coefficient for different exit emotion decay radii.

The evacuation time under different exit emotion decay radii and exit emotion decay coefficients is shown in Fig. 13. It can be found that evacuation time decreases as exit emotion decay radius or exit emotion decay coefficient increases, because the reduction of pedestrian panic level is conducive to the improvement of evacuation efficiency. However, as mentioned before, the exit capacity will limit the further improvement of evacuation efficiency, so the evacuation time no longer declines as exit emotion decay radius and exit emotion decay coefficient increase to a certain extent.

In sum, enhancing the influence of both emotion self-decay way and exit emotion decay way can suppress the spread of emotion and reduce the pedestrian panic level, whereupon the evacuation efficiency improves effectively. Hence, it is necessary to strengthen pedestrian emotional self-regulation

ability and environmental adaptability so that pedestrians can stay as calm as possible during the evacuation. Furthermore, administrators should reinforce the influence of the exit on evacuees by setting up guide signs, arranging guidance staff or broadcasting radio, and so on, which can help pedestrians to know the information about the exit location quickly and keep calm while queuing at the exit. In addition, in order to avoid the jam at the exit, it is also important to increase the exit capacity. It is worth noting that the emotion decay is also considered in Ref. [41], where it was supposed that the emotion intensity will decrease over time without any stimulus in their model. Compared with the model in Ref. [41], the model in the present paper considered not only the time influence, *i.e.*, emotion self-decay way, but also the space influence, *i.e.*, exit emotion decay way. Though the model and simulation process in the present work are quite different from those in Ref. [41] in many ways, we obtain the similar results to those in Ref. [41], *i.e.*, enhancing the influence of emotion decay will benefit the evacuation process. Hence, the work in this section will be a good supplement to Ref. [41].

3.3. Effect of panic threshold

In real life, each individual has a tolerance to panic emotion, and individuals will get into a panic if their panic level exceeds the tolerance. Hence, a parameter called panic threshold is defined in this model to represent pedestrian tolerance to panic emotion. We set $n_{st} = n_{se} = 150$ and the values of other parameters are the same as the counterparts in Subsection 3.1, then the mean of pedestrian initial panic parameters μ_{st} and μ_{se} and panic thresholds λ_{st} and λ_{se} are adjusted to investigate the influence of the panic threshold on evacuation.

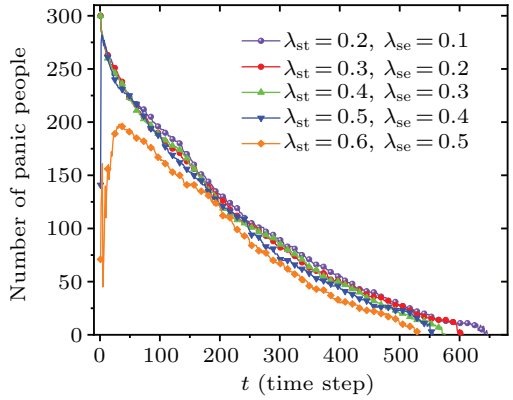


Fig. 14. Variations of the number of panic people in the room with time step for different panic thresholds.

Figures 14 and 15 present the variations of the number of panic people and pedestrian average panic parameter with time step under different panic thresholds when $\mu_{st} = \mu_{se} = 0.5$ respectively. In Fig. 14, it can be found when the time step is the same, the higher the pedestrian panic threshold, the less the number of panic people is. For example, with the time step of 100, it is obvious that the number of panic people when $\lambda_{st} = 0.6$ and $\lambda_{se} = 0.5$ is less than that when $\lambda_{st} = 0.2$ and $\lambda_{se} = 0.1$. On the one hand, the increase of pedestrian panic threshold makes it more difficult for normal pedestrians to become panic, for their tolerance to panic emotion is improved. On the other hand, the increase of pedestrian panic threshold makes it easier for panic pedestrians to become normal, for their panic parameter is easier to decay below the panic threshold. Hence, the number of panic people during the evacuation decreases as the pedestrian panic threshold increases. Moreover, as shown in Fig. 15, the increase of pedestrian panic threshold will also effectively reduce the pedestrian average panic parameter during the evacuation. It is not difficult to explain this: because the number of panic people decreases as the panic threshold increases, which leads the spread speed of emotion to slow down, so pedestrian average panic parameter decreases correspondingly.

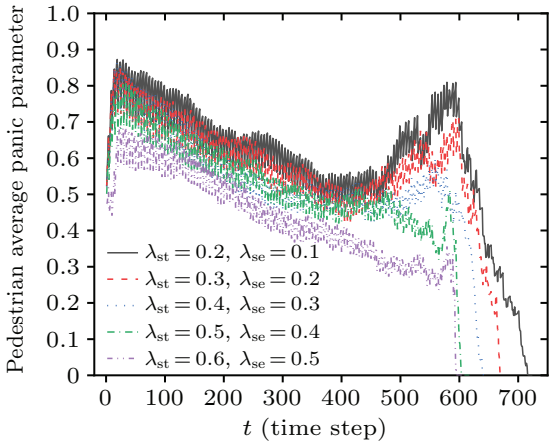


Fig. 15. Variations of pedestrian average panic parameter with time step for different panic thresholds.

Then the influence of panic threshold on evacuation time is explored. Figure 16 shows the relationships between the panic threshold and the evacuation time under different mean of pedestrian initial panic parameter. As can be seen in Fig. 16, if the mean of pedestrian initial panic parameter is constant, the evacuation will decrease with the increase of panic threshold and finally tend to a stable value. When pedestrian panic threshold is low, normal pedestrians are easy to be affected by emotion and become panic, as well as panic pedestrians are difficult to recover from panic to normal, so the number of panic people and pedestrian average panic parameter are large (see Figs. 14 and 15). Thus, panic pedestrians are prone to move randomly because of high panic level, which causes low evacuation efficiency and long evacuation time. When pedestrian panic threshold turns larger, the number of panic people and pedestrian average panic parameter will decrease (see Figs. 14 and 15), which means that more people will make the optimal movement decision-making to find the exit, so the evacuation time will decrease. If pedestrian panic threshold increases to a certain value, *i.e.*, the mean of pedestrian initial panic parameter is smaller than the panic threshold, all

the pedestrians will stay normal at the beginning of evacuation and gather together near the exit quickly, so the evacuation time cannot continue to decrease in this scenario for the limited exit capacity. Another result that can be found in Fig. 16 is that the mean of pedestrian initial panic parameter also affects the evacuation time a lot. Before the exit capacity reaches saturation, *i.e.*, before the evacuation time tends to be stable, the evacuation time is positively associated with the mean of pedestrian initial panic parameter if the panic threshold is equal. That is to say, if the initial panic level of the pedestrians is high, it is not good for an efficient evacuation. Because the higher the initial panic level of the pedestrians, the more likely they are to panic at the initial moment, especially when the panic threshold is low. Hence, the speed and frequency of emotion contagion among the crowd will be strengthened when the evacuation starts, which leads the pedestrian average panic parameter to keep large for a long period. As a result, it is difficult for people to keep rational and make the optimal movement decision-making thus prolonging the evacuation time.

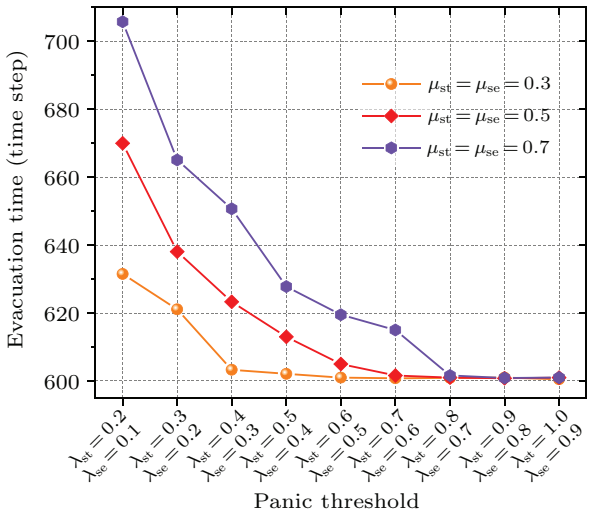


Fig. 16. Variations of evacuation time with panic threshold for different mean of pedestrian initial panic parameter.

In a word, we can find that raising pedestrian panic threshold can effectively reduce the number of panic people and pedestrian average panic parameter during the evacuation, which will help pedestrians keep normal and make the optimal movement decision-making, so the evacuation time decreases. Besides, the mean of pedestrian initial panic parameter also affects the evacuation time a lot, it is a good way to improve the evacuation efficiency by reducing the mean of pedestrian initial panic parameter. Therefore, individuals should increase their tolerance to panic emotion and intensify the psychological quality to avoid getting into a panic in the evacuation process. In addition, in order to ensure that the evacuation is carried out quickly and effectively, it is important for the management department to appease the crowd and reduce the group panic level as soon as possible at the beginning of evacuation.

4. Conclusions

This work aims to study the pedestrian dynamics considering panic emotion and personality traits. Combined with the relevant theories of the psychological OCEAN personality model and the epidemiological SIS model, an extended cellular automata evacuation model with floor field method is established to investigate the dynamics mechanism of emotion among crowds and pedestrian behaviors under the influence of emotion. In the model, in view of the fact that pedestrians with different personality traits may have different responses to emotion in reality, the pedestrians are divided into stable pedestrians and sensitive pedestrians, and their emotional state can be normal or panic. This group classification not only conforms to the distribution law of personality traits but also shows the diversity of panic emotion in different groups more truly. In addition, emotion contagion, emotion decay, and the influence of emotion on pedestrian movement decision-making are also taken into account simultaneously. Then the effects of the initial number of pedestrians, emotion decay, and panic threshold on evacuation are studied. The main simulation results are summarized as follows.

(i) Panic emotion will prolong the evacuation time to a certain extent for panic pedestrians may act maladaptive evacuation behaviors to reduce the evacuation efficiency.

(ii) The evacuation time will increase as the number of evacuees rises. With the influence of emotion, when stable pedestrians and sensitive pedestrians are not mixed, the same number of stable pedestrians have faster evacuation speed than sensitive pedestrians. Moreover, when stable pedestrians and sensitive pedestrians are mixed in different proportions, the local minimum evacuation time under certain conditions can be obtained if these two types of pedestrians are mixed in an appropriate proportion and the proportion may change with the total number of pedestrians.

(iii) Emotion decay has an important influence on pedestrian evacuation. Enhancing both the influence of emotion self-decay way and exit emotion decay way can suppress the spread of emotion and reduce the pedestrian panic level, whereupon the evacuation efficiency improves apparently.

(iv) As the panic threshold increases, *i.e.*, pedestrian tolerance to panic emotion increases, the number of panic pedestrians and pedestrian average panic parameter during the evacuation will decrease well, which reduces the evacuation time. Besides, the initial panic level of pedestrians will affect the evacuation time a lot, so it is important for the management department to appease the pedestrians and reduce the group panic level as soon as possible at the beginning of evacuation.

(v) The exit capacity will limit the further improvement of evacuation efficiency, so it is necessary to enhance the exit capacity by increasing the number and width of the exit, etc.

This work is expected to provide a valuable insight into optimizing evacuation strategies for the pedestrians in panic situations. The simulation results demonstrate that the proposed model has reproduced some real characteristic features of pedestrian panic psychologies and behaviors to some extent. While pedestrian panic psychologies, pedestrian panic behaviors, and the dynamics mechanism of panic emotion, *etc*., in reality, are much more complicated and unpredictable, thus certain reasonable simplifications and assumptions have to be made. In fact, some factors such as more than one exit, more personality traits of pedestrians in response to emotion, more complex building structures, more maladaptive panic behaviors, like herding behavior, larger move speed, and other parameters not discussed in this work may affect the pedestrian dynamics. Therefore, these factors will be the focus of our next step. Besides, the calibration of the model is important, in the face of the present situation that real data for panic pedestrian dynamics are very scarce, some virtual reality experiments will be performed to validate and improve the model in the future.

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