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Analysis of Cooperation Behaviors and Crowd Dynamics during Pedestrian Evacuation with Group Existence

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Abstract: At most public places where large-scale events are held, the crowd as a pedestrian particle system is a mixture of individuals and groups rather than a pure collection of individuals. The interaction behaviors of pedestrians within the same group and between different groups are significantly disparate, which makes the crowd evacuation process more complex. To address this issue, a new pedestrian evacuation model is proposed incorporating the cellular automaton model and game theory. In the model, two game theory models named prisoner's dilemma and harmony game are applied to depict the interaction mechanism between pedestrians, and the decision-making of one pedestrian regarding route choice is subject to the environment factor and interaction payoffs between his neighbors. The influences of the intensity of interaction between pedestrians, the willingness to cooperate, the number of groups, the size of groups, and the initial distribution pattern of groups on the evacuation dynamics and cooperation evolution of the crowd are discussed. Simulation results show that it is beneficial to the evacuation efficiency and the formation of cooperation behaviors when pedestrians have a low intensity of interaction. As the willingness of large groups to cooperate is high, an increase in group sizes and numbers can improve the cooperation fraction of the crowd but prolongs evacuation time. Groups in the crowd gathered together initially negatively affect the evacuation efficiency of the crowd.

Keywords: pedestrian evacuation; groups; cooperative behaviors; evacuation time; evacuation model



Citation: Ma, Y.; Liu, X.; Huo, F.; Li, H. Analysis of Cooperation Behaviors and Crowd Dynamics during Pedestrian Evacuation with Group Existence. *Sustainability* **2022**, *14*, 5278. <https://doi.org/10.3390/su14095278>

Academic Editors: Mohcine Chraïbi, Jun Zhang, Jian Ma and Antoine Tordeux

Received: 30 March 2022

Accepted: 22 April 2022

Published: 27 April 2022

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1. Introduction

Individuals and groups of pedestrians are two fundamental constituents of a crowd. Groups usually consist of two or more pedestrians who share common aims or interests or have certain relationships, such as families, friends, tourist groups from different cities or travel agencies in a scenic spot, and sports delegations from different countries or provinces at an opening ceremony. During movement, individuals and group members engage in interaction with the environment and other neighboring pedestrians [1]. When interacting with members of the same group and members of different groups, there may be differences in the behaviors exhibited by pedestrians. It is well known that the behavior of pedestrians is heterogeneous, which is related to the evacuation environment, physique, and mentality [2]. The presence of groups can also contribute to the heterogeneity of pedestrian behavior. Groups in crowds affect interactions between pedestrians to a certain extent and facilitate diverse interaction behaviors, thereby increasing the difficulty and complexity of pedestrian evacuation. The influence of groups on pedestrian behavior and evacuation dynamics is therefore worth exploring.

Current research on groups primarily focuses on the movement characteristics of small groups and the influences of small groups on macroscopic crowd dynamics. First, the behavioral characteristics and movement properties of groups have been studied. Most

pedestrians moved in groups with a size of two to four members [3]. Pedestrians in a small group usually evacuate together in shapes such as side-by-side, V-shaped, streamlined, and U-shaped [4,5], depending on factors such as pedestrian density and group size. In addition, members in a group always seek to adjust their speed to maintain the group formation. Groups move slowly and decrease the speed of the pedestrians. However, group members can move faster than individuals in high-density scenarios [6]. Differences in speed among individual pedestrians and groups are affected by age, gender, social ties, evacuation environment, group size, and other factors [7–10]. Second, the effect of groups on evacuation efficiency and the macroscopic dynamics of a crowd has been studied. Pedestrians take longer to initiate their movement in groups [11]. Explicit cooperation among group members results in a stronger aggregation of group members, thus reducing the evacuation efficiency of a crowd [12]. However, the presence of groups can cause a decrease in the evacuation times of a crowd in some scenarios. A group is basically positive in low visibility conditions and contributes to a faster movement speed [13,14]. In a tall office building evacuation, the evacuation efficiency of a crowd is improved when group members know each other and move down together in pairs [15].

However, the effect of groups on the evolution of behavior during evacuation has not yet been investigated. Evacuation behaviors are not merely mechanical, as physiological, psychological, social, and environmental factors, as well as the spatial structures of pedestrians influence them [16–19], and evacuation behaviors are dynamic, evolving with the factors mentioned above and interacting pedestrians [20]. Behavior evolution has attracted the attention of many researchers since it is an increasingly important area in pedestrian evacuation. Guan et al. [21] studied the evolution of the cooperative behavior of a crowd using the CA model and spatial games in which multiple pedestrian behaviors and multiple behavioral imitation mechanisms were considered. Wang et al. [22] investigated the evolution of exit selection behavior in different vision ranges by integrating game theory into a CA model. Chen et al. [23] researched the impact of compassion effect on pedestrian position conflict and the evolution of cooperative behavior. Huang et al. [24] constructed an evacuation model considering the interaction of neighbors as well as environmental factors and analyzed the effects of emergency degree and environmental familiarity on the evolution of cooperative behavior and evacuation efficiency. Shi et al. [25] considered defector herding to modify the lattice model, which they used to investigate the impact of fear degree and pedestrian density on the evolution of defection behavior. Bouzat et al. [26] combined the lattice model and game theory to analyze the influence of pedestrian density, the number of pedestrians, and punishment for defection on pedestrian behavioral evolution with different fractions of cooperators. Zheng et al. [27] built a pedestrian evacuation model by coupling game theory and the CA model with consideration of rationality, herding effect, and conflict cost to study the behavior evolution process of a crowd.

Although extensive research has been carried out on groups, studies on the behavior and movement characteristics of groups and their impact on evacuation have focused on small groups and have been conducted in the context of groups of evacuees moving together or in relative clusters. Additionally, the evolution of pedestrian behaviors with group presence has not been researched. Groups play an important role in evacuation and behavioral evolution, mainly due to their impact on pedestrian interaction, which is not limited to situations where groups are small or group members evacuate together. As mentioned earlier, large groups are prevalent in a variety of realistic evacuation scenarios. Therefore, it is necessary to further study the influence of groups, especially large groups, on the interaction between pedestrians, crowd evacuation dynamics, and the cooperative behavior evolution of a crowd.

In this paper, using the method of combining a CA model with game theory and considering the multiple interaction mechanisms of pedestrians and the evolution of cooperative behavior, we construct an evacuation model of a crowd with the presence of groups. In the model, the interaction mechanism of in-group members differs from that of out-group members. The main purpose of this research is to demonstrate how groups

influence the evacuation efficiency and cooperation evolution of a crowd under different values of the intensity of interaction, the willingness to cooperate, the number of groups, the size of groups, and the initial distribution pattern. The remainder of this paper is organized as follows. In Section 2, the complete description of the model is offered. In Section 3, simulations are presented, and the resulting data are analyzed and discussed. Finally, in Section 4, the conclusion of the study is drawn.

2. Model Description

2.1. Transition Probability

Our model is based on a square domain with discrete grids. Each grid might be empty or occupied by exactly one pedestrian. The grid size in our work is 0.4 m × 0.4 m. The simulation step length is 0.3 s. As shown in Figure 1, each pedestrian can move to one of its unoccupied Moore neighbors in each step. In this paper, pedestrians asynchronously update their positions in a random sequence.

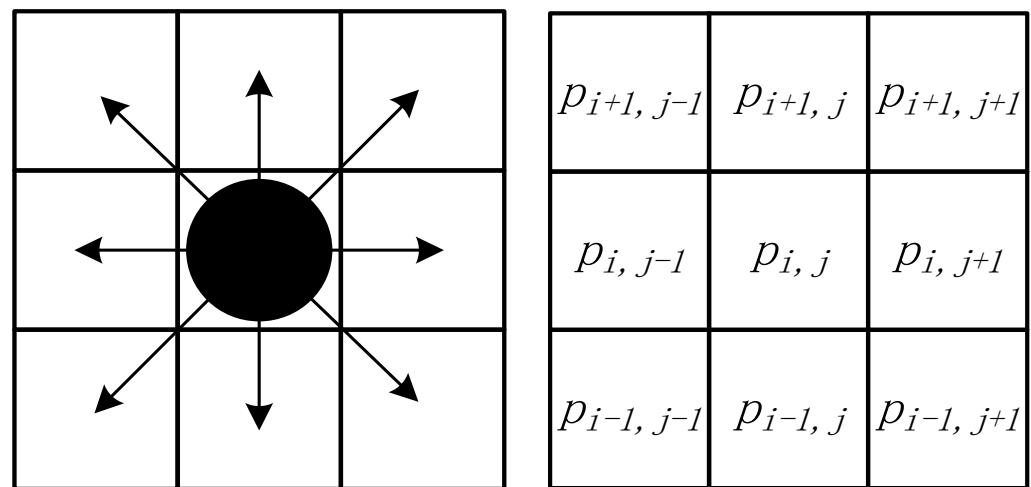


Figure 1. Moore neighbor and the transition probability of pedestrians for next step.

The movements of pedestrians are affected by both environmental factors and interactions between pedestrians, so the transition probability P_{ij} of one pedestrian to a target cell can be formulated as:

$$p_{ij} = \frac{\exp(k_E E_{ij} + k_B B_{ij})}{\sum_{(i,j) \in \Omega} \exp(k_E E_{ij} + k_B B_{ij})} (1 - n_{ij}) \quad (1)$$

where E_{ij} is the static floor field to represent the tendency of pedestrians moving towards exits, which references the floor field model; B_{ij} represents the benefits obtained by a pedestrian as a result of their interactions and quantifies the effect of neighbors on pedestrians; both k_E and k_B are sensitivity parameters where k_E denotes the familiarity of a pedestrian with the exits and k_B denotes the intensity of interaction between a pedestrian and his neighbors—the larger the value of k_B , the more willing the pedestrian is to interact with his neighbors; Ω is the set of neighbors of the present cell; n_{ij} is the occupation number of the target cell, i.e., $n_{ij} = 1$ if the target cell is occupied, otherwise $n_{ij} = 0$.

E_{ij} allows pedestrians to find the shortest path to an exit, which can be formalized as:

$$E_{ij} = \max_{(i,j)} \left\{ \min_{(x_e, y_e)} \left\{ \sqrt{(x_e - x)^2 + (y_e - y)^2} \right\} - \sqrt{(x_e - x_{ij})^2 + (y_e - y_{ij})^2} \right\} \quad (2)$$

where (x, y) is the position of the present cell, (x_e, y_e) is the position of the exit, and (x_{ij}, y_{ij}) is the position of the target cell (i, j) .

B_{ij} represents the benefits obtained from interaction behaviors for a pedestrian escaping from the present cell to the target cell, which rely on the payoffs of interacting with neighbors, namely:

$$B_{ij} = U_{ij} - U_{xy} \quad (3)$$

where U_{xy} and U_{ij} are the payoffs of a pedestrian interacting with his neighbors at the target cell and the present cell, respectively. The measurement of U_{xy} and U_{ij} will be introduced next.

2.2. Behavioral Interaction Mechanism

The payoffs of a pedestrian interacting with his neighbors are connected to the behavioral interaction mechanism. According to socio-behavioral studies, pedestrians are rational individuals who pursue the maximization of their self-benefit and for whom personal benefits take precedence over collective benefits. In the evacuation, we can understand the benefit simply as evacuation time. Therefore, when two pedestrians interact, they want to evacuate quickly and care less if the interacting object can also evacuate. However, at the same time, the moral cognition and collective responsibility of pedestrians prompt them to balance their own benefits with the benefits of the group to which they belong. Thus, when two in-group members interact, they act in a way that enables them and the other interacting member to evacuate as soon as possible because they are from the same group. To sum up, out-group members interacting with each other only want to achieve their own safe and rapid evacuation, while in-group members interact with the aim of evacuating both themselves and each other quickly.

The prisoner's dilemma lies in the fact that individually rational behavior leads to an individually optimal and collectively sub-optimal outcome, which means that the behaviors adopted by out-group pedestrians may make their own evacuation time the shortest, but the overall evacuation time of pedestrians and their interacting objects increases. Therefore, the interaction between out-group pedestrians is similar to the prisoner's dilemma, and it can be indicated in this game [28,29]. The harmony game is based on the idea that the individual optimal strategy is the same as the collective optimal strategy. That is, the interaction of pedestrians can be conducive to the evacuation of both themselves and the group. Accordingly, the interaction between pedestrians belonging to the same group is depicted by the harmony game.

It can be seen from the above that there are two different types of interaction mechanisms between pedestrians in a crowd. Pedestrians interact with out-group members by following the payoff matrix of the prisoner's dilemma, as calculated from Equation (4). Pedestrians interact with in-group members by following the payoff matrix of the harmony game, as calculated from Equation (5).

$$U = \sum_{j \in \Omega_i} s_i^T P_1 s_j \quad (4)$$

$$U = \sum_{j \in \Omega_i} s_i^T P_2 s_j \quad (5)$$

where P_1 is the payoff matrix of the prisoner's dilemma and P_2 is the payoff matrix of the harmony game. At each time step, each pedestrian interacts with all of his neighbors and obtains the payoffs according to the payoff matrix. s_i and s_j represent the behavior of pedestrians i and j , respectively. $s = [0, 1]$ when the pedestrian is a cooperator and $s = [1, 0]$ when the pedestrian is a defector. Ω_i is the set of neighbors of pedestrian i . U is the payoff for pedestrian i interacting with his neighbors. The payoff matrix of the prisoner's dilemma is shown in Table 1, and the payoff matrix of the harmony game is shown in Table 2, where P_R and H_R represent reward, P_P and H_P represent punishment, P_T and H_T represent temptation, and P_S and H_S represent the sucker's payoff. Table 3 lists the parameters in the prisoner's dilemma and the harmony game, which are determined with reference to the study by Huang et al. [30]. It should be noted that $r > 0$. In our

work, r reflects the willingness to cooperate among pedestrians in the same group during evacuation as a measure of psychological factors. The willingness of pedestrians influences their behaviors. Therefore, the larger the value of r , the more likely pedestrians in the group are to adopt cooperative behavior.

Table 1. Payoff matrix of the prisoner's dilemma.

	Cooperation (C)	Defection (D)
Cooperation (C)	P_R, P_R	P_S, P_T
Defection (D)	P_T, P_S	P_P, P_P

Table 2. Payoff matrix of the harmony game.

	Cooperation (C)	Defection (D)
Cooperation (C)	H_R, H_R	H_S, H_T
Defection (D)	H_T, H_S	H_P, H_P

Table 3. Setting of parameters in game theory models.

Parameter	Description	Value
P_R	Payoffs of out-group pedestrians when they are both cooperators	1
P_S	Payoffs of cooperators when the interacting member of different groups is a defector	0
P_T	Payoffs of defectors when the interacting member of different groups is a cooperator	1.5
P_P	Payoffs of out-group pedestrians when they are both defectors	0
H_R	Payoffs of in-group pedestrians when they are both cooperators	$1 + r$
H_S	Payoffs of cooperators when the interacting member of the same group is a defector	0.5
H_T	Payoffs of defectors when the interacting member of the same group is a cooperator	1
H_P	Payoffs of in-group pedestrians when they are both defectors	0

2.3. Behavior Updating Rule

From the present cell to the target cell, the behavior of the pedestrian updates in response to changes in environmental factors and changes in neighbors' behavior. In this paper, a modified Fermi update rule is proposed to update pedestrian behaviors at each step, taking the neighbor with the highest benefit as the imitation object and imitating the behavior of the neighbor with probability P , namely:

$$p = \frac{1}{1 + \exp[(U_i - \max(U_{\Omega_i})) / \kappa]} \quad (6)$$

where U_i is the payoff for a pedestrian i interacting with his neighbors, Ω_i is the set of neighbors of pedestrian i , U_{Ω_i} is the payoff of a neighbor of pedestrian i , and κ characterizes some noise to allow for uncertainty during the behavior imitation, which is taken as 0.1 for the sake of simplicity.

To sum up, the simulation process of pedestrian evacuation is shown in Figure 2. First, initialize the positions and behaviors of individuals and groups. Pedestrians can be distributed randomly or in clusters. The interaction behaviors of pedestrians include cooperation and defection. Then, the transition probability for each pedestrian is computed. The interaction payoffs of out-group members and in-group members are calculated according to Equations (4) and (5), respectively. After that, pedestrians asynchronously update their positions in a random sequence. Finally, pedestrians update their behaviors. A simulation ends after all pedestrians are evacuated. Each test is simulated 50 times, and the average values are displayed.

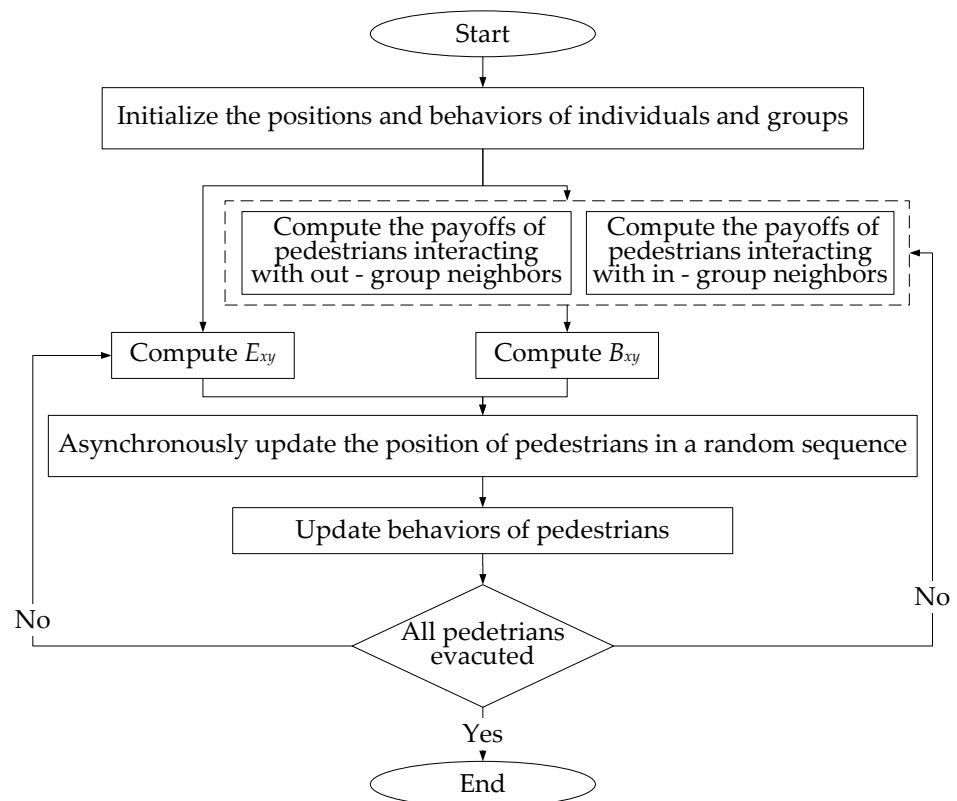


Figure 2. Flowchart of the simulation process of evacuation.

3. Simulation and Results

The simulations are carried out in an $8\text{ m} \times 8\text{ m}$ room with two exits 0.4 m wide. We assume that all pedestrians are initially distributed with a density of 0.8 and a cooperation fraction of 0.5 . The fraction of cooperation equals the pedestrian who is the cooperator in the crowd. We record the behavior of pedestrians in the last step to calculate the fraction of cooperation for the pedestrian who escapes from the evacuation space. It is worth mentioning that pedestrians evacuate in groups or as individuals. As shown in Figures 3 and 4, we assume all individual pedestrians are initially randomly distributed, and pedestrians within the same group are initially randomly distributed or clustered together. Gray symbols donate individual pedestrians in Figures 3 and 4, while every other color symbol represents a group. Unless otherwise specified, we use the number of groups $n = 4$ and the group size $s = 60$ in the following, which means each group includes 60 pedestrians.

3.1. Effect of the Initial Distribution Pattern

The impact of the initial distribution pattern on evacuation time and cooperative behavior is shown in Figure 5. We compare the evacuation time and the cooperation fraction of the crowd under different parameters when pedestrians in the same group are clustered together and randomly distributed. It is found that the evacuation time of the crowd is longer and the cooperation fraction of the crowd is higher when pedestrians belonging to the same group are distributed together. In addition, with in-group members gathered together, the cooperation fraction of the crowd is higher than the initial fraction of 0.5 and closer to 1 . As pedestrians in the same group are randomly distributed, the cooperation fraction of the crowd is lower than 0.5 .

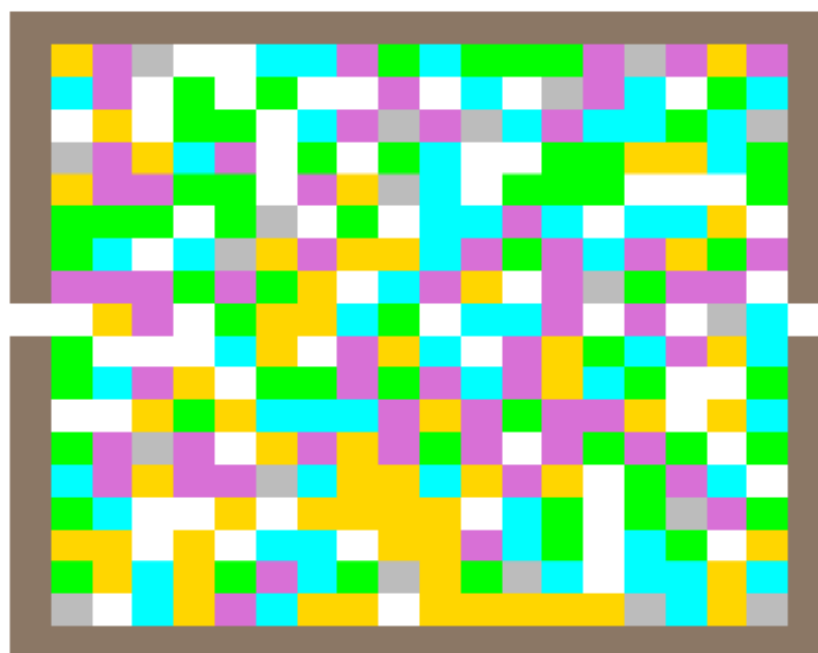


Figure 3. Example of random distribution.

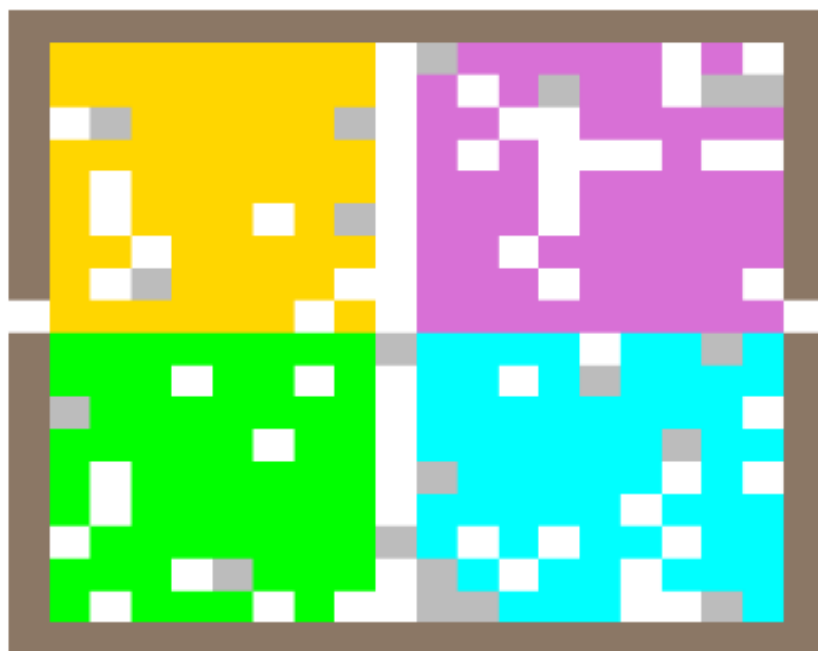


Figure 4. Example of clustered distribution.

To work out the reasons for the change in the fraction of cooperation and evacuation time under different distribution patterns, the evolution of cooperation fraction over time is presented in Figure 6, and the evolution of pedestrian evacuation behavior over time is presented in Figures 7–10. In Figures 7 and 9, the gray square symbols represent individual pedestrians, whereas each of the other color square symbols represents a group. In Figures 8 and 10, the red square symbols indicate cooperators, whereas the yellow square symbols indicate defectors. As shown in Figure 6, the trends in the evolution of cooperative behavior are quite different. The fraction of cooperation increases rapidly and eventually remains at a large value in Figure 6a, whereas the fraction of cooperation decreases rapidly in Figure 6b. It is indicated that the clustered distribution pattern is more conducive to maintaining cooperative behavior. Furthermore, as shown in Figures 7–10, the aggregated

pedestrians belonging to the same group are more likely to cooperate, which is determined by the interaction mechanism of groups. Figure 7 illustrates that in-group members who adopt the clustered distribution pattern are always gathered together during the evacuation process. Figure 9 shows that in-group members who adopt the random distribution pattern always scatter during evacuation. Therefore, the clustered distribution pattern is excellent for generating cooperative behavior. These results indicate that the clustered distribution pattern motivates the generation and maintenance of cooperative behavior. Consequently, the fraction of cooperation in the crowd is higher when pedestrians belonging to the same group are initially distributed together.

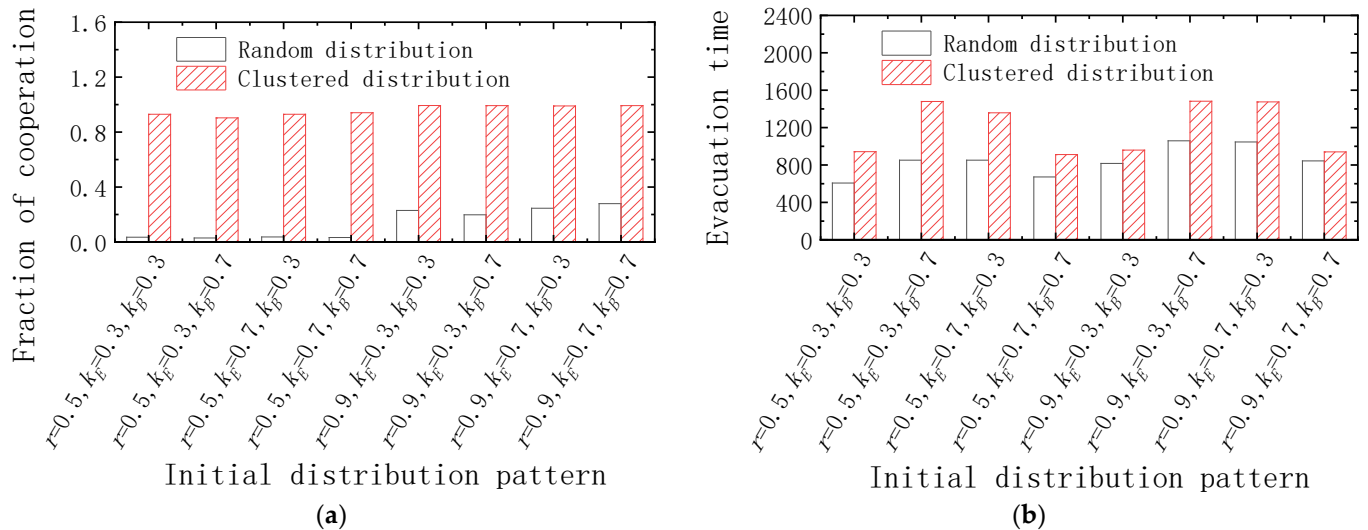


Figure 5. Plots of fraction of cooperation and evacuation time versus distribution pattern: (a) fraction of cooperation; (b) evacuation time.

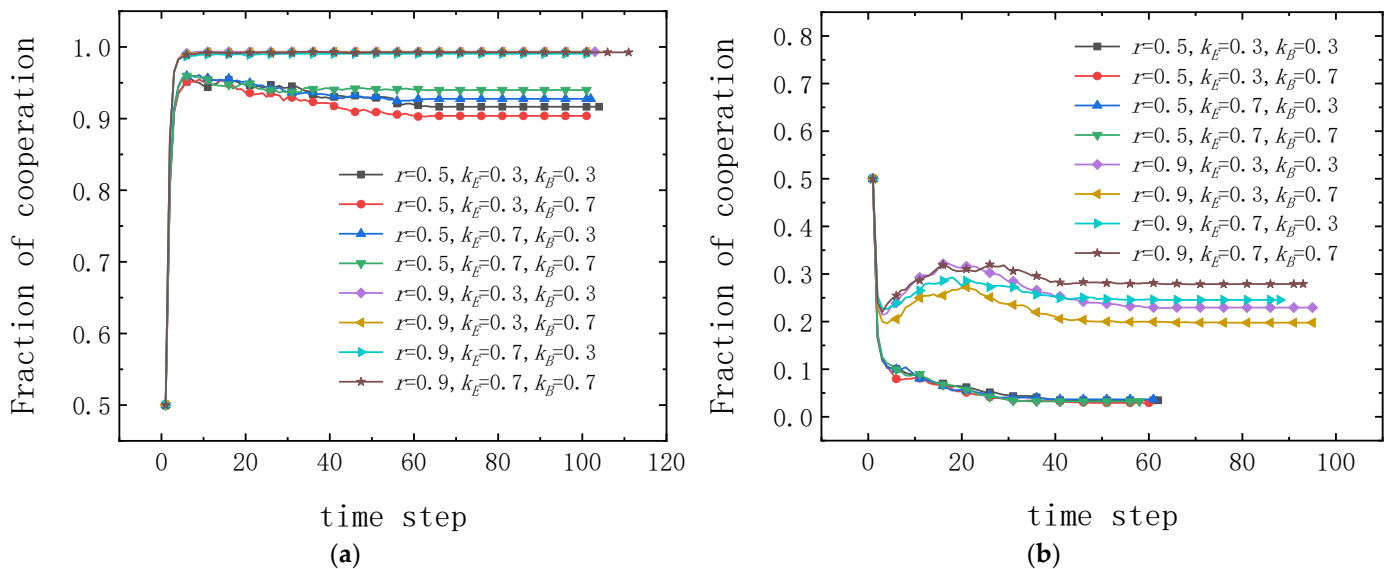


Figure 6. Time-evolution process of fraction of cooperation with different distribution patterns: (a) the clustered distribution pattern; (b) the random distribution pattern.

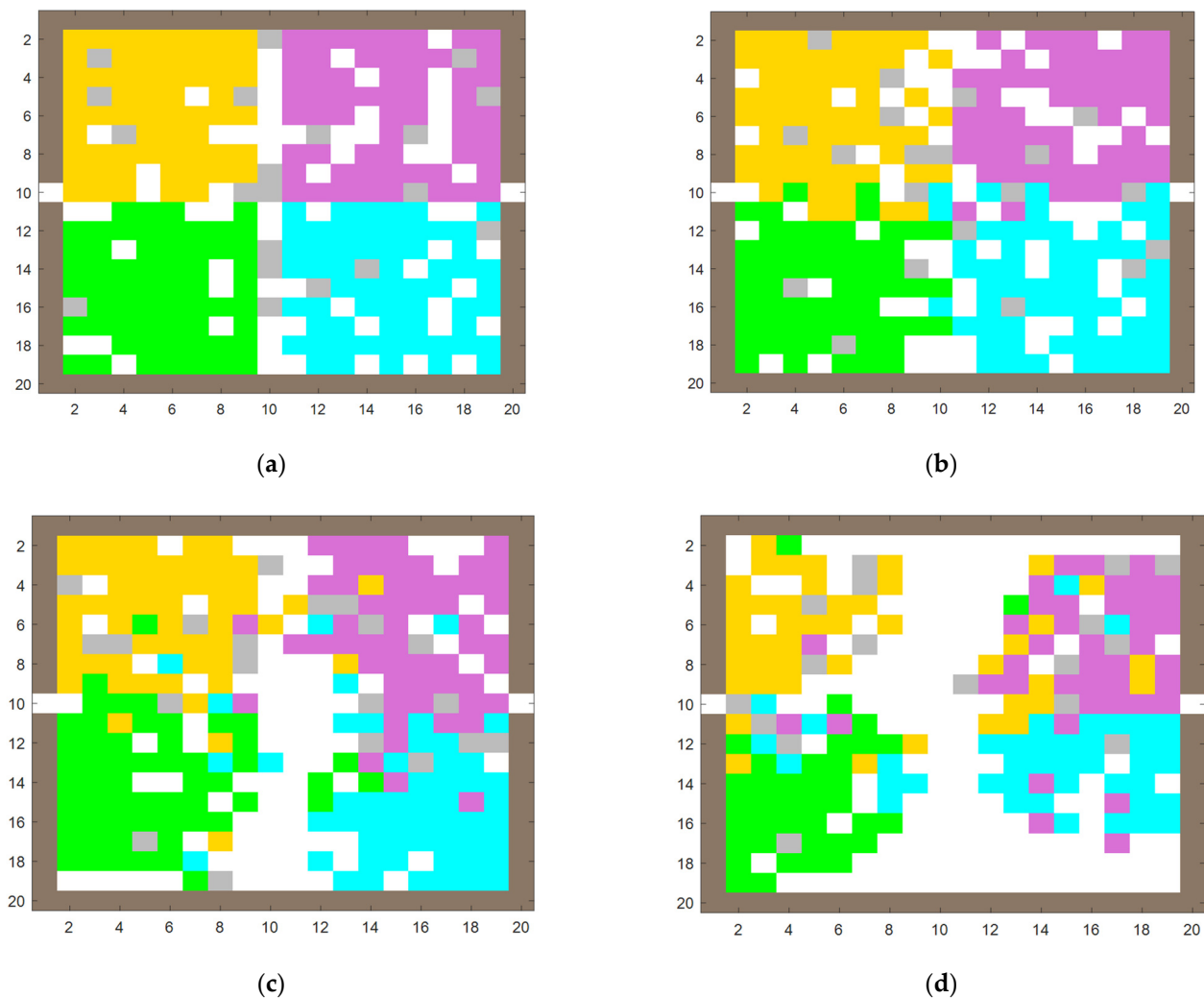


Figure 7. Group members' typical snapshots under clustered distribution at time steps 1, 2, 10, and 30: (a) $ts = 1$; (b) $ts = 2$; (c) $ts = 10$; (d) $ts = 30$.

There is a link between the time it takes pedestrians to evacuate and their behaviors. From a behavioral standpoint, we investigate the explanation for the difference in evacuation time. As shown in Figure 8, when pedestrians in the same group are clustered together initially, the number of cooperators increases rapidly at time step 2, and after time step 10, all pedestrians become cooperators. Figure 10 illustrates that when pedestrians in the same group are randomly distributed initially, there are a few cooperators in the crowd, and after time step 50, all pedestrians become defectors. Cooperation between pedestrians is crucial to facilitate evacuation, but when members of each group gather together, cooperative behaviors may spread throughout the crowd, causing the behaviors in the crowd to converge upon cooperative behavior. Consequently, the attraction between members of the same group increases, leading to evacuation delays as members gather with one another [12]. Therefore, the clustered distribution pattern reduces the evacuation efficiency of the crowd compared to the random distribution pattern. This finding suggests that the gathering arrangement of in-group members during an event may be manageable, but it can lengthen the evacuation time of the crowd.

From Figure 5, we can see that the fraction of cooperation and evacuation time change when the willingness of pedestrians to cooperate r and the intensity of interaction k_B take different values, indicating that these two parameters equally affect crowd evacuation. Evacuation time is the essential indicator of crowd evacuation in practice. Considering that the evacuation time of the crowd reduces when members from the same group are

randomly distributed initially, the role of the willingness to cooperate and the intensity of interaction in evacuation under random distribution patterns will be further analyzed.

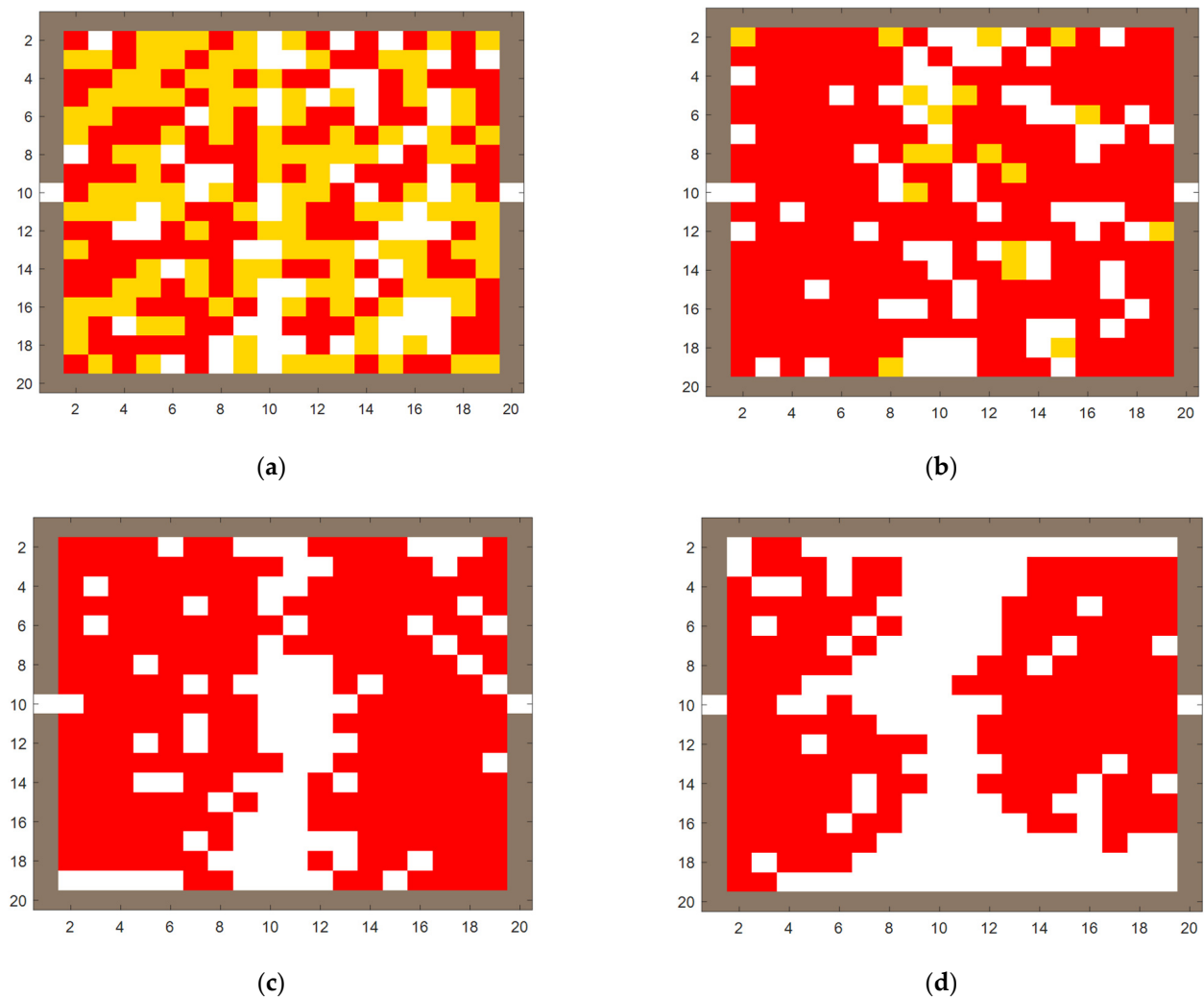


Figure 8. Pedestrian behaviors' typical snapshots under clustered distribution at time steps 1, 2, 10, and 30: (a) $ts = 1$; (b) $ts = 2$; (c) $ts = 10$; (d) $ts = 30$.

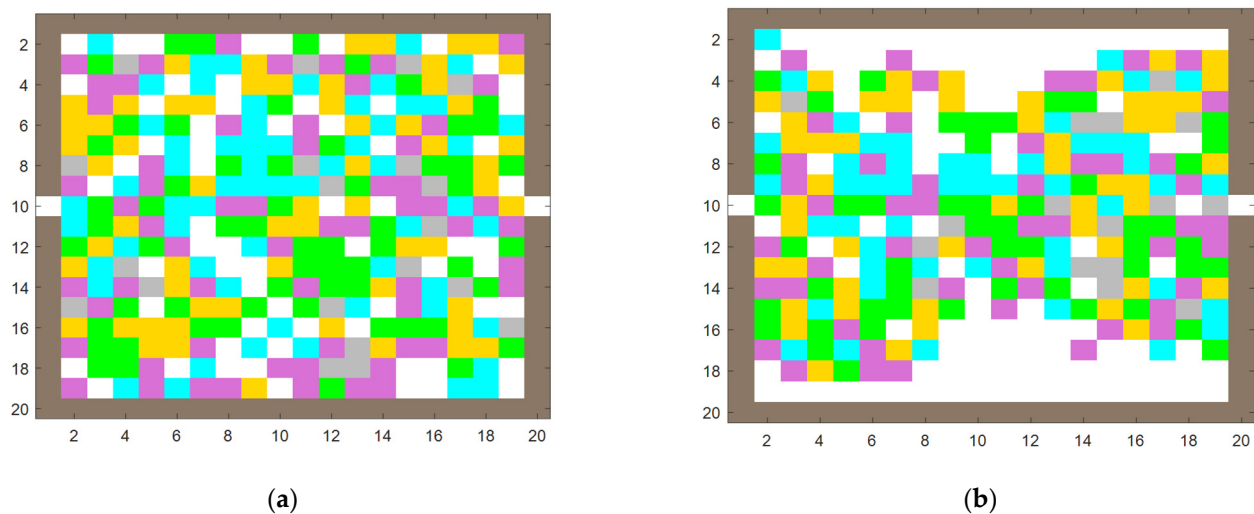


Figure 9. Cont.

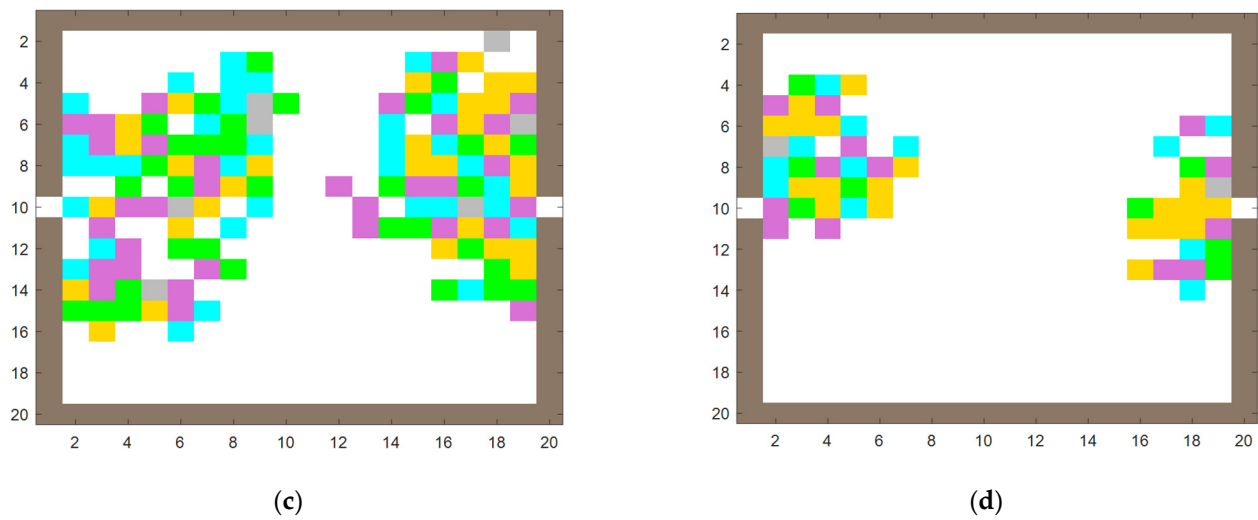


Figure 9. Group members' typical snapshots under random distribution at time steps 1, 10, 30, and 50: (a) ts = 1; (b) ts = 10; (c) ts = 30; (d) ts = 50.

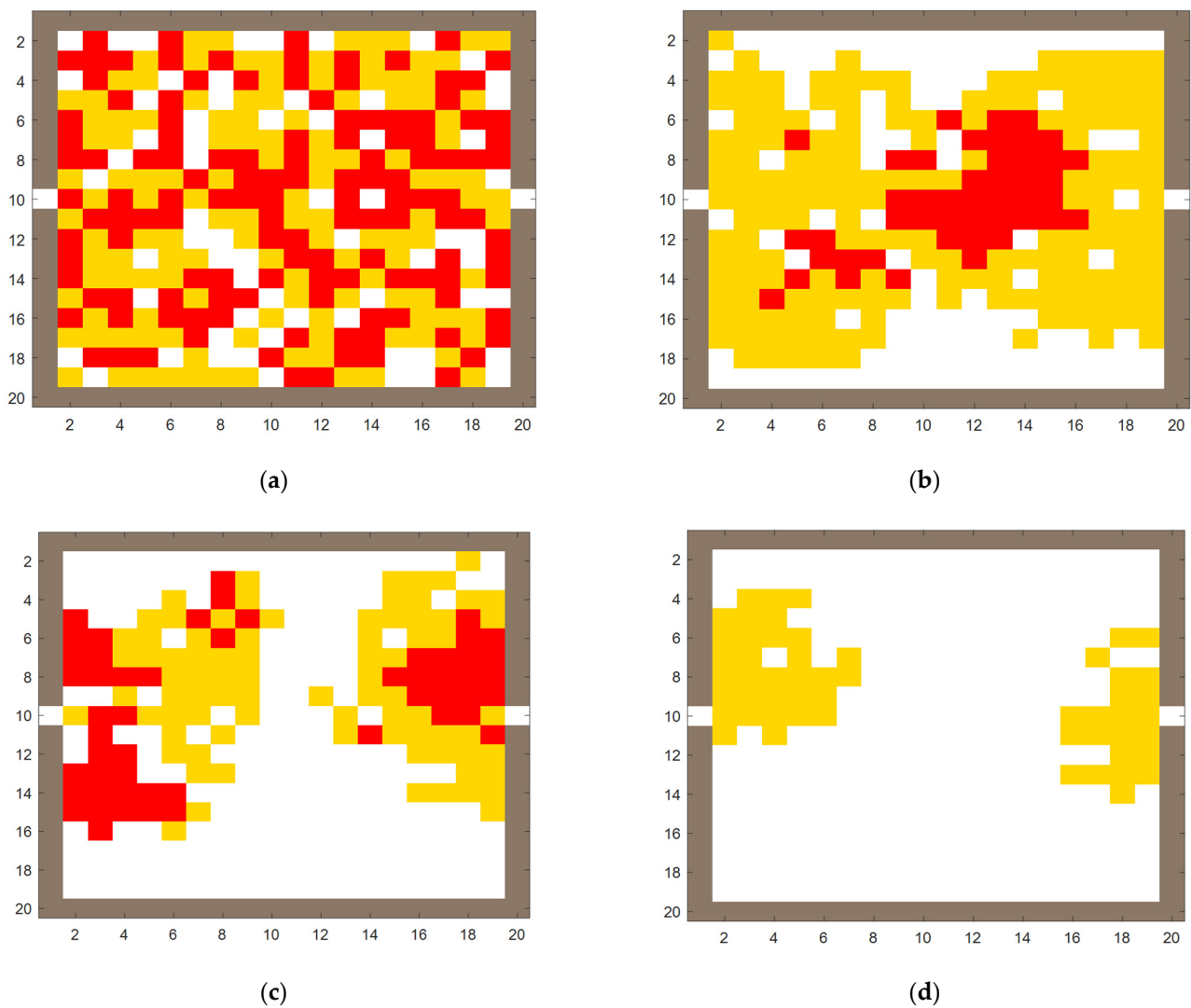


Figure 10. Pedestrian behaviors' typical snapshots under random distribution at time steps 1, 10, 30, and 50: (a) ts = 1; (b) ts = 10; (c) ts = 30; (d) ts = 50.

3.2. Influence of the Willingness to Cooperate

Figure 11 presents the fraction of cooperation and evacuation time with different values of the willingness to cooperate r . The fraction of cooperation and evacuation time increase with a rise in the value of r and only slightly decrease at some data points, indicating that increasing the willingness of group members to cooperate effectively promotes pedestrian cooperation but reduces the efficiency of pedestrian evacuation. Pedestrians with a strong willingness to cooperate are more willing to cooperate with others. Therefore, as the willingness of group members to cooperate improves, so does the fraction of cooperation. The willingness to cooperate influences evacuation time in the same way as the initial distribution pattern. A higher willingness to cooperate among members of the same group results in stronger group cohesion. The movement of pedestrians is determined by both environmental factors (exit) and human factors, so it is apparent that the attraction of pedestrians in the same group prolongs the evacuation time.

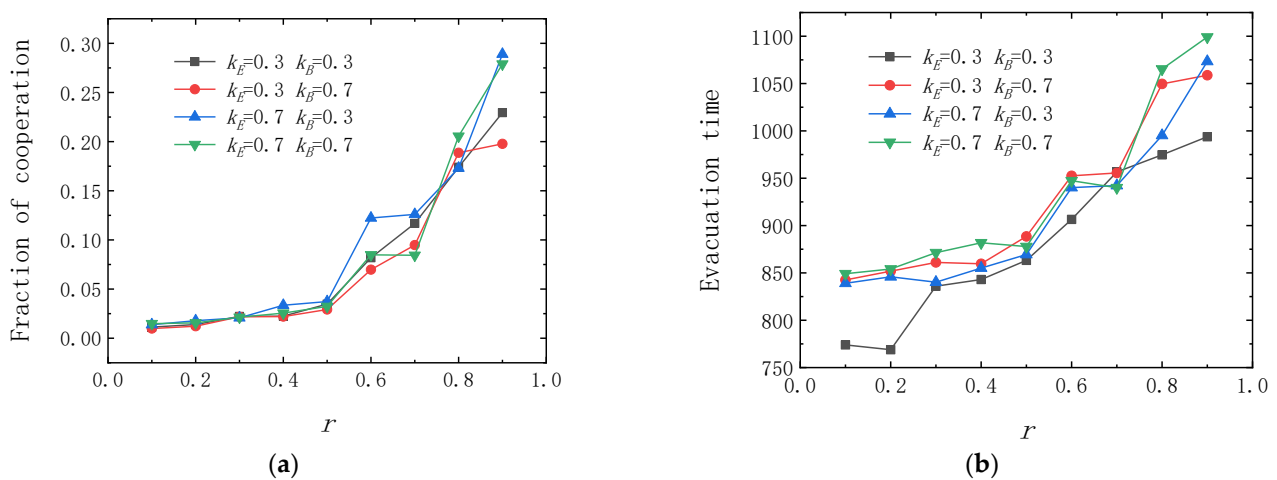


Figure 11. Plots of fraction of cooperation and evacuation time versus r for different values of k_E and k_B : (a) fraction of cooperation; (b) evacuation time.

What stands out in Figure 11 is that even though the fraction of cooperation and evacuation time increase as r grows, the influence of r is more prominent comparatively when the value of r is larger than 0.5, which is related to the value of P_T in the prisoner's dilemma payoff matrix. According to the effect of different values of r , r will be set to 0.1, 0.5, and 0.9 in the following analysis.

3.3. Influence of the Intensity of Interaction

Figure 12 illustrates how the intensity of interaction k_B affects the fraction of cooperation for different values of r . The overall analysis reveals that the fraction of cooperation decreases as the intensity of interaction increases. However, the fraction of cooperation at $k_B = 0$ is higher than the fraction of cooperation at $k_B = 0.1$ within specific parameters, such as $k_E > 0.7$ in Figure 12a, $k_E > 0.5$ in Figure 12b, and $k_E = 0.7$ in Figure 12c. This outcome reveals that a small degree of interaction between pedestrians is conducive to the formation of cooperative behavior, whereas too much interaction decreases the cooperative behaviors of pedestrians. Looking at the three subplots in Figure 12, the fraction of cooperation is significantly higher when the willingness to cooperate is greater under the same conditions, which is consistent with the above findings (Figure 11).

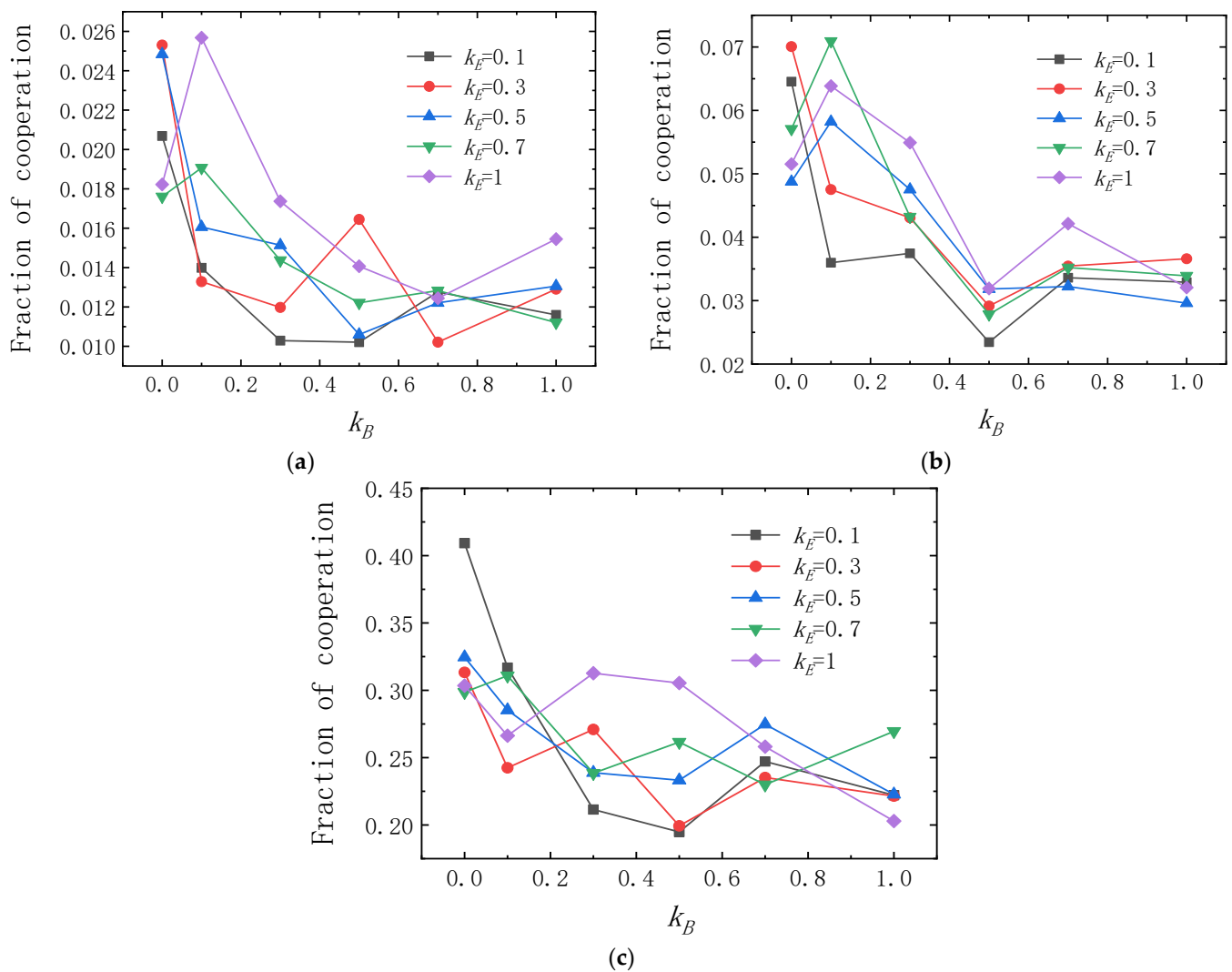


Figure 12. The relationship between fraction of cooperation and k_B with different values of k_E for (a) $r = 0.1$; (b) $r = 0.5$; and (c) $r = 0.9$.

The effect of the intensity of interaction k_B on the evacuation time for different values of r is demonstrated in Figure 13. It is clear that the trends in the evolution of evacuation time are similar for different values of r . In overall terms, the evacuation time increases with a higher value of k_B , suggesting that a small value of the intensity of interaction is relatively beneficial for pedestrian evacuation. The combined analysis of Figures 12 and 13 suggests that pedestrians should interact to a small extent during the evacuation, promoting cooperative behavior and improving the evacuation efficiency of the crowd. Due to the shorter evacuation time and the higher fraction of cooperation with $k_B = 0.1$ and $k_E = 0.7$, the simulations for such a situation will be carried out later.

3.4. Influence of the Number and Size of Groups

To further investigate the effects of the number and size of groups in the crowd, the number of groups n is set from 1 to 130, and the group size s is set from 2 to 60. The fraction of cooperation with different values of n and s is presented in Figure 14, which indicates that both the number and size of groups have an effect on the fraction of cooperative behaviors during the process of pedestrian evacuation. The effects of n and s on the fraction of cooperation are related to the value of s . When the value of s is large, such as $s > 40$ in Figure 14a and $s > 20$ in Figure 14b,c, larger values of n or s lead to a higher fraction of cooperation. When the value of s is small, the effect of n and s on the fraction of cooperation

cooperation is not significant. Specifically, the fraction of cooperation increases or decreases slightly with an increase in n and s for $s < 40$ in Figure 14a, and the fraction of cooperation is almost unchanged as n and s increase for $s < 20$ in Figure 14b,c. Therefore, when the group size is larger, the increase in the number and size of groups is conducive to promoting cooperation.

Figure 15 depicts the evacuation time with different values of n and s . It is apparent that the impact of n and s on the evacuation time is associated with the value of r . As shown in Figure 15a, when the value of r is small, the time it takes for pedestrians to evacuate varies depending on the value of n and s . With an increase in the value of s , the evacuation time reduces if $n = 7$ and $s > 3$ but increases if $n = 10$ and $s > 3$. However, as shown in Figure 15b,c, when the value of r is larger, the evacuation time remains basically unchanged and then increases as a whole. In Figure 15b, the evacuation time grows with an increase in s for $s > 50$. In Figure 15c, evacuation time grows with an increase in n and s for $s > 30$. The above analysis indicates that in situations where group sizes are large and the willingness to cooperate is high, increasing the number and size of groups can prolong the evacuation time of the crowd.

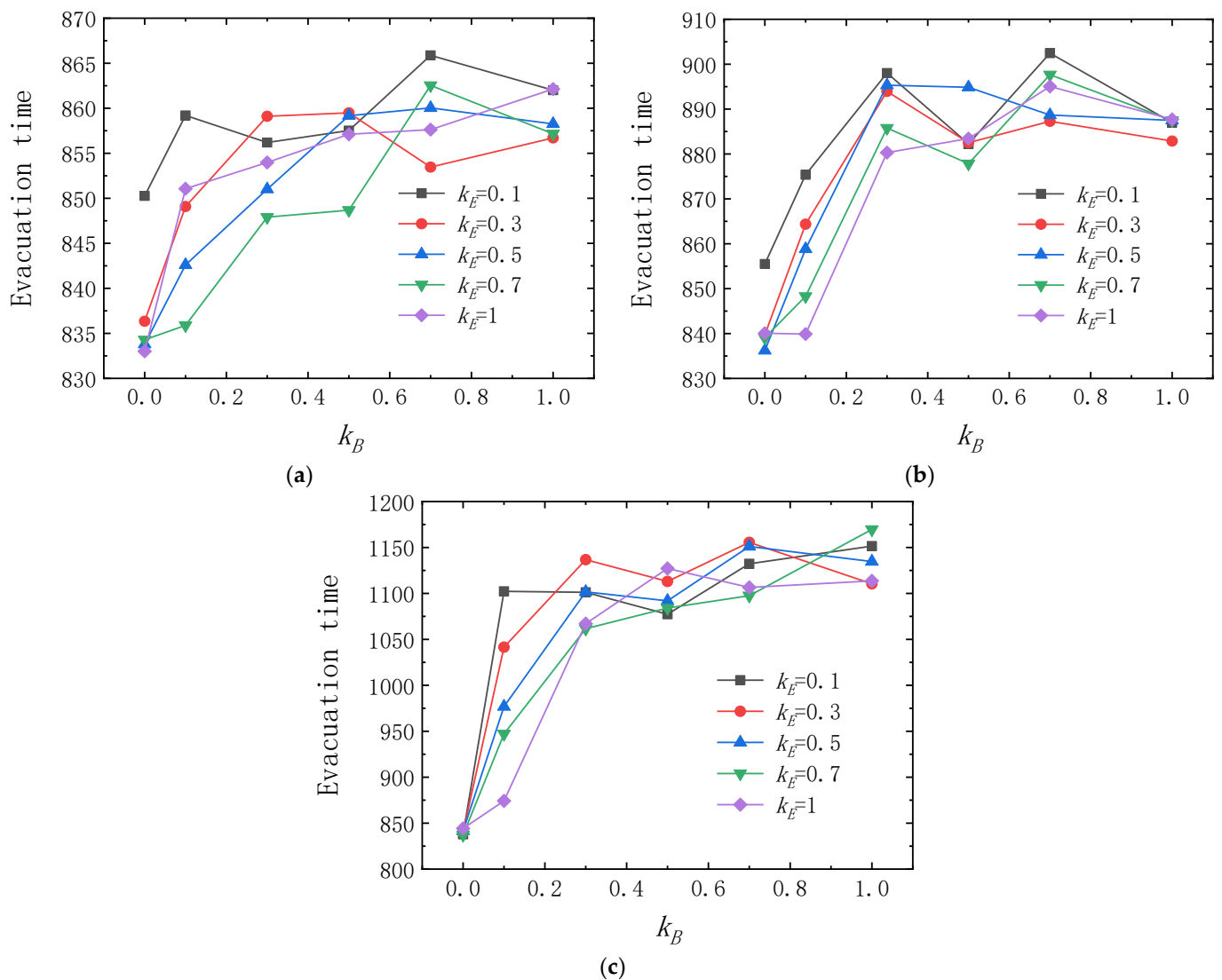


Figure 13. The relationship between evacuation time and k_B with different values of k_E for (a) $r = 0.1$; (b) $r = 0.5$; and (c) $r = 0.9$.

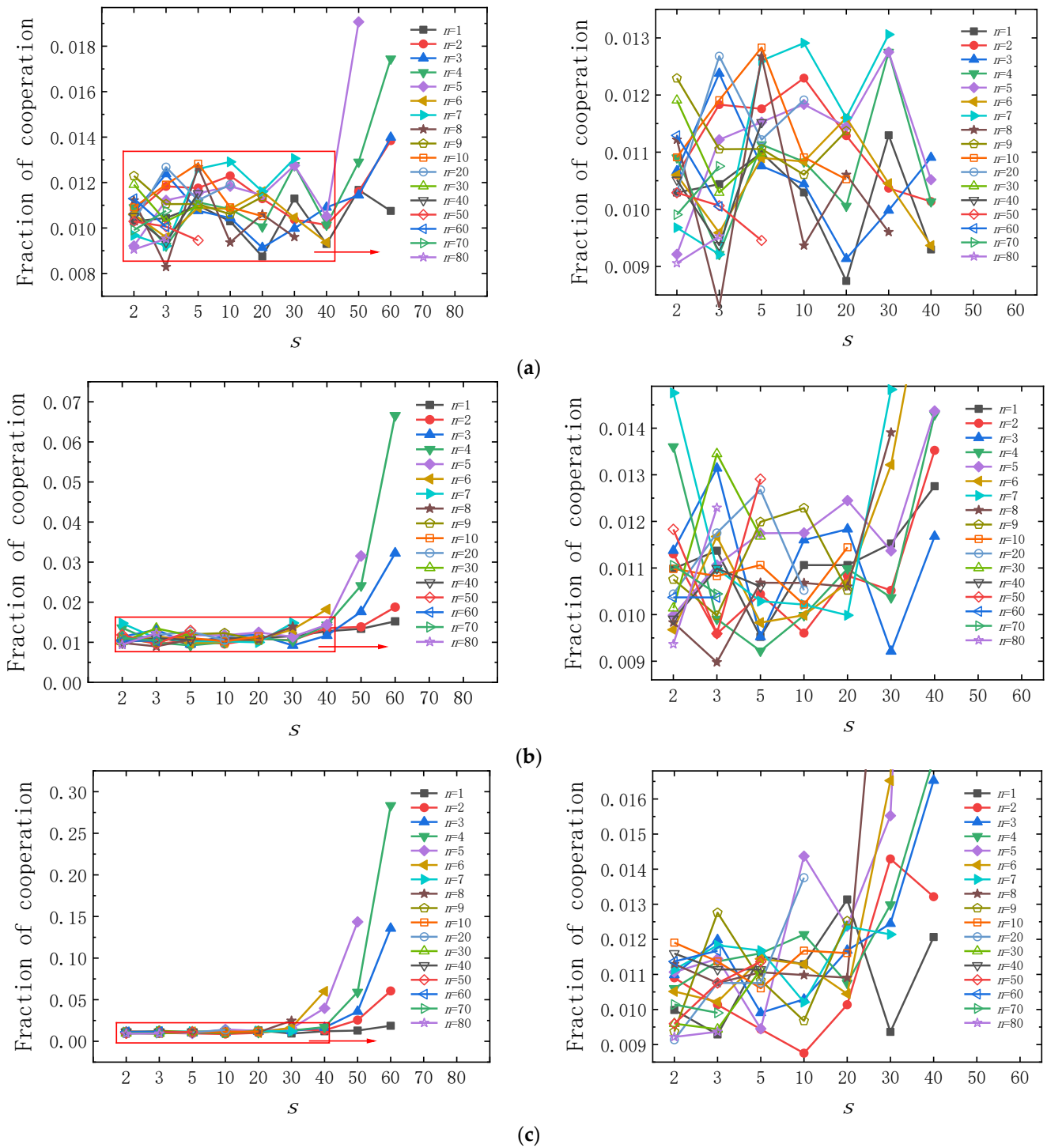


Figure 14. Fractions of cooperation with different values of n and s for (a) $r = 0.1$; (b) $r = 0.5$; and (c) $r = 0.9$.

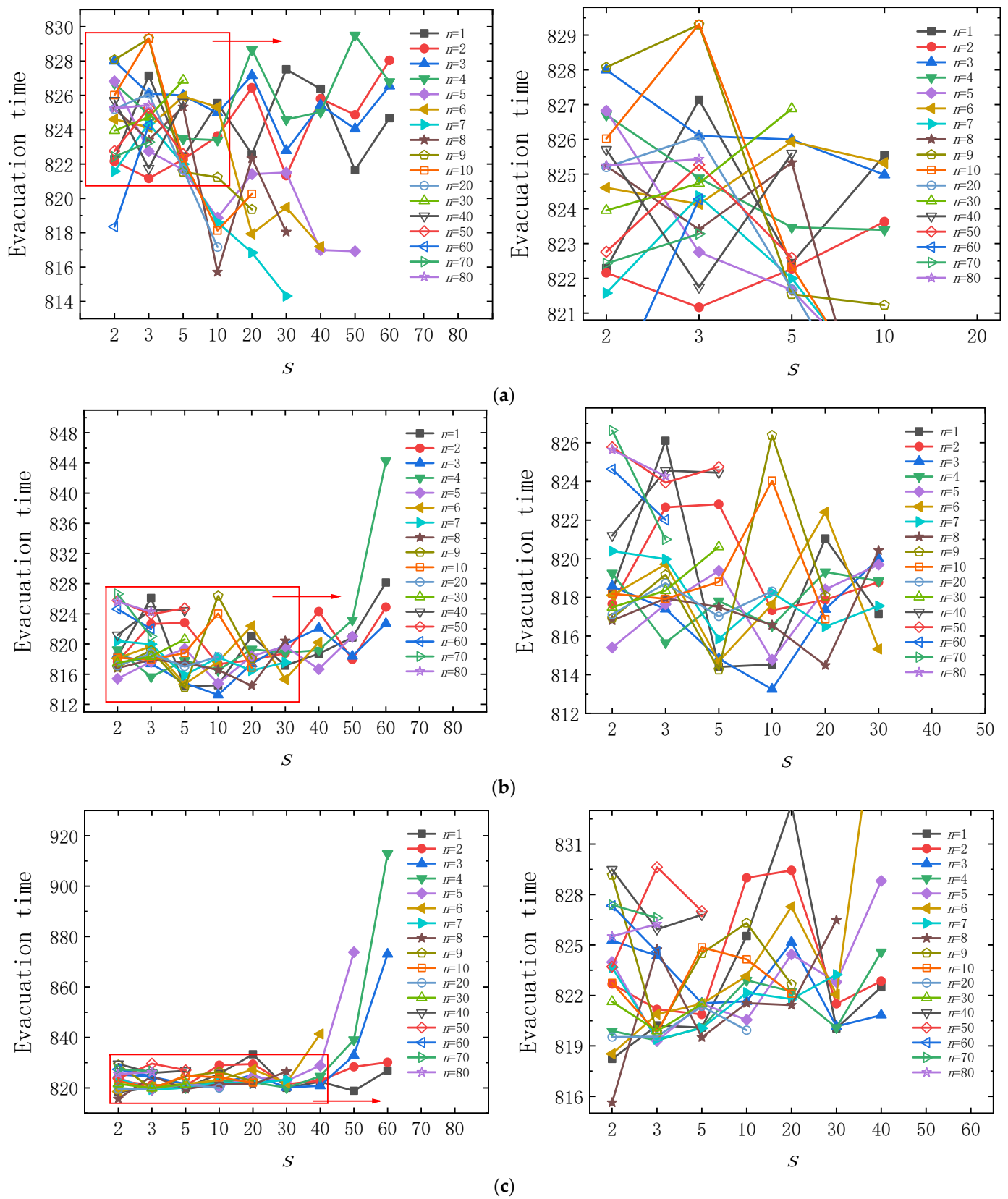


Figure 15. Evacuation time with different values of n and s for (a) $r = 0.1$; (b) $r = 0.5$; and (c) $r = 0.9$.

4. Conclusions

In this paper, an extended CA model based on game theory is proposed, which considers group effects on pedestrian behavioral interactions. In the model, the behavioral

interactions of pedestrians in the same group are represented by the harmony game, and the behavioral interactions of pedestrians with out-group members are represented by the prisoner's dilemma. A modified Fermi rule is applied to update the cooperative or defective behavior of pedestrians. Based on the model, the influence of the initial distribution pattern, size and number of groups, willingness to cooperate, and intensity of interaction on the evacuation process and cooperation evolution of a crowd containing groups are analyzed. The simulation results suggest that pedestrian interactions in a certain range promote cooperative behavior and also improve evacuation efficiency. The evacuation time and cooperation fraction of the crowd are larger when the groups are initially distributed in clusters, which has important implications for how groups in actual events are arranged geographically. The increase in the willingness to cooperate among in-group members also promotes pedestrian cooperation but prolongs the evacuation time of the crowd. The effect of the willingness to cooperate is distinctive for $r > 0.5$. For larger groups in the crowd, the increase in the number and size of the groups is conducive to the formation of cooperation. However, when the willingness of the group members to cooperate is high at the same time, the total evacuation time also lengthens.

The conclusions gleaned from this study contribute to our understanding of pedestrian interactions during evacuation and are of assistance when developing evacuation strategies for dense crowds with the presence of groups. The interaction of pedestrians within a certain range is conducive to evacuation, which reminds trainers to instill the concept of interaction in emergency evacuation drills and training. The formulation of evacuation strategies and the design of evacuation systems should also play a role in promoting pedestrian interaction and providing pedestrians with an evacuation environment that facilitates interaction. However, for groups, the cooperation of interacting group members should be moderately suppressed to improve evacuation efficiency. Combined with the conclusions of the influence of the group's initial distribution pattern, measures to separate the members of the group can be taken before or during the evacuation, including setting up obstacles. Therefore, from the perspective of rapid evacuation, it is not entirely reasonable to arrange the positions of pedestrians in groups when holding large events or in other scenarios with a large number of groups. In the meantime, the number and size of groups should be set by comprehensively considering cooperative behavior and evacuation efficiency.

The study also has certain limitations. In the study, the behaviors of pedestrians are simplified to cooperation or defection, whereas the behaviors that pedestrians exhibit when interacting with others may be more complicated in real situations. Moreover, group cohesion is not considered, which also has a specific impact on the interaction of pedestrians. These limitations will be studied in future work. In spite of its limitations, this work provides new insight into the understanding of the dynamic mechanism of pedestrian evacuation and is also a crucial step toward the safe management of dense crowds.

Author Contributions: Conceptualization, Y.M. and X.L.; methodology, Y.M. and X.L.; software, F.H. and H.L.; formal analysis, F.H. and H.L.; writing—original draft preparation, X.L.; writing—review and editing, Y.M. and F.H. All authors have read and agreed to the published version of the manuscript.

Funding: This research was supported by the Fundamental Research Funds for the Central Universities (2021III053JC, 2021III052JC).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data presented in this study are available from the corresponding author upon reasonable request.

Conflicts of Interest: The authors declare no conflict of interest.

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