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Evacuation flow of pedestrians considering compassion effect*

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By means of game theory, the effect of compassion mechanism on the evacuation dynamics of pedestrians from a room is studied based on a cellular automaton model. Pedestrians can choose to cooperate or defect in a snowdrift game during the movement. With the compassion mechanism, pedestrians share their payoff to the poorest peer when several pedestrians compete for the same empty cell. Simulation results show that the escape time grows with fear degree r of the snowdrift game, and the compassion mechanism will have a different effect on the system compared with the situation of a spatial game with fixed population. By payoff redistribution, the compassion can help the minor strategy to survive. When the fear degree r is large, the compassion can sustain the cooperative behavior, and spontaneously decreases the escape time. When the fear degree r is small, the compassion will decrease the cooperation frequency, and slightly increase the escape time. The phenomenon is explained by the evolution and competition of defectors and cooperators in the system. Finally, the effect of initial cooperator proportion, the effect of two exits, and the effect of "Richest-Following" strategy, and the effect of initial density are also discussed.

Keywords: compassion, evacuation, cooperation

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1. Introduction

With the rapid growth of population density and urban size, there are more and more large crowds of people in public transit stations, streets and markets. Especially, pedestrian evacuation occurs frequently and may develop into tremendous accidents due to congestion. In order to save life and lessen injuries, much research has been paid to the problem of pedestrian evacuation dynamics. Intriguing phenomena in pedestrian evacuation experiment have been identified, including clogging, 'Faster-is-slower effect', mass behavior, and so on.[1–4] Various simulation methods are also introduced to the field of pedestrian evacuation, including the social force models,[1,5–7] and the cellular automaton models.[8–13] Social force models are renowned for the precision, but maybe only suitable for small-scale evacuation due to its complicated calculation. On the other hand, the cellular automaton models can be applied to large-scale evacuations.

In social science, the emerge of cooperation behavior has been widely studied in the past two decades.[14] Recently, some researches have pointed out that the compassion behavior plays an important role in the widespread of cooperation.[15–17] As a matter of fact, compassion behavior not only involves in human society but also exists in animal world.[18] In human society, charity system are established and developed to help the poor members. Compassion allows us to help disadvantaged individuals in suffering or with low income.[19,20] There is no doubt that compassion help resolve social dilemma, and let us choose to cooperate with others. Recently, the effect of compassion on the evolution of cooperation in the spatial prisoner's dilemma game (PDG) has been studied, showing that the cooperation frequency could be significantly promoted.[17] In the evacuation process, an evolutionary game occurs when several pedestrians compete for the same empty position. Game theory is therefore introduced to evacuation dynamics in order to gain a better view of pedestrian conflict behaviors.[21–27] The payoff matrix is relate to the complicated interactions among pedestrians and can be used to determine the movement of pedestrians. During evacuation, people might show compassion towards to the disadvantaged individuals. Nevertheless, the effect of compassion mechanism is missed in the literature. Due to the population-decreasing feature and the panic nature of the evacuation process, one can expect that the compassion will have different effect on the cooperation frequency and the final escape time.

In this paper, we study the effect of compassion on the evacuation dynamics, in which the compassion is represented by a payoff redistribution mechanism. By simulation, we show that the compassion will have different effect on the evacuation dynamics depending on the fear degree. Compassion helps the minor strategy to survive in the process of evacuation. We show that the escape time will decrease with compassion when the fear degree is high, with an enhanced co-

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operation frequency. However, when the fear degree is low, the escape time will increase with compassion, together with a slightly lowered cooperation frequency. To better understand the phenomenon, we investigate the evolution and competition of cooperators and defectors in the system. The effect of initial cooperator frequency,the effect of "Richest-following" strategy, and the effect of pedestrian density are also discussed.

The rest of this paper is organized as follows. In Section 2, we describe the evacuation model considering compassion mechanism. In Section 3, we show the simulation results and discuss the phenomenon in detail. Finally, the study is summarized in Section 4.

2. Mathematical Model

In this paper, a cellular automaton (CA) model is adopted to simulate the pedestrian behavior during evacuation. In the model, a room with one exit is considered. The room is represented by a square lattice of 25×25 cells, in which each cell represents a space of 0.4 m×0.4m and can be empty or occupied by only one pedestrian. An exit of 3 cells is located at the center of the bottom wall. Pedestrians always advance towards the exit without back steps during the evacuation process. Once the pedestrians arrive at the exit, they are eliminated from the system.

Table 1. The payoff matrix. In the table, C indicates pedestrian adopts cooperate strategy, D indicates pedestrian choose to defect, E indicates an empty neighbor cell..

	C	D	E
C	(R,R)	(S,T)	$(e,/)$
D	(T,S)	(P,P)	$(e,/)$

Obviously, there will be conflicts when several pedestrians select the same cell as their destination. The conflict is modelled by a snowdrift game. Pedestrians can choose to be cooperator or defector in the game. Generally speaking, the cooperators will follow the evacuation instructions and be more polite to the surrounding pedestrians, while the defectors will tend to ignore the instructions and act individually to maximize their profits. When two individuals are involved in a snowdrift game, they will receive a payoff according to the payoff matrix (Table 1). To be specific, if two cooperators encounter, they receive a reward (R), while two defectors will both receive a punishment (P) when they encounter. Meanwhile, defector receives a temptation (T) and cooperator receives a sucker's payoff (S) when a cooperator interacts with a defector. In a snowdrift game, one has $T > R > S > P$. Furthermore, a pedestrian will gain a payoff of empty (e) when he has an empty cell (E) in his neighborhood. The payoff $\overline{P}$ of a pedestrian is the cumulative payoff that the pedestrian received from all his neighbors divided by the numbers of pedestrians in the neighborhood. The payoff represent the energy of pedestrians, which will determine the pedestrians' movement and strategy update. Without loss of generality, we set $T = 1 + r$, $R = 1$, $S = 1 - r$, $P = 0$, and $e = 1$ in the payoff matrix, where the parameter r ($0 \le r \le 1$) describes the pedestrian's fear degree during the evacuation. A high fear degree describes the situation in which most pedestrians are too scared to judge rationally.

This study is based on the floor field model for pedestrian evacuation. Generally speaking, pedestrians tend to select the cell approaching the exit due to their wish to leave the room as soon as possible. The probability of a pedestrian located in cell i selecting an empty cell j as destination is described as follows:

$$P_d(i \to j) = \frac{\exp(k_s s_j)}{\sum\limits_{j \in \phi_i} \exp(k_s s_j)} \tag{1}$$

where s_j is the static floor field of $s_j = 1/d_j$, with d_j as the minimum steps from possible destination cell j to the exit; k_s is the pedestrians' sense of distance; and ϕ_i denotes the set of destination cells for pedestrian i. Here we set $k_s = 50$.

After all pedestrians determined their destinations, the situation of several pedestrians compete for one empty cell is identified. The compassion mechanism is applied by redistributing the pedestrians' payoff involved in the competition. In the case, pedestrian i select the poorest pedestrian j who has the same destination, and compare his payoff with pedestrian j. If $\overline{P}_i > \overline{P}_j$, compassion mechanism takes effect and their payoff will be modified as:

$$\begin{cases} F_i = \overline{P}_i - c(\overline{P}_i - \overline{P}_j), \\ F_j = \overline{P}_j + c(\overline{P}_i - \overline{P}_j), \end{cases} \tag{2}$$

where $c \in [0,1]$ is the compassion level parameter, and F denotes the fitness of pedestrians. The model reduces to the case of no compassion when $c = 0$, and represents the case of altruism when $c = 1$.

Then, to reflect the conflicts when several pedestrians compete for the same cell, the probability of a pedestrians i entering the empty cell j is expressed as follows:

$$P_e(i \to j) = \frac{\exp(k_e F_i)}{\alpha \sum\limits_{i \in \varphi_j} \exp(k_e F_i)}, \tag{3}$$

where k_e denotes the pedestrians' judgement parameter when conflict occurs[21] (here $k_e = 0.1$), φ_j represents the set of pedestrians who choose the same empty cell j as destination, and α represents the conflict cost coefficient, which is related to the number of defectors n in φ_j:

$$\begin{cases} \alpha = 1, \ n < 2, \\ \alpha = n, \ n \ge 2. \end{cases} \tag{4}$$

Apparently, the conflicts between pedestrians will become intense when two or more defectors compete for the same position. As a result, it might happen that no one can move into the empty cell. This phenomenon brings a negative effect on the evacuation compared with the case when there is only one or no defector involved in the conflict. In Fig. 1, two examples of conflict are illustrated. In the red rectangle, five pedestrians compete for cell A. In the blue rectangle, two pedestrians compete for cell B. The payoff of each pedestrian and their final fitness value after the redistribution are illustrated.

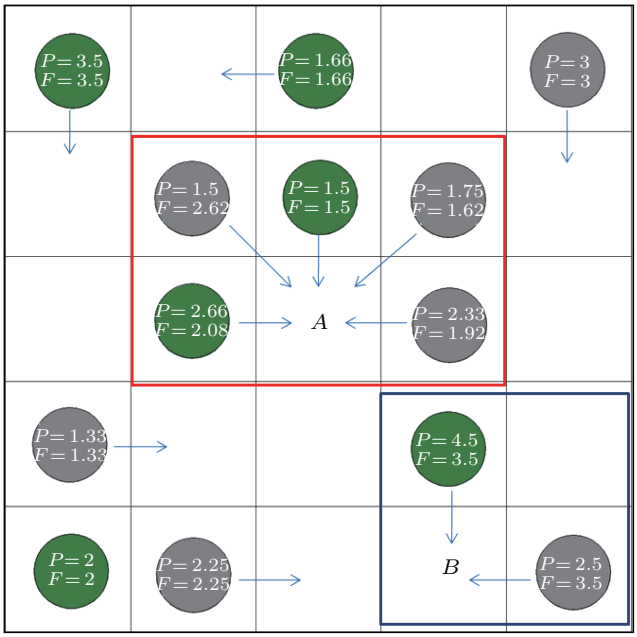


Fig. 1. (color online) Illustration of conflicts between pedestrians and the compassion-based payoff redistribution process. Here the grey circle denotes cooperators, the green circle denotes defectors, and the arrows express the intended direction of movement. Parameters are $r = 0.5$ and $c = 0.5$.

Finally, pedestrians update their game strategies (cooperate or defect) synchronously after they move into empty cells or stand still. In each time step, pedestrians will choose a random neighbor and learn from the neighbors' strategy. The probability of pedestrian i learning from j is expressed by a Fermi-alike function:

$$W_{s_i \to s_j} = \frac{1}{1 + \exp\left(\dfrac{F_i - F_j}{k_n}\right)}, \tag{5}$$

where s is the strategy of pedestrian, k_n is the noise amplitude in decision, $k_n = 0$ corresponds to the deterministic updating situation. Without loss of generality, we set $k_n = 0.1$ as in the literature.[17,24,25]

To be specific, the evolution of pedestrian dynamics are listed as follows:

(i) Pedestrians play snowdrift games with neighbors and get payoff by Table 1;

(ii) Pedestrians select their destinations by Eq. (1);

(iii) Identify the cases of several pedestrians compete for one cell. Apply the compassion mechanism by Eq. (2);

(iv) Determine the pedestrian's probability to occupy the empty cell by Eq. (3), make the movement;

(v) Update pedestrians' gaming strategies by Eq. (5);

(vi) Go back to Step (i) and continue the loop until the evacuation ends.

3. Simulation results and discussions

In this section, we show the simulation results of the model of pedestrian evacuation with compassion. Initially, $N = 500$ pedestrians are distributed randomly in the room with initial proportion of cooperators $\rho_{\mathrm{IC}} = 0.5$. All data are averaged over 500 simulation runs.

First, we feature the pedestrian escape time as a function of fear degree r, as shown in Fig. 2. The escape time increases with r, especially when $r \geq 0.4$. The fear among evacuees will greatly prolong the evacuation process. In order to evacuate quickly, pedestrians should remain calm, instead of hypertension. On the other hand, one can see that the compassion mechanism greatly affect the escape time. In particular, the compassion mechanism will increase the escape time slightly when $r \leq 0.4$, while it will decrease the escape time when $r > 0.4$. When the crowd is with high panic ($r = 0.9$), the escape time can be decreased for almost 10% with $c = 1.0$.

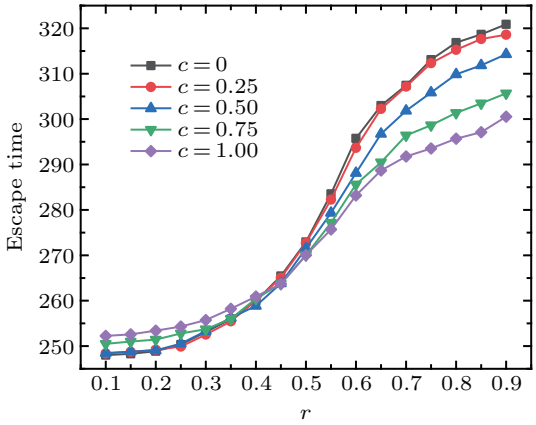


Fig. 2. (color online) Escape time versus fear degree r with different compassion levels.

In order to explain the variation of escape time, we investigate the competition between cooperators and defectors, as shown in Fig. 3. When the fear degree is low (see Fig. 3(a)), cooperators dominate the system during the entire process of evacuation. The number of cooperators increases to a maximum, and then decline until all cooperators leave the room, while the number of defectors remain decreasing all the time. When the fear degree increase to $r > 0.4$, more defectors will appear than cooperators in the system, as shown in Fig. 3(b), 3(c), and 3(d). When $r = 0.9$, the overwhelming majority of

pedestrians will defect instead of cooperate (see Fig. 3(d)). The fear degree r affects the evacuation dynamics, simply because the pedestrians could be significantly tempted to defect with the increment of r. However, according to Eq. (3), the existing of too many defectors in the neighborhood may lead to a dilemma that all pedestrians stay still without movement. As a result, a higher r with more defectors will lead to longer escape time due to intense competition.

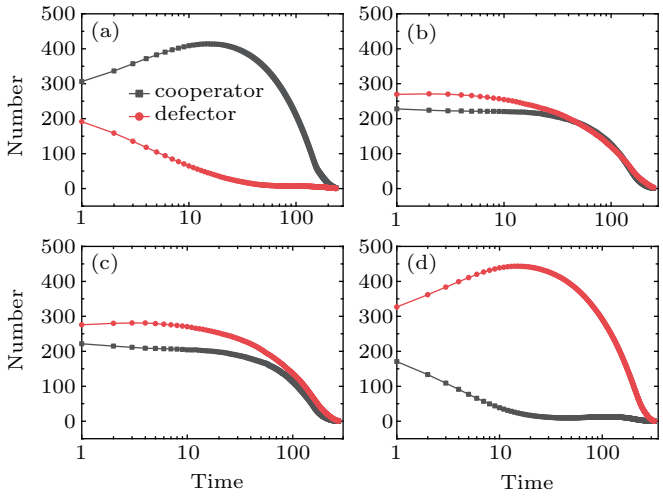


Fig. 3. (color online) Competition between cooperators and defectors with different r while $\rho_{\rm IC} = 0.5$. (a) $r = 0.1$; (b) $r = 0.47$; (c) $r = 0.5$; (d) $r = 0.9$. Note here the initial numbers of cooperators and defectors are equal at Time = 0.

To understand how compassion mechanism affect the evacuation dynamics, we investigate the evolution of cooperator proportion $\rho_{\rm C}$ with different compassion level. In Fig. 4, in the first several steps, the cooperator proportion increases with low fear degree, while it decreases with high fear degree. The compassion mechanism slightly reduces the cooperation level for $r = 0.1$, while it increases the cooperation level for $r = 0.47$, 0.5 and 0.9. In fact, with compassion mechanism, the minority strategy will have more opportunity to survive during the evacuation process. As a result, compared with the case of no compassion mechanism, the escape time for $r = 0.1$ will increase because of more defectors appear, and it decreases for high r values with less defectors. This is in consistent with the result of Fig. 2. Note here the effect of compassion is different as compared to the case of fixed population games.[17] In the spatial prisoner's dilemma game,[17] the compassion always lead to a higher cooperator frequency. However, in the evacuation dynamics, the compassion can either decrease or increase the cooperator frequency depending on the value of fear degree.

Another interesting phenomenon appears in Fig. 4, where the end-piece of cooperator proportion's variation with time seems disorder. To explain this phenomenon, we studied the average payoff of pedestrians. As shown in Fig. 5(a), in the early stage, the average payoff of pedestrians changes smoothly and slowly. The average payoff increases greatly and then decreases at the ending stage. This is explained as follows. In the ending stage of evacuation, there are only a few pedestrians in the room, and the pedestrians can have more empty cell neighbors than in the early stage. The empty neighbors will lead to higher pedestrian payoff. Higher payoff bring priority of individuals when they competes for empty cells, and increase the probability of others learning their strategies. Therefore, the instability of average pedestrian payoff will result in the disordered variation of cooperator frequency.

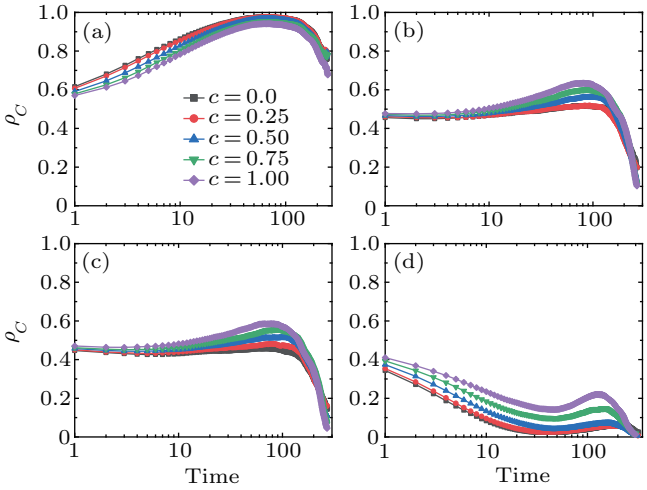


Fig. 4. (color online) Evolution of Cooperator proportion ρ_C with different compassion level c, and we set $\rho_{\rm IC} = 0.5$ at Time = 0. (a) $r = 0.1$; (b) $r = 0.47$; (c) $r = 0.5$; (d) $r = 0.9$.

To confirm the fact that compassion mechanism helps the disadvantaged strategy, we investigated the pedestrian strategy transfer frequency for different c. As shown in Fig. 5(b), with the increment of c, the value of $W_{C\to D} - W_{D\to C}$ is positive and decrease when $r = 0.1$, while it is negative and increase when $r = 0.7$ and 0.9. Therefore, when compassion level increases, the number of cooperators transfer into defectors less than defectors transfer into cooperators for $r = 0.1$, but on the contrary for $r = 0.7$ and 0.9. Besides, the variation of $W_{C\to D} - W_{D\to C}$ with compassion level is more eminent $r = 0.9$, which indicates that the compassion helps the disadvantaged cooperator to survive more efficiently with high fear degree. As a result, the escape time will decrease more for high fear when compassion works. Meanwhile, the value of $W_{C\to D} - W_{D\to C}$ remain almost unchanged with the variation of compassion parameter c for $r = 0.3$, 0.5. This demonstrates that the compassion has tiny effect on the evacuation dynamics in this range.

Figure 6 shows the snapshots of pedestrian evacuation when $r = 0.47$ and $c = 0.25$. At Time = 0, pedestrians are distributed randomly in the room with the initial proportion of $\rho_{\rm IC} = 0.5$. While pedestrians leave the room one by one, pedestrian arching appears, while cooperators and defectors coexist all the time [Fig. 6(b) and 6(c)].

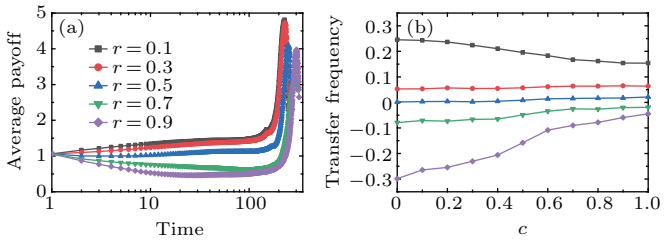


Fig. 5. (color online) (a) Variation of average payoff $\overline{P}$ for different r while $\rho_{\rm IC} = 0.5$. (b) The difference of transfer frequency $W_{C\to D} - W_{D\to C}$ as a function of the compassion parameter c for different r, and $\rho_{\rm IC} = 0.5$.

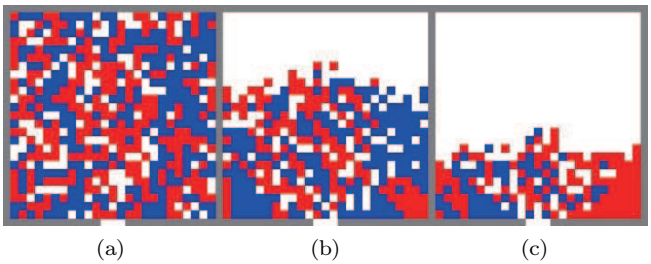


Fig. 6. (color online) Snapshots of room evacuation at $r = 0.47$ and $c = 0.25$. (a) Time = 0; (b) Time = 65; (c) Time = 130. Here the white cells represent empty sites, the blue cells represent cooperators, the red cells represent defectors, and the gray cells represent walls.

To better understand the compassion mechanism, we discuss the examples of conflict illustrated in Fig. 1. In the red rectangle, five pedestrians select empty cell A as their destinations. After the payoff redistribution, the poorest cooperator at upper-left corner receives a extra fitness of 1.12, which give him a highest fitness among others. In the blue rectangle, one cooperator compete with a defector for cell B. Although the defector has a originally higher payoff, they have the same fitness after the payoff redistribution. Therefore, due to the compassion mechanism, the disadvantaged pedestrians' payoff is enhanced and the advantaged pedestrians' payoff is weaken. As a result, pedestrians with advantaged strategy may learn from disadvantaged strategy. This will help the disadvantaged strategy to survive during the evacuation process.

In Fig. 7, we investigate the effect of initial cooperator proportion on the escape time. One can see that $\rho_{\rm IC} = 0$ will produce a maximum escape time, and $\rho_{\rm IC} = 1$ will lead to a minimum escape time. Obviously, the escape time will remain immutable with c for $\rho_{\rm IC} = 0$ and $\rho_{\rm IC} = 1$, because the initial pure strategy state will continue and the strategy learning mechanism does not work. With the increase of $\rho_{\rm IC}$, the escape time decrease in different style with different r. With low fear degree ($r = 0.1$), the escape time is a convex function with $\rho_{\rm IC}$, and the compassion mechanism leads to slightly longer escape time. With high fear degree ($r = 0.9$), the escape time is a concave function with $\rho_{\rm IC}$, and the compassion mechanism leads to shorter escape time. With middle fear degree ($r = 0.5$), the compassion mechanism will prolong the escape time slightly when $\rho_{\rm IC} \le 0.4$, and reduce the escape time when $\rho_{\rm IC} > 0.4$. The compassion mechanism helps cooperators to survive for small values of $\rho_{\rm IC}$, and helps defectors for large values of $\rho_{\rm IC}$. Therefore, compassion leads to longer escape time for $\rho_{\rm IC} < 0.4$ and shorter escape time for $\rho_{\rm IC} > 0.4$.

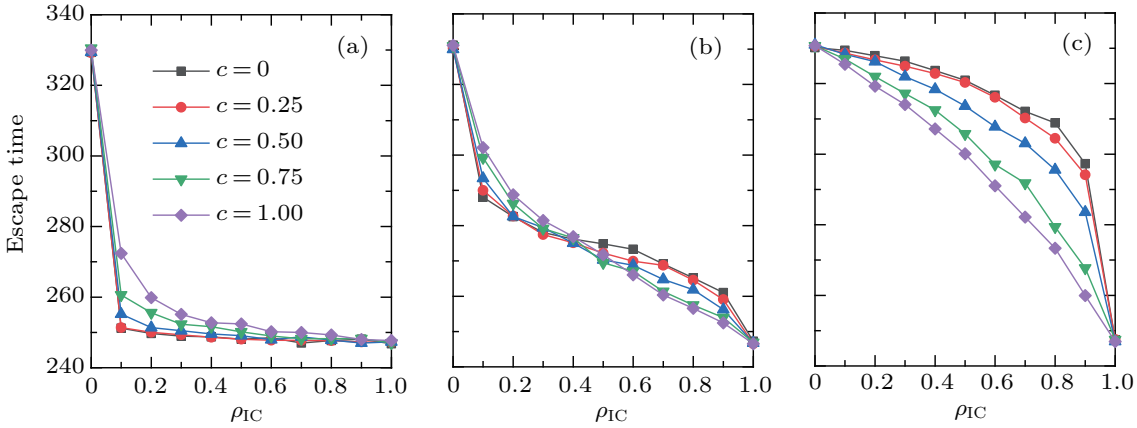


Fig. 7. (color online) Escape time as a function of the $\rho_{\rm IC}$. (a) $r = 0.1$; (b) $r = 0.5$; (c) $r = 0.9$.

We further examine the situation of more than one exits. In the study, two exits with size 3 cells at the bottom side are separated by 7 cells. The pedestrians select the closer exit as their moving direction. In Fig. 8, we show the simulation results of escape time variation with the fear degree. One can see that the results are similar as that in Fig. 2. The escape times show similar variation with the fear degree r. Moreover, the escape times are roughly half of those in Fig. 2.

The pedestrians' game-strategy-updating mechanism may also affect the final escape time. Here we investigate the situation that the pedestrians will learn from the neighbor who successively move into an empty cell if there is such neighbor. We can loosely define this situation as a "Richest-Following" strategy, since the neighbor who move into an empty cell can be seem to have the richest payoff. Figure 9 shows the variation of escape time with the fear degree r and with different compassion level. One can see that the escape time increases with the fear degree, and the results are qualitatively similar

to those in Fig. 2 and Fig. 8. The only exception is the case of $c = 1.0$. When $c = 1.0$, the escape time only shows slight increase with the fear degree.

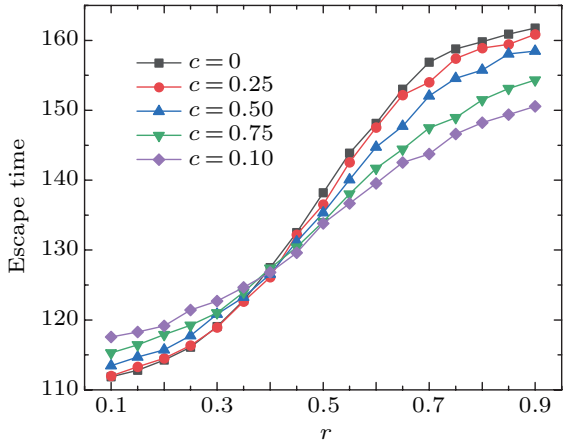


Fig. 8. (color online) Escape time versus fear degree r with different compassion levels and with two exits at the bottom.

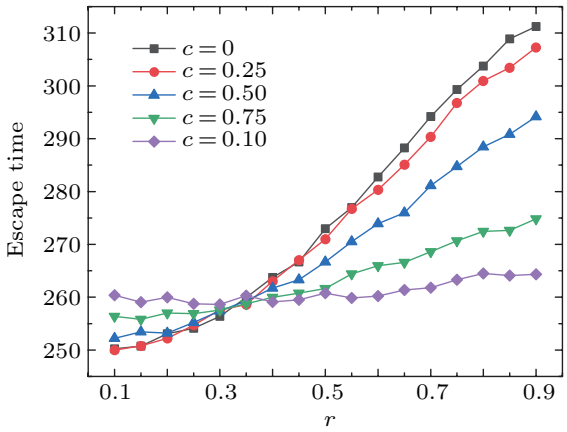


Fig. 9. (color online) Escape time versus fear degree r with different compassion level and with Richest–Following Fermi learning strategy.

We note that the results shown here will depend on the initial density of pedestrians. We have checked the dependence of escape time on pedestrian density in the room. When the number of pedestrians is big enough, the results are similar as in Fig. 2. However, when the density of pedestrians is low, loosely defined as less than 100 people, the results of escape time will be randomly distributed. This phenomenon is explained as follows. When the initial density is low, there are more empty cells in the room, and the distances among pedestrians will be larger. As a result, the average payoff for pedestrians will increase and the conflict between pedestrians during evacuation will reduce. The final escape time will change disorderly depending on the initial positions of pedestrians generated in each simulation. Due to these instability factors, the effect of compassion become unpredictable. Similar phenomena appears in end-piece of evacuation Fig. 4, and we have discussed this phenomenon by Fig. 5(a).

4. Conclusion

In summary, we have investigated how the compassion mechanism impact the dynamics of pedestrian evacuation from a room in the paradigm of evolutionary games. With the compassion mechanism, pedestrians share their payoff to poorest individual who has the same destination. Thus the disadvantaged strategy will have more opportunity to survive. The compassion can increase the cooperate frequency, and reduce the escape time when the fear degree is high. When the fear degree is low, the compassion will slightly decrease the cooperation frequency, and prolong the escape time. Furthermore, the initial cooperator proportion can also affect the evacuation. Due to the agent-number-decreasing feature of the evacuation problem, the results are intrinsically different from the situations with a constant number of agents.

Since compassionate behavior is common in nature and society, our results can be relevant to the understanding of the emergence of cooperation and the evacuation dynamics.

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