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A study of group effects in pedestrian crowd evacuation: Experiments, modelling and simulation

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ABSTRACT

The presence of social groups in pedestrian crowds can have a substantial effect on the overall evacuation process. However, crowds are mostly simplified as a collection of individuals, and the influence of grouping has not been widely considered in pedestrian crowd simulations. In this study, a novel model that accounts for social groups was implemented based on a social force framework to investigate evacuation dynamics in pedestrian crowds. The associated model parameters were calibrated via two group experiments to provide more credible and realistic simulation results. The effects of certain variables (e.g., group size, desired speed, exit width) on the overall evacuation performance and local group behaviour were investigated. The simulation results indicate that group effects facilitated overall crowd evacuation, especially when the exit was wide. The total evacuation time of a pedestrian crowd was shorter when the groups within the crowd were larger. The time intervals for groups of various sizes did not show a significant difference. The group shape was approximated as a rectangle, and the group features were therefore quantified by shape-related parameters (e.g., aspect ratio and area). The rectangle was shown to orient itself along the moving direction. An elongated configuration of the group became increasingly notable when the leader–follower relationship intensified, resulting in a queue-like formation that facilitated the overall evacuation. A certain trend was found that showed an increase in the aspect ratio and a decrease in the normalised area over time. The larger-sized group often seemed to have a smaller aspect ratio but required more space per person during movement. This study deepens the understanding of crowd evacuation dynamics featuring social groups.

1. Introduction

The increasing scale of group activities and the growing size of pedestrian crowds present new challenges to security. As a consequence, a safe evacuation system to minimise injuries in case of emergency has been a primary concern. Current approaches for investigation of evacuation dynamics fall into two main categories: experiments and models. According to recent review articles (Haghani, 2020a, 2020b), the most heavily studied topics remain pedestrian flow at bottlenecks (Shiwakoti and Sarvi, 2013), route choice (Lovreglio et al., 2014), movement speed (Ronchi et al., 2018) and human behaviour (Bode and Codling, 2013). Meanwhile, new emerging topics, such as the effects of social groups (Haghani et al., 2019; Xie et al., 2020; Hu et al., 2020), are receiving increasing attention. Recognition of group effects on evacuation dynamics is key to optimal crowd management in an emergency.

Grouping is a common phenomenon in streets, shopping centres, transport systems and other places. A sequence of studies demonstrated that groups, rather than individuals, actually account for most of the population in a pedestrian crowd (Singh et al., 2009; Aveni, 1977). Pedestrians with a bond of kinship or friendship tend to walk together. Over the years, social groups have been widely studied in social psychology, with focus placed on motivation, aggregation and categorisation (Turner, 1985), whereas the movement dynamics of groups are considered in computer science. Particle system methods like the Reynolds 'boids' model have been extensively used to simulate group behaviour regarding animal motion, such as bird flocks and fish schools (Reynolds, 1987). A growing number of models no longer treat pedestrian crowds as a collection of isolated individuals but instead take social groups into consideration. Zhang et al. (2018a) developed an improved social force model (SFM) that included group behaviour based on social

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comparison theory. Under the framework of the SFM, Huang et al. (2018) simulated social group behaviours in virtual geographic environments. Lu et al. (2017) evaluated the influence of group behaviour on crowd evacuation using an extended cellular automaton model and found that the evacuation time increased dramatically due to the presence of pedestrian groups. The grouping phenomenon was also simulated with an agent-based model (Karamouzas and Overmars, 2012) that considered local group behaviours. Above all, the SFM has an advantage in integrating physical, sociopsychological and behavioural components into the model but with relatively simple rules. The authors of the present study have argued that the framework of SFM is appropriate for use in the study of crowd evacuation dynamics with social groups.

The group effects on the crowd dynamics of motion have become a hot and controversial topic. At first, negative group effects were reported (i.e., a reduction in the overall evacuation efficiency). Bode et al. (2015) indicated that the presence of social groups in a pedestrian crowd increased both premovement time and movement time. Gorrini et al. (2014) found that group proxemics behaviour had a negative effect on walking speed due to the need of avoiding group dispersion. Köster et al. (2011) and You et al. (2016) reported that the evacuation time increased and the evacuation efficiency decreased with the size of the social groups in a crowd. In contrast, some studies reported positive group effects. Von Krüchten et al. (2016) found that the evacuation time decreased as the social group size increased. Cooperative behaviours were observed member-to-member in groups, whereas competitive behaviours were presented group-to-group. Social group behaviour was advantageous for overall evacuation, especially in front of the door, where the group members waited behind each other (i.e., self-ordering effects). Studies by other researchers have supported both positive and negative group effects, which evidently depend on situational factors such as population density (Vizzari et al., 2013), group size (Qiu and Hu, 2010) and visibility (Zhang et al., 2018b). Gorrini et al. (2016) found that dyads walked 30% slower than singles to meet the needs of communication. It is generally thought that groups have a slower movement speed than individuals in a similar circumstance. However, recent experimental studies have noted that groups tend to move faster than individuals in cases of very limited visibility (Xie et al., 2020). To sum it up, the influence of social groups on crowd evacuation dynamics remains an open problem that requires further exploration.

Group shape (or structure) is another important aspect that has been studied to show the characteristics of social groups during movement. Köster et al. (2011) found that group members tended to walk abreast in a free path but one behind the other through a bottleneck. Similar conclusions can be found in other studies, which reported group shapes as 'side-by-side', 'V-like' and 'river-like' under low-, medium- and high-density pedestrian crowds, respectively (Moussaïd et al., 2010; Karamouzas and Overmars, 2012; Fu et al., 2019; Schultz et al., 2012). Most analyses of group shapes have remained at a qualitative level of description, so an appropriate method to quantify the features related to the shapes of a group is still needed. In one controlled experiment (von Krüchten and Schadschneider, 2017), the social groups were treated as ellipses. Qiu and Hu (2010) characterised the group shape as changing dynamically based on interpersonal distance (i.e., Euclidian distance), moving target and social proximity. For example, a 'clustered' group structure can dynamically change into a 'linear' group structure when approaching the narrow entrance of a building. Wei et al. (2014) found that the intra-group distance of groups with two men, two women, a couple and ordinary friends were 0.60, 0.57, 0.44 and 0.72 m, respectively. In another field study, Fu et al. (2019) compared the differences in the average distance among groups walking on stairs and walking on flat surfaces. Note that the group shape addressed above represents the outward appearance that a social group presents in space. There is, in fact, an invisible structure of groups (i.e., the hierarchy leader–follower pattern). Psychologists and sociologists agree that the leader–follower relationship is an essential property of social groups (Hogg et al., 2012). It is difficult to investigate social groups without thinking about leadership. For example, leadership has been extensively studied in biological and physical systems, in which collective motion or swarming were modelled using approaches such as the Vicsek self-propelled particle model (Vicsek et al., 1995; Mwaffo et al., 2018). Haghani et al. (2019) wrote that leadership was the dominant group decision-making mechanism in an evacuation. Schultz et al. (2012) found that a clear leader–follower structure would benefit movement when the crowd density increased. A leader–follower group was shown to perform better than a clustered group when moving in a constrained space (Qiu, 2010). However, the connections among leadership, group shapes, group distance and overall crowd performance in motion remain unclear.

Previous studies have used group movement speed (Gorrini et al., 2014), group effects (von Krüchten & Schadschneider, 2017), group shapes (Moussaïd et al., 2010), intra-group distance (Wei et al., 2014), group behaviour (Bode et al., 2015) and leadership (Schultz et al., 2012) as keywords for social group research. Note that the existing research has predominantly addressed walking groups in non-emergency situations. Very few studies have accounted for the effects of grouping on the dynamics of crowd movement in an emergency. Care should be taken when applying the classical conclusions gained from walking groups to groups during an evacuation. The performance of an evacuation system must be studied in emergency situations with crowds that include social groups. The key research question is to understand how and to what extent the group behaviour will influence the overall crowd evacuation dynamics.

This study aims to investigate the effects of group behaviour on the evacuation dynamics of a pedestrian crowd. A novel model that accounts for groups was developed for evacuation simulation. The model parameters were calibrated based on two preliminary experiments to provide more realistic and credible simulation results. The overall evacuation time and group characteristics were further explored. The remainder of this paper is organised as follows. Section 2 introduces the model and methods. Next, the associated parameters in the group model are calibrated in Section 3. Section 4 includes an analysis of the simulation results, and Section 5 includes a discussion of the study's limitations. Finally, our conclusions are summarised in Section 6.

2. Model and methods

2.1. Introduction of social force model

The SFM is a microscopic model that aims to simulate the motion of pedestrians based on a series of forces (Helbing et al., 2000). Three key components are included in the SFM: the self-driving force $\mathbf{f}_i^0$, the interaction forces $\sum_{j(\neq i)}\mathbf{f}_{ij}$between pedestrians and the interaction forces $\sum_W\mathbf{f}_{iw}$between pedestrians and boundaries. The mathematical expression of the SFM is interpreted via Newton's second law, as shown below

$$m_i\frac{\mathrm{d}\mathbf{v}_i(t)}{\mathrm{d}t} = \mathbf{f}_i^0 + \sum_{j(\neq i)}\mathbf{f}_{ij} + \sum_W\mathbf{f}_{iw} \tag{1}$$

In Eq. (2), the 'driving force' $\mathbf{f}_i^0$ describes the pedestrians' motivation to move to the target at a desired speedv_i^0in direction$\mathbf{e}_i^0$. To achieve this, a pedestrian is assumed to adjust his or her actual speed $\mathbf{v}_i(t)$ to desired speed v_i^0within a characteristic time τ_i. In Eq. (3), the 'interaction force' $\mathbf{f}_{ij}$ works to avoid body collisions between pedestrians. $\mathbf{f}_{ij}$ consists of a psychological repulsive force, a physical 'body compressive force' and a 'sliding friction force'. A_i,B_i, k and κ are constants, and r_{ij} represents the sum of the body radius of pedestrians i and j. $d_{ij} = \|\mathbf{r}_i - \mathbf{r}_j\|$denotes the distance of the centres of mass between pedestrians i and j. $\mathbf{n}_{ij} = (n_{ij}^1, n_{ij}^2) = (\mathbf{r}_i - \mathbf{r}_j)/d_{ij}$is the normalised vector pointing from pedestrian j to i. The function$g(x)$equals $x$only when $x > 0$ (i.e., $d_{ij} < r_{ij}$) and otherwise equals zero. That is, the physical force will only exist when pedestrians make bodily contact with each other. $\mathbf{t}_{ij} = (-n_{ij}^2, n_{ij}^1)$represents the tangential direction, and $\Delta v_{ij}^t = (\mathbf{v}_j - \mathbf{v}_i)\cdot\mathbf{t}_{ij}$ indicates the tangential speed difference. In Eq. (4), the interaction force $\mathbf{f}_{iw}$ between pedestrians and obstacles is treated as analogous to the interaction force $\mathbf{f}_{ij}$.

Finally, the positions of the pedestrians are updated according to the change in movement speed, as formulated in Eq. (5).

$$\mathbf{f}_i^0 = m_i \frac{v_i^0(t)\mathbf{e}_i^0(t) - \mathbf{v}_i(t)}{\tau_i} \tag{2}$$

$$\mathbf{f}_{ij} = A_i exp[(r_{ij} - d_{ij})/B_i]\mathbf{n}_{ij} + kg(r_{ij} - d_{ij})\mathbf{n}_{ij} + \kappa g(r_{ij} - d_{ij})\Delta v_{ij}^t \mathbf{t}_{ij} \tag{3}$$

$$\mathbf{f}_{iw} = A_i exp[(r_i - d_{iw})/B_i]\mathbf{n}_{iw} + kg(r_i - d_{iw})\mathbf{n}_{iw} - \kappa g(r_i - d_{iw})(\mathbf{v}_i \cdot \mathbf{t}_{iw})\mathbf{t}_{iw} \tag{4}$$

$$\mathrm{d}\mathbf{r}_i = \mathbf{v}_i(t)\cdot \mathrm{dt} \tag{5}$$

The original specification (OS) of the SFM has been extensively applied to simulate pedestrian motion due to its simplicity and its good performance in reproducing typical phenomena, such as arching at a bottleneck or lane formation observed in pedestrian crowds. However, the flaw of the OS SFM is that it only accounts for the relative position of pedestrians to avoid collisions, but does not include any term based on velocity. This makes the collision avoidance unrealistic to some extent. The flaw of the OS SFM in collision avoidance cannot be avoided even by setting the same value of the desired velocity for all pedestrians. The limitation of the OS SFM is discussed in Section 5.

2.2. Modelling group behaviour

Individuals in a crowd are mostly treated equally, and the influence of grouping has not been widely incorporated into pedestrian crowd simulations. Some researchers have thus attempted to include social group behaviour in a pedestrian crowd simulation based on the SFM framework. Xu and Duh (2010) and Li et al. (2017) each incorporated a new force in the SFM to describe group behaviour – a bonding force and a group attractiveness force, respectively. Both studies adopted an exponential relationship of the grouping force with a formation similar to the psychological repulsive force in the original SFM. In another study, Huang et al. (2018) adopted a logarithmic function to describe the property of group force. Scholars have thus provided various mathematical expressions to determine group force. However, the specific choices of grouping mentioned above have not been validated and they show a clear drawback in that the mathematical expressions formulated in these studies generally lacked physical connotations with respect to the nature of forces.

The interactions among pedestrians in social groups should have the characteristic of being repulsive at short range but attractive at a long distance. The main challenge in constructing the group force turns to find a mathematical expression properly reflects the dual properties. The first thought comes to our mind is the Lennard-Jones potential (Lennard-Jones, 1924), which is the most widely used potential in describing the molecular interactions due to its computational simplicity compared with other potentials. The Lennard-Jones potential (also called the L-J or 6–12 potential) is normally applied in the simulations of interactions in molecular models. However, it is quite instructive in providing us a fundamental understanding of various types of bonding, particularly in regard to a balance in short-range repulsion and long-range attraction. The L-J potential is therefore supposed to work in describing the dual properties of pedestrians grouping. In the later section, the good performance of the proposed model in reproducing the experimental results confirms the feasibility of assumption on group force according to the L-J potential. As seen in Eq. (6), the L-J potential consists of two terms. The first half of the L-J potential is the repulsive term (Pauli repulsion), which describes the inter-electron repulsion once two particles come near each other. The second half of the L-J potential is known as London dispersion, which describes the attraction between molecules at long range.

$$V_{LJ} = 4\varepsilon[(\frac{\sigma}{r})^{12} - (\frac{\sigma}{r})^6] = \varepsilon[(\frac{r_{min}}{r})^{12} - 2(\frac{r_{min}}{r})^6] \tag{6}$$

where ε is the potential well depth, σ is the distance at which the inter-particle potential equals zero, $r$represents the distance between the two particles and r_{min} is the distance at which the potential reaches a minimum. At r_{min}, the attractive and repulsive forces are exactly balanced so it also represents an equilibrium position, that is, $r_{min} = \sqrt[6]{2}\sigma \approx 1.122\sigma$.

The L-J force is obtained by differentiating the L-J potential with respect to the distance r between two molecules (see Eq. (7)). On this basis, the group force is built into Eq. (8) by taking the same form as the L-J force. The general variable r in Eq. (7) is transformed to the specific distance d_{ij} between pedestrians i and j in Eq. (8), and $\mathbf{n}_{ij}$ represents the normalised vector pointing from pedestrian j to i. For the definition of the traditional SFM term, please refer to Section 2.1. ε_f and σ_f are the parameters that influence the maximum attractive force and the equilibrium distance ($1.122\sigma_f$). The values of group force-related parameters are calibrated later in Section 3.2. Finally, the improved SFM that includes the new group force is formulated, as shown in Eq. (9).

$$F = -\frac{dV_{LJ}}{dr} \tag{7}$$

$$\mathbf{f}_{i\mathrm{Group}} = \mathbf{n}_{ij}\cdot\varepsilon_f[2(\frac{\sigma_f}{d_{ij}})^{12} - (\frac{\sigma_f}{d_{ij}})^6]/d_{ij} \tag{8}$$

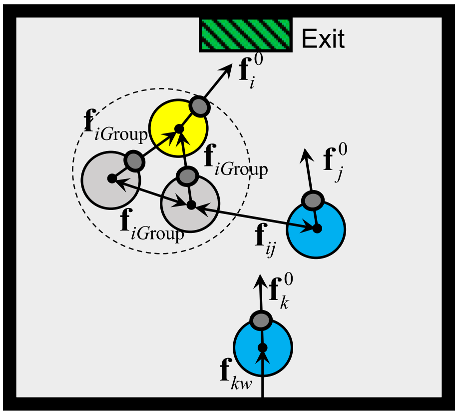
$$m_i \frac{\mathrm{d}\mathbf{v}_i(t)}{\mathrm{dt}} = \mathbf{f}_i^0 + \sum_{j(\neq i)} \mathbf{f}_{ij} + \sum_{W} \mathbf{f}_{iw} + \sum_{j(\neq i)} \mathbf{f}_{i\mathrm{Group}} \tag{9}$$

Fig. 1(a) visualises the forces among pedestrians. Fig. 1(b) illustrates that the nature of the group force is actually the combination of the repulsive term and the attractive term. It can be seen that the repulsive term dominates at short distances and the attractive term dominates at greater distances. Note that the attractive force is assumed to diminish when the distance between two members is too great. This assumption is based on controlled experiments and a questionnaire survey (Xie et al., 2020; Zhang et al., 2018b). The group members were observed to cease moving towards each other when at a long distance. Some participants in the controlled experiments reported that they did intend to leave the room at first but thought that just keeping their companions within visual range was fine. Therefore, we believe that a group force like in Fig. 1 (b) is appropriate in situations in which evacuation occurs in a room and the evacuees move to a common and clear target. The limitations and generalisations of the developed group model are discussed in Section 5.

2.3. Social identity theory of leadership

Psychologists have claimed that leadership is a core feature of social groups (Hogg et al., 2012). It is difficult to investigate social groups without thinking about leadership. As suggested by the social identity theory of leadership, 'group identification constructs an intragroup prototypicality gradient that invests the most prototypical member the appearance of having influence' (Hogg, 2001). In an emergency, a sense of common identity and shared fate will make social groups more connected than usual. An intragroup prototypicality gradient is likely to arise during evacuation as a result of individual disparities in personality, knowledge and physiological and psychological states. It is believed that the most suitable member will emerge as a leader. Thus, we incorporate leadership into the improved group model, in which the pedestrians' motions obey the following rules:

(i) A crowd with N evacuees is divided into n groups, with each group size of N/n. One leader is set in each group according to a certain rule. In this study, it is assumed that the person closest to the exit will act as leader due to his or her advantageous position.



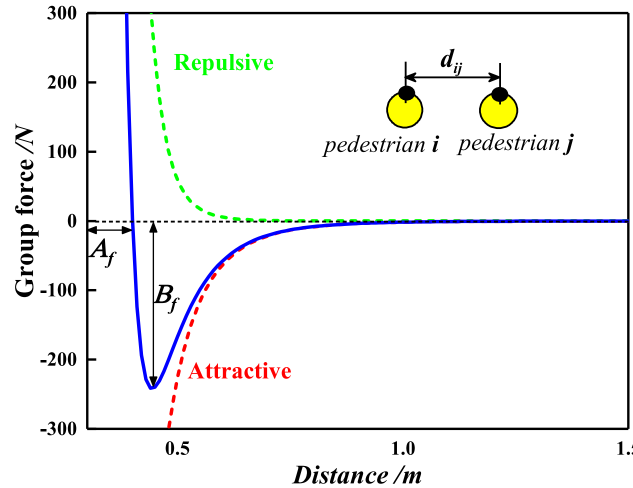


Fig. 1. Illustration of forces in group model. (a) Interactive forces between evacuees and (b) physical expression of group force. Repulsive/attractive term works when distance is shorter/longer than an equilibrium distance.

(ii) The group leaders will move directly to the exit, and the group members will tend to move towards the exit and follow the group leader to avoid falling behind. The desired directions of the leader and the group members are represented as $\mathbf{e}^l_{Groupi}$ and $\mathbf{e}^m_{Groupi}$, respectively (see Eqs. (10) and (11)). α is a group harmony coefficient, which represents the degree to which a group member wishes to follow the leader. The values of α are set to 0, 0.5 and 1, respectively, in the later simulations. A larger value for α represents a greater desire of the members to follow the leader.

(iii) Evacuees in the same group will stick together during movement. Note that the group force acts between each member of a group, not just the leader and followers. As displayed in Fig. 1(b), B_f and A_f are responsible for adjusting the magnitude of the maximum group force and the equilibrium distance between group members, and are called the group cohesion coefficient and the group proximity coefficient, respectively.

$$\mathbf{e}^l_{Groupi} = \frac{\mathbf{r}_{exit} - \mathbf{r}^l_i(t)}{\|\mathbf{r}_{exit} - \mathbf{r}^l_i(t)\|} \tag{10}$$

$$\mathbf{e}^m_{Groupi} = \alpha \frac{\mathbf{r}^l_i(t) - \mathbf{r}^m_i(t)}{\|\mathbf{r}^l_i(t) - \mathbf{r}^m_i(t)\|} + (1-\alpha)\frac{\mathbf{r}_{exit} - \mathbf{r}^m_i(t)}{\|\mathbf{r}_{exit} - \mathbf{r}^m_i(t)\|} \tag{11}$$

3. Empirical data

3.1. Description of two evacuation experiments

The proposed group model was calibrated on the basis of two previously published evacuation experiments. The first, denoted as Experiment (I), was performed by von Krüchten and Schadschneider (2017) in a square room, as shown in Fig. 2(a). The experimental runs were performed with 32 to 46 participants. The participants were assigned to groups of one (i.e., individuals), two, four, six or eight. The effects of social groups on overall crowd evacuation were investigated. In addition, Fig. 2(b) shows the second test, Experiment (II), recently conducted by Xie et al. (2020), in which 36 participants were involved in a room evacuation. The participants were recruited from college students and staff members, including the typical social groups of friends, classmates

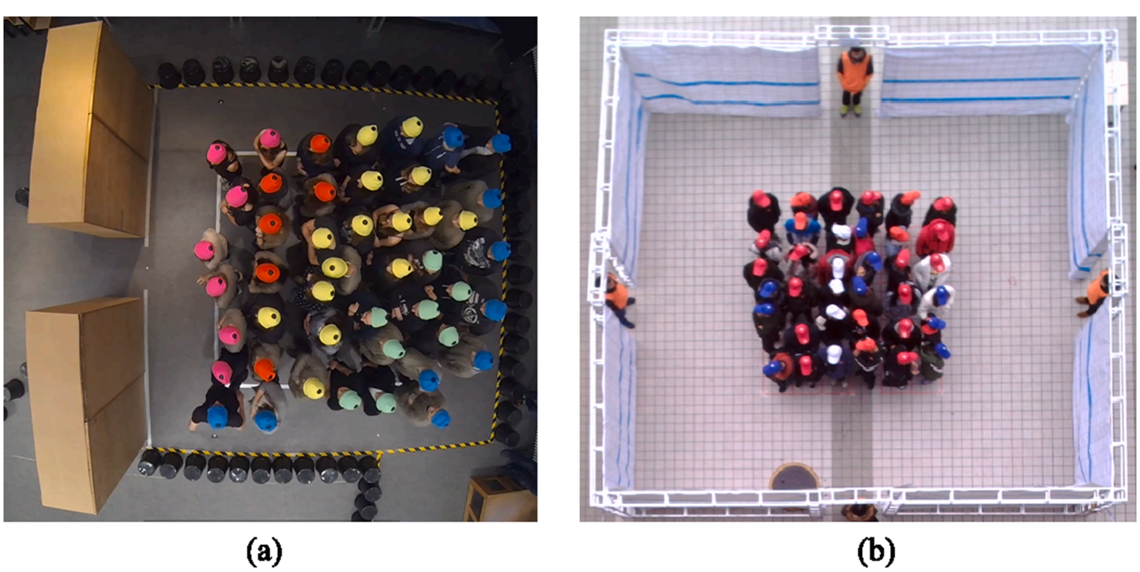


Fig. 2. Model calibration using experimental data from evacuation experiments. (a) Experiment (I) performed by von Krüchten and Schadschneider (2017), (b) Experiment (II) performed by Xie et al. (2020).

and colleagues. The pedestrian crowds in the experiment consisted purely of individuals (i.e., individual experiment) or a mixture of individuals and groups of two, three and five (i.e., group experiment). The social groups were based on the actual social relationships among the pedestrians using a social network analysis method. The pedestrians in groups were required to evacuate as a group, and communication was permitted during movement. More details about the two experiments were published by von Krüchten and Schadschneider (2017) and Xie et al. (2020).

3.2. Calibration of model parameters

This section describes our reproduction of the experimental process using the proposed group model. The key step was to adjust the associated parameters in the SFM and to adopt the appropriate group-related parameters. The differential evolution (DE) algorithm was used in this study for parameter calibration and optimization. DE has fast convergence speed and performs well in achieving the global optimal solution. In this study, a two-step calibration and optimization process were performed. At first, the traditional SFM parameters were calibrated to minimize the value of *F1*, as shown in Eq. (12). Secondly, the group-related parameters were calibrated to minimize the objective function *F2* in Eq. (13), while keeping the SFM parameters the same as the first step.

$$\textbf{\textit{To minimize}}: \quad F1 = \sum_{i=1}^{n} \left(T_i^{experiment} - T_i^{simulation}\right)^2 \tag{12}$$

Where $T_i^{experiment}$ and $T_i^{simulation}$ represents the leaving time of the ith evacuated person in condition of experiment and simulation, respectively. i denotes each evacuee, and the total number of evacuees are n ($n = 30$). The DE search space of four calibrated SFM parameters are: $0 < A_i \leqslant 3000N$, $0 < v_i^0 \leqslant 5m/s$, $0 \leqslant k \leqslant 3 \times 10^5 kg/s^2$, $0 \leqslant \kappa \leqslant 3 \times 10^5 kg/(m \cdot s)$.

$$\textbf{\textit{To minimize}}: F2 = \sum_{t=t1}^{t2} \sum_{i=1}^{Ngroup} \left\{Cp_i^{experiment}(t) - Cp_i^{simulation}(t)\right\}^2 + \sum_{t=t1}^{t2} \times \sum_{i=1}^{Ngroup} \left\{Ar_i^{experiment}(t) - Ar_i^{simulation}(t)\right\}^2 \tag{13}$$

Where $Cp_i^{experiment}(t)$ and $Cp_i^{simulation}(t)$ denotes the central position of each group at time t in experiment and simulation, respectively. A rectangle is formed which includes members within each group and achieves the minimum area (see details in Section 4.3). $Ar_i^{experiment}(t)$ and $Ar_i^{simulation}(t)$ are the aspect ratio of the rectangle at time t in experiment and simulation respectively. *Ngroup* is the total number of groups (*Ngroup* = 7). The coordinates of group members at each frame with duration of 2 s (i.e., from $t1 = 1$ s to $t2 = 3$ s) are extracted. The DE search space of three group-related model parameters for calibrations are: $0 \leqslant \alpha \leqslant 1$, $0 < A_f \leqslant 2m$, $0 < B_f \leqslant 2000N$.

Figs. 3 and 4 compare the evacuation speed curve in the two experiments (von Krüchten and Schadschneider, 2017; Xie et al., 2020), the original SFM (Helbing et al., 2000), and the simulations with the improved group model in this study. The experimental data from the individual runs in Experiment (I) and from the individual and group runs in Experiment (II) were used for calibration. Table 1 displays the corresponding parameters optimized in the simulations (the numbers are rounded). By using the model parameters after calibration and optimization (i.e., $A_i = 600$, $B_i = 0.08$, $k = 1000$, $\kappa = 500$), Fig. 3 and Fig. 4(a) show the simulated number of evacuated people in the time elapsed agreed well with the experimental results in Experiment (I) and Experiment (II). However, the simulation results were quite different when the parameters were set as the original SFM. Next, the associated group parameters (i.e., α, A_f, B_f) were calibrated according to the group run of Experiment (II) aiming to minimize the objective function (F2). Fig. 4(b)

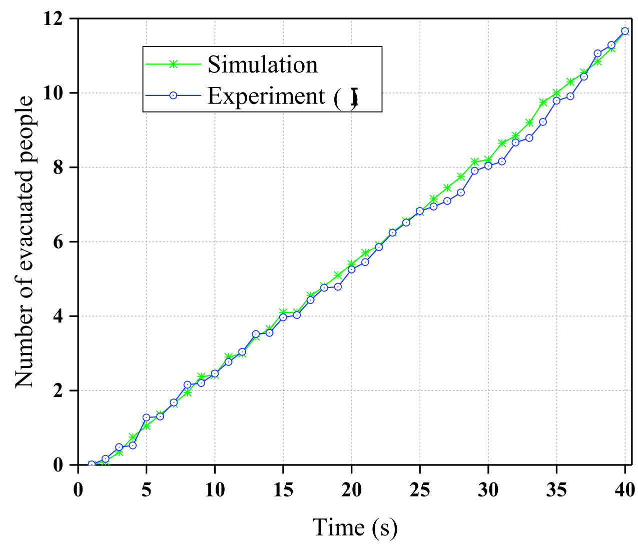


Fig. 3. Comparison of number of evacuated people between Experiment (I) and simulation.

clearly indicates that the improved SFM, which considers group behaviour, reproduced the real experimental process well by setting the parameters as $A_i = 600\ N$, $B_i = 0.08\ m$, $k = 1000 kg/s^2$, $\kappa = 500 kg/(m \cdot s)$, $\alpha = 0.5$, $A_f = 0.4$ m and $B_f = 240\ N$. Note that, the model parameters (A_i, k, κ) after calibrations were obviously smaller than the original SFM. The possible reason could be that the participants in experiments knew each other well and most of them were social groups of friends, classmates and colleagues. As a consequence, a closer psychological distance was permitted. In addition, an analysis of the DE calibration and optimization process shows that the specific values of the physical force coefficients were not significant. Thus, the parameters of the SFM should be calibrated properly in order to obtain the realistic evacuation simulation results in accordance with the specific real scenarios.

Finally, the evacuation process in a single-exit room (15 × 15 m) was simulated using the improved model with calibrated parameters. Eighty evacuees were initially randomly distributed throughout the room. The simulated pedestrian crowd consisted of individuals or groups of two, four, five or eight. Four exit widths were considered: 1, 2, 3 and 4 m. Forty-nine evacuation scenarios were simulated, and each case was conducted 50 times.

4. Simulation and results

4.1. Overall evacuation performance

The overall evacuation performance is discussed first. Fig. 5 compares the evacuation times of pedestrians in groups of various sizes with the four exit widths. Gi in the x-axis represents the group size of i (i = 1, 2, 4, 5, 8). The average evacuation time is shown with a 95% confidence interval. The figure quantitatively indicates that the overall evacuation time decreased as the exit width increased. The average evacuation time fell by 62.4%, 35% and 17.01%, respectively, with each 1-m increase in the size of the exit (i.e., from 1 to 4 m). In other words, when the exit was larger than 2 m, further enlargement of the exit width no longer contributed significantly to the overall evacuation process. In addition, a clear trend in Fig. 5 shows that crowds containing larger groups had shorter overall evacuation times. However, it should be noted that the data within the 95% confidence interval partially overlap among some cases. As a consequence, a *t*-test was performed with various scenarios to quantify the exact statistical significance. The results of the statistical analyses are illustrated in Table 2, where Gi (i = 1, 2, 4, 5, 8) and Ej (j = 1, 2, 3, 4) represent the group size of i and the exit width of j,

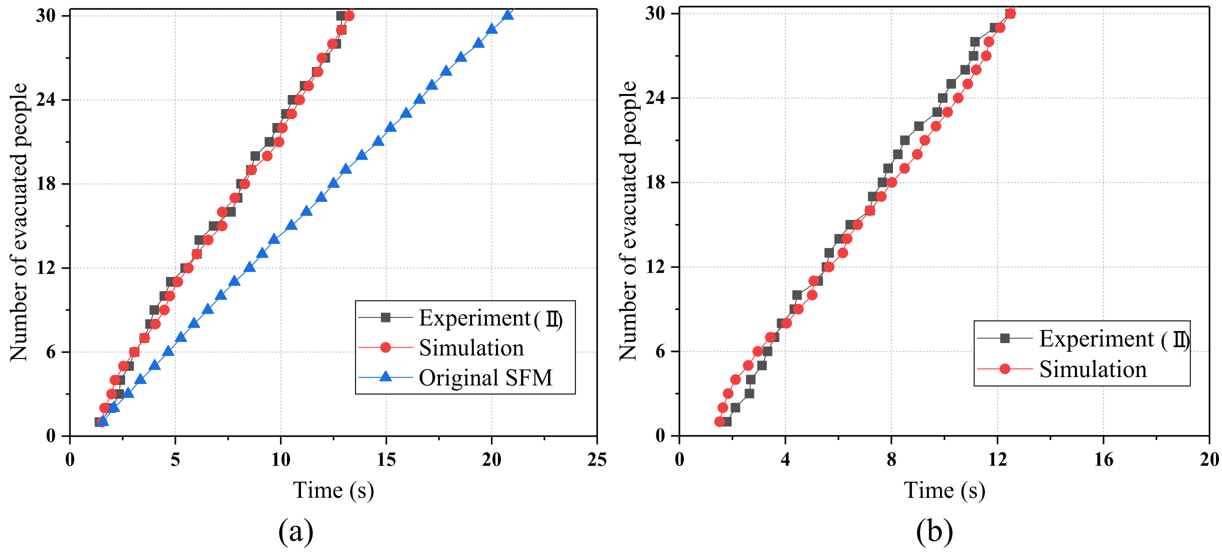


Fig. 4. Comparison of number of evacuated people between Experiment (II) and simulation. (a) Individual experiment; (b) group experiment.

Table 1
Associated parameters used in SFM and group model in calibrations.

	Original SFM	Group model-Experiment (I)	Group model-Experiment (II)
m_i(kg)	64	64	64
r_i(m)	0.2	0.2	0.2
v_i^0(m/s)	2.2, 2.4	2.2	2.4
τ_i(s)	0.5	0.5	0.5
A_i(N)	2000	600	600
B_i(m)	0.08	0.08	0.08
k–kg/s^2	120,000	1000	1000
κ–$kg/(m{\cdot}s)$	240,000	500	500
α	–	–	0.5
B_f(N)	–	–	240
A_f(m)	–	–	0.4

respectively. Significant differences ($p < 0.05$) were found in all but a few situations. The differences were not significant in the situations of E1 (G5-G8), E2 (G2-G4-G5) and E4 (G4-G5). One possible explanation may be that the evacuation performances between the groups of various sizes differed little with certain exit widths due to a cancelling effect. To be specific, the larger groups had a space advantage but also faced a challenge in maintaining group cohesion because they were easier to split up. Although the observed trend revealed that a larger group size may facilitate the overall evacuation, another ascertainable finding was that a crowd made up of individuals (i.e., a group size of 1) tended to take longer than groups in all simulated evacuation scenarios. That is, the group effect is positive on overall crowd evacuation performance based on our simulation results; this finding agrees well with the experimental findings in the literature (von Krüchten et al., 2016). The positive group effects on overall evacuation time may due to the orderly movement mode of groups, which will be discussed in details in Section 4.3.

To analyse the group effects from the perspective of velocity, Fig. 6 compares the velocity fields of pedestrians in groups of various sizes with narrow and wide exit widths. Group sizes of 1, 4 and 8 are illustrated as examples. In Fig. 6, arrows are the velocities at t = 5 s and the color map depicts the magnitude of the velocities. For the narrower exit (i.e., 1 m), clogging around the exit was observed in each situation. The larger-sized group had slightly higher local velocity. For the wider exit (i.e., 4 m) as shown in the second row of Fig. 6, we found the velocities in larger-sized groups tend to be faster than that of individuals. Clogging areas (i.e., v = 0) could be seen around the left and right sides of the exit when group size is 1 and 4 (Fig. 6(d), (e)). The central portion of the exit is shown not fully used since the pedestrians are navigated through the exit from the nearest point within the door width, rather than the central point of the door. From the velocity fields, a more orderly movement was shown in groups compared with the individuals. This may due to the leader-following effect governed by the group harmony coefficient α of the model. A discussion on the impact of α is performed in Section 4.3. Note that, the above results suggest the positive group effects on improving the movement speed and decreasing the overall evacuation time. Groups may lead to some possibly more dangerous or more safe dynamics from a local view point (e.g., local oscillation, pressure), and this is not investigated in this study.

To investigate how the desired speed influenced the overall evacuation time, the differences in the evacuation performances of groups of various sizes with two desired speeds are further compared in Fig. 7. The desired speed was set to 1.2 m/s and to 2.5 m/s, corresponding to a normal speed and running speed in an emergency, respectively. The overall evacuation times at a desired speed of 2.5 m/s were about half those with a desired speed of 1.2 m/s. In situations with various exit widths (1 to 4 m), the faster desired speed shortened the overall evacuation time (i.e., 'faster is faster'). In addition, a downward trend was presented in both situations when the exit width was 2, 3 and 4 m, which indicates that crowds consisting of larger groups required less evacuation time. However, a different trend was found when the exit width was only 1 m. The evacuation time decreased as the group size increased when $v = 1.2$ m/s, but the trend reversed when $v = 2.5$ m/s. Therefore, it is advantageous for a crowd to consist of larger groups with a slower desired speed or smaller groups with a faster desired speed when the exit width is limited (i.e., 1 m in this study), possibly because a larger group will have difficulty maintaining group cohesion if the desired speed is too fast, which increases the overall evacuation time.

4.2. Time interval during evacuation

Detailed information during the evacuation process can be revealed to analyse the flow intermittence. Fig. 8 shows the time interval (Δt) between two successive evacuated persons for various group sizes and under various exit widths. The first and last 10 evacuated people are omitted, and the plot shows the flow at the exit from the 10th to the 70th evacuee. Fig. 8 shows that the lines of the time interval tend to zigzag with slight fluctuations. The average Δt remains relatively stable over

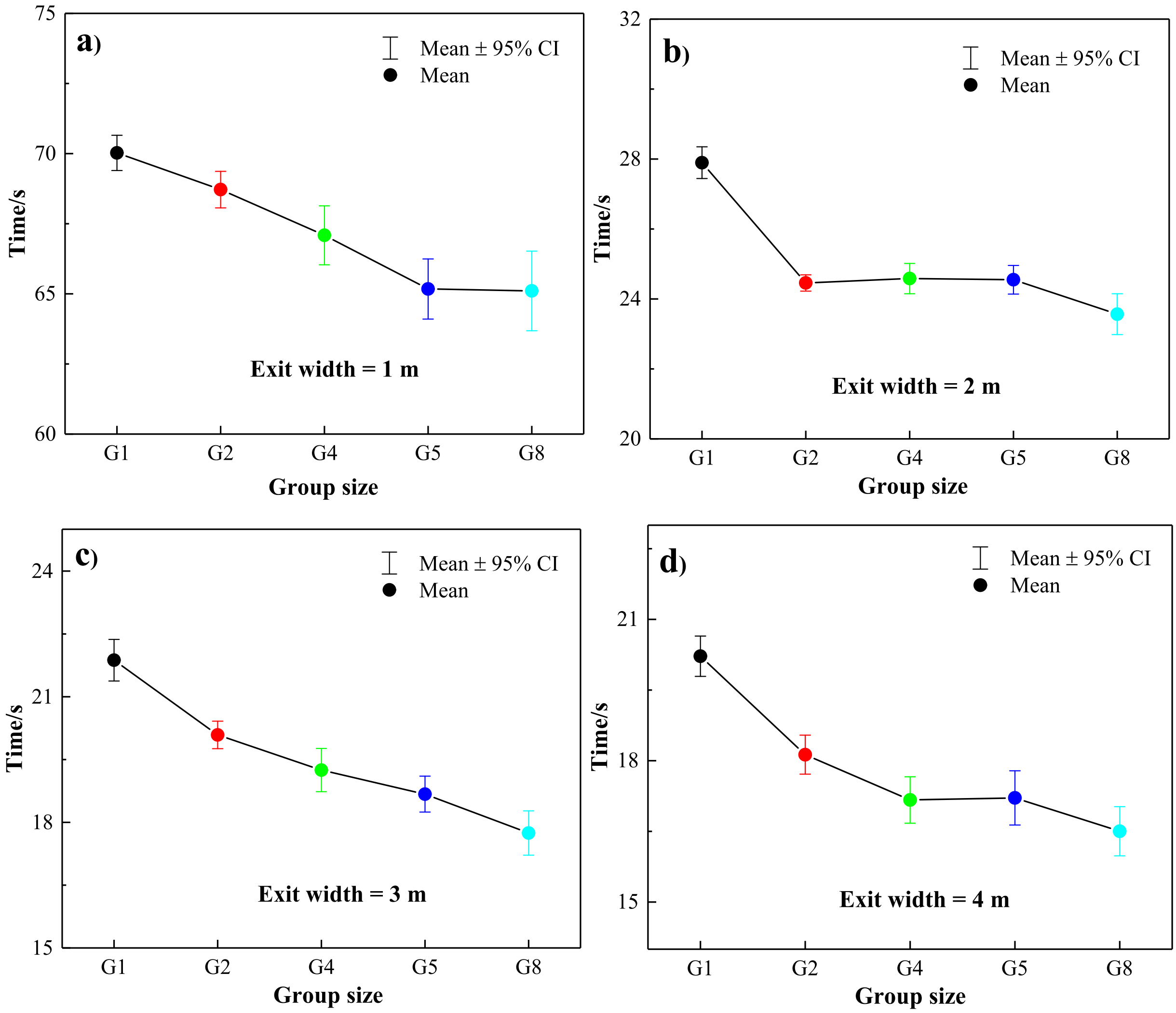


Fig. 5. Evacuation times of pedestrians with various group sizes. (a)–(d) Exit widths are 1, 2, 3 and 4 m, respectively.

Table 2
p values of *t*-test for various simulation scenarios.

Exit width	G1*-G2	G1-G4	G1-G5	G1-G8	G2-G4	G2-G5	G2-G8	G4-G5	G4-G8	G5-G8
E1*	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	0.012	0.025	$p = 0.939$
E2	<0.01	<0.01	<0.01	<0.01	$p = 0.590$	$p = 0.678$	<0.01	$p = 0.907$	<0.01	<0.01
E3	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	0.076	<0.01	<0.01
E4	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	$p = 0.901$	0.055	0.058

* Gi represents group size of *i*, Ej means exit width of *j*.

time, indicating an even and steady passing flow at the exit. The lines of various colours partially overlap and present a possible trend in which the time interval for singles (G1) is slightly higher than those for groups (G2, G4, G5 and G8). The plot of the time interval also indicates that the group size has little influence on the pedestrian flow at the exit. It should be noted, however, that differences in the time interval are notable with different exit widths. The average time intervals for the four exit widths (i.e., 1, 2, 3 and 4 m) were 0.84 ± 0.059 s, 0.27 ± 0.042 s, 0.19 ± 0.041 s and 0.17 ± 0.037 s, respectively. The percentages of the reduction in Δt were 67.9%, 29.6% and 10.5% with each 1-m increase in the exit width, respectively. This indicates that the evacuation process around a narrower exit (i.e., 1 m) is slower, less smooth and fluctuating. Enlarging the exit, for example, from 1 to 2 m, will significantly reduce the time interval and hence facilitate the overall crowd evacuation performance. Such promoting effect was not substantial when the exit was larger than 2 m.

Fig. 9 shows the number of evacuated persons plotted against the evacuation time for the various simulation scenarios. When the exit was 1 m wide, the timelines overlapped partially, and no appreciable differences could be found among the size groups. The divergence then became notable when the exit widened (i.e., to 2, 3 and 4 m). The figure clearly indicates that the line for individuals is higher than the group lines, which means that crowds consisting of individuals evacuated more slowly than those composed of social groups. The group effects were positive for the overall evacuation, especially when the exit was wide. The differences among groups of various sizes were less significant than the differences between individuals and groups. Another interesting finding is that the cumulative number of evacuated persons with larger groups was less than that with smaller groups at an early stage of evacuation, but this trend reversed over time.

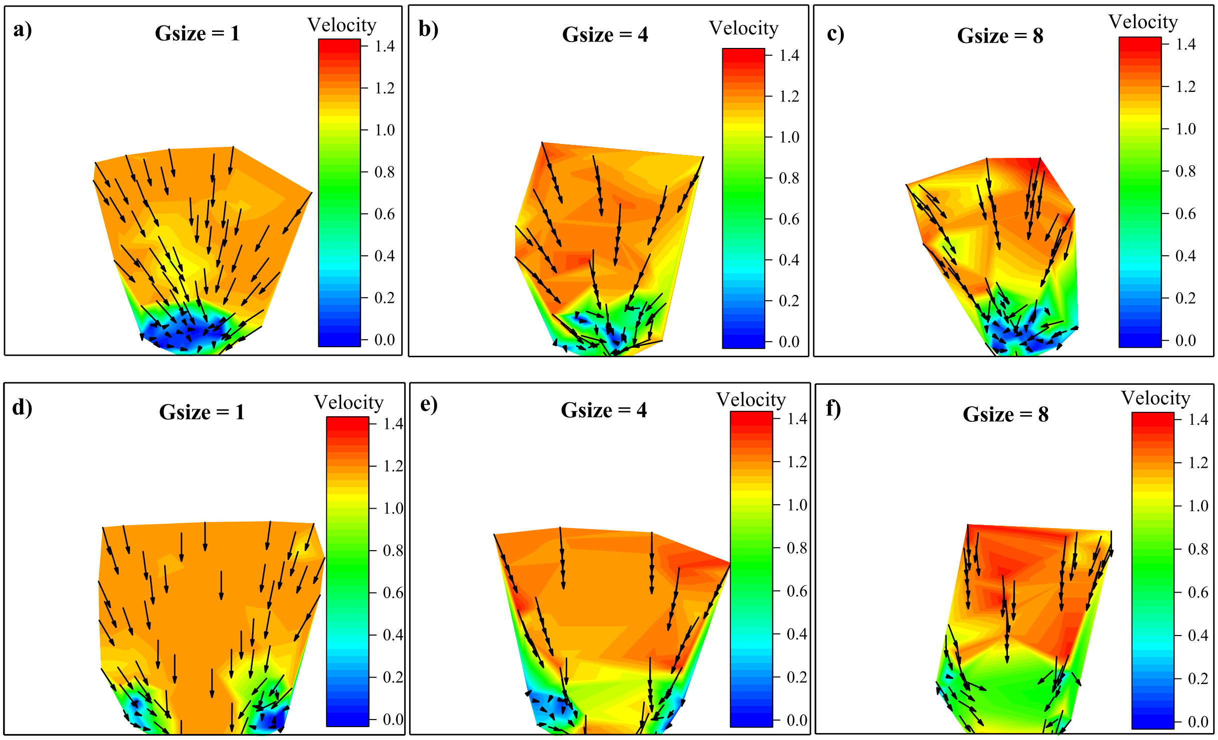


Fig. 6. Velocity fields of pedestrians in groups of various sizes. Arrows are the velocities at t = 5 s and the color map depicts the magnitude of the velocity as values indicated in the color bars. (a)–(c) Exit width = 1 m, and (d)–(f) exit width = 4 m.

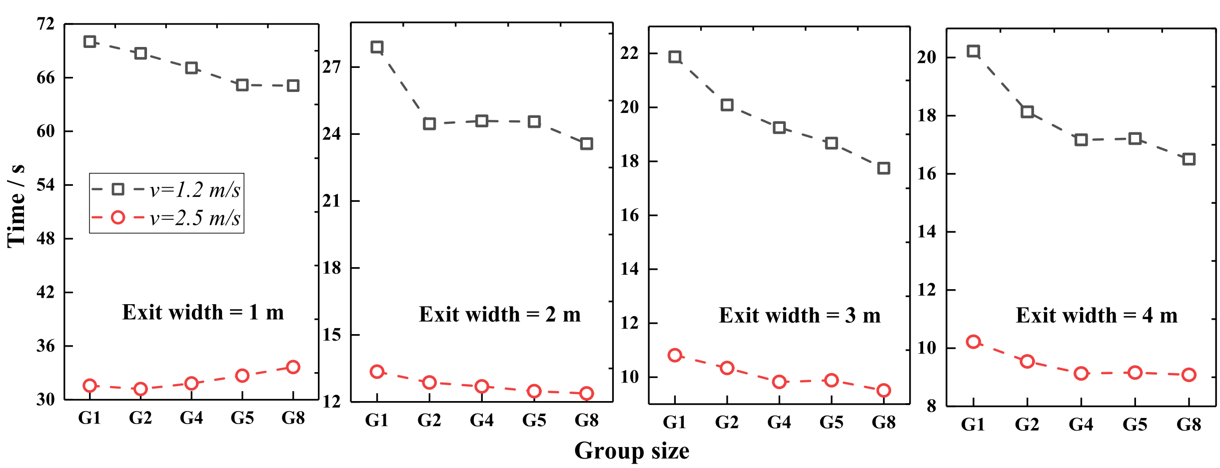


Fig. 7. Comparison of evacuation times with various group sizes, exit widths and desired speeds.

4.3. Group shape

In addition to the overall evacuation performance, the local behaviour of groups is worthy of attention. The group shape (or group structure) is an important parameter to show the local group characteristics during movement. In this study, each group structure is approximated as a rectangle with length L and width W. As illustrated in Fig. 10, the rectangle is determined according to a rule (i.e., including all group members and achieving the minimum area). The aspect ratio and the area of the rectangle are two key components, which will be analysed in this section.

The aspect ratio depicts the ratio between the length and width of the rectangle. The aspect ratio is obtained by dividing the long side of the rectangle by the short side. Fig. 11 shows the mean aspect ratio of groups of various sizes at an early stage of movement from 0.1 to 2.0 s. The corresponding error bands are displayed as colored areas in the figure. Different values for the group harmony coefficient α (0, 0.5, 1.0) are considered. α represents the members' willingness to follow the group leader, which equals 1.0 when each member's moving direction depends totally (100%) on the leader. As clearly displayed in Fig. 11, a gradual increase in the mean aspect ratio appears once movement starts before approaching the exit. The average aspect ratio increases from 1.6 to 2.0 to 2.6 as the value of α increases (i.e., the leader-follower relationship intensifies), which indicates the groups tend to move more orderly when α is larger. Another finding is that the order of aspect ratio for groups with different sizes varies slightly with different values of α. To be specific, when $\alpha = 0$, G5 > G4 > G8; when $\alpha = 0.5$, G4 ≈ G5 > G8; and when $\alpha = 1$, G4 > G5 > G8. The largest group has the smallest aspect ratio, whereas the smaller groups tend to a more orderly distribution along the moving direction. It can also be seen that the error band of a group of four is quite large when t = 2 s in Fig. 11(c), which tells us that the shape of a group of four is unstable and changeable when

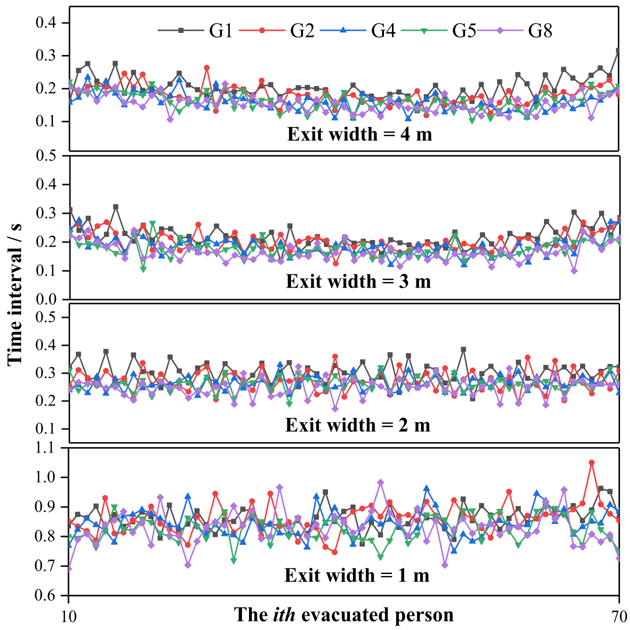


Fig. 8. Time interval Δt between two successive evacuated persons for various exit widths.

can be found in other studies, such as 'river-like' (Moussaïd et al., 2010; Karamouzas and Overmars, 2012; Schultz et al., 2012) and 'linear structure' (Qiu and Hu, 2010). In Fig. 12, the elongated configuration of groups becomes increasingly notable as α increases. The observed 'queue-like' formation suggests that the moving direction of the group will follow the long side of the rectangle. That is, the leader-follower structure of groups contributes to the queue-like shape (or linear pattern) of groups during evacuation.

It should be noted that, although the queue-like formation is geometrically equivalent to the river-like formation described in other literature, it has a different cause. A stable movement mode (i.e., queue-like shape) of group is formed due to the leader-following effect in this study, whereas the river-like pattern emerges to perform the collision avoidance (Moussaïd et al., 2010). The queue-like formation indicates a self-organised and cooperative behaviour among the group members that facilitates the evacuation process. Interestingly, another explanation was given for why a larger group size reduces the overall evacuation time, from the perspective of cooperation and competition (von Krüchten et al., 2016). The authors suggested that group members are in competition only with persons of other groups but cooperative with persons within their own groups. Increasing the group size reduces the number of possible competitors and conflicts, which eventually has a

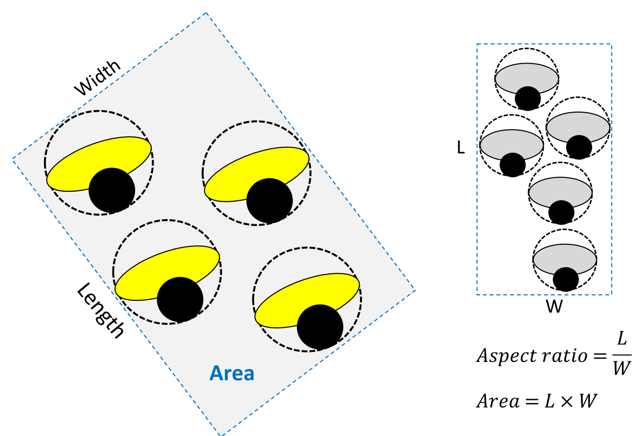


Fig. 10. Illustration of group shape approximated as rectangle with length L and width W.

approaching the exit.

The analysis in Fig. 11 quantitatively indicates that the aspect ratio of the group's rectangle increases when the leader–follower relationship intensifies or when the group is approaching the exit. To visualise this and make it easier to understand, Fig. 12 illustrates the locations of evacuating groups at various times with different values for the group harmony coefficient α. Taking a group of five as an example, we can see that the group shape changes dynamically over time and that the classical arched distribution is presented when evacuees gather around the exit. Interestingly, a 'queue-like' pattern is displayed when the group's leader–follower relationship intensifies, that is, the value of α increases. The term 'queue-like' was originally adopted from the group experiments of von Krüchten and Schadschneider (2017) and was intended to describe the phenomenon in which members of larger groups tended to move single-file through a bottleneck. Meanwhile, similar descriptions

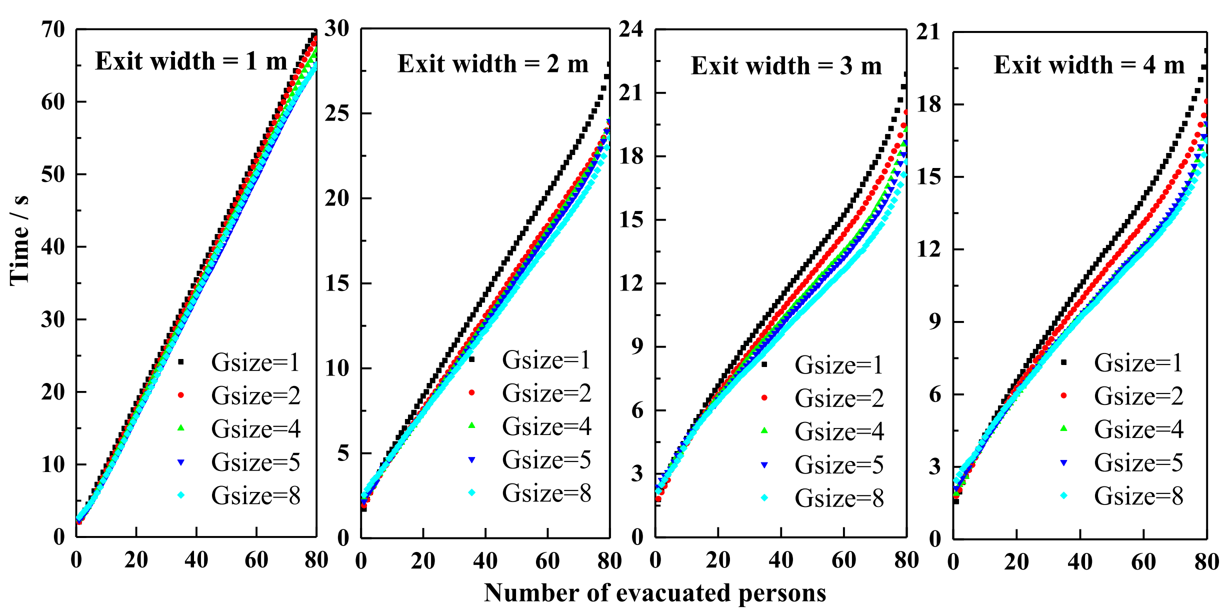


Fig. 9. Evacuation times of pedestrians with different group sizes.

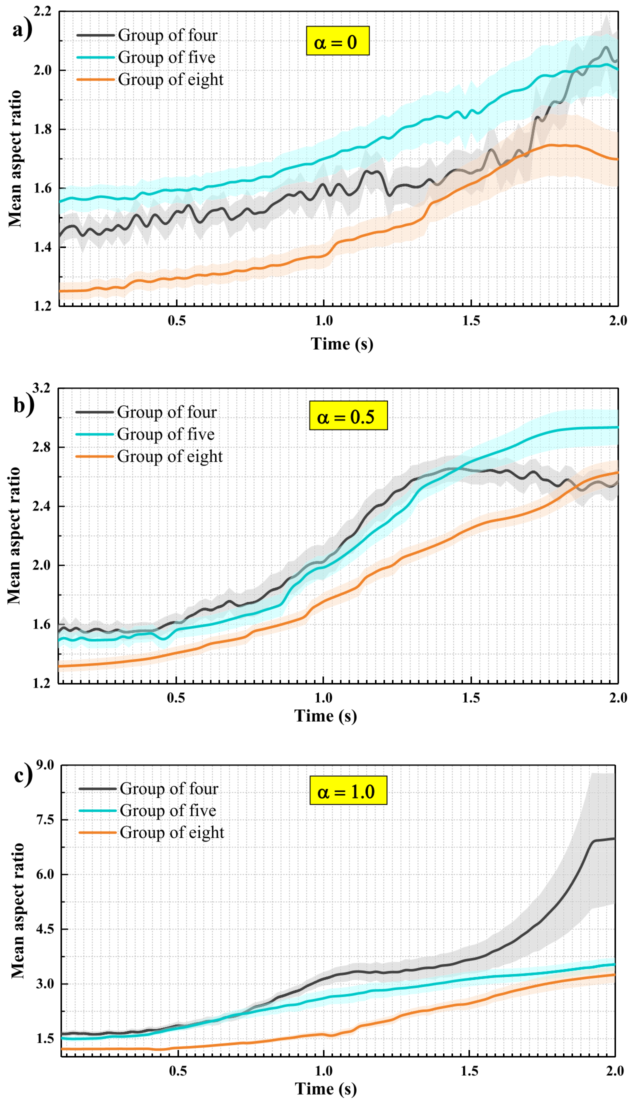


Fig. 11. Mean aspect ratio of group rectangles with various values of α.

favourable influence on the evacuation time. The above discussion regarding Fig. 12 agrees well with the statistical analysis based on Fig. 11.

The area of the rectangle is also of interest for analysis of local group characteristics. The mean normalised area (i.e., per capita occupied area; m^2/person) is used to directly compare the areas of groups of various sizes. The normalised area is an important indicator in evaluating group dispersion. Fig. 13 shows the mean normalised area of various groups when α equals 0, 0.5 and 1.0. The normalised area decreases sharply with time and then tends to stabilise as the group members achieve an equilibrium distance. It is clear to see that the space requirement per person in a larger group (G8) is significantly greater than in the smaller groups (G4 and G5). As indicated by our simulation results, the average stable normalised areas for groups of four, five and eight were 0.12, 0.14 and 0.18 m^2 per person, respectively. This result is highly consistent with those from controlled experiments (von Krüchten and Schadschneider, 2017) (i.e., 0.1 to 0.2 m^2 per person). The normalised area of the group is proportional to the group size. Larger groups seem often to require more space and have greater group dispersion.

5. Limitations

The limitations of this study are discussed below:

(1) The flaw in the SFM is that its collision avoidance mechanism could be unrealistic because it does not include the relative velocity. In this study, we used the OS of the SFM to simulate evacuation for two main reasons. First, the OS has the merit of simplicity and shows a good fit with the experimental results in describing group behaviour. Second, the OS still performs well when studying evacuation issues under certain conditions. For example, it is appropriate to explain the clogging around an exit, where the pedestrians' velocity falls to nearly zero and 'pushing' behaviour dominates 'avoiding' behaviour. We would like to address that the collision avoidance up to the clogging condition is negligible, given the geometry of the problem and the choice of equal desired velocity in the simulations of this study.

(2) Group behaviour was simulated using a new group force with a formation similar to that of the L-J force. However, it should be noted that no angular dependence was included in the group force, so the simulated evacuation may be more efficient than the real case. Another limitation to be addressed is the generality of the assumption on the group force. The attractive term in the group force is assumed to diminish as the distance between two members increases. This conforms with the experimental results but may be not applicable to all social groups. For example, a social group of families will try to stay together in an emergency even if they are separated by an extremely long distance. The interactions within social groups are quite complex in real life, so it is suggested that group behaviour be formulated from a distinctive view to make it reasonable for specific situations.

(3) The simulation results in this study fit well with the experimental data. However, as addressed above, the model's ability to represent all real cases in an emergency is limited. It is reasonable to account for leadership in crowd evacuation simulations that include social groups, but the leader-follower rule setting in a simulation may overly reduce the evacuation time; that is, the presence of a clearly defined leader may excessively facilitate the group's approach to the exit because it adjusts the movement to the group level. In a real case, it is unrealistic to think that a parent leader would simply walk to the exit without checking whether the children were close and safe. In addition, the group shape was approximated as a rectangle in this study, which tends to be relatively simplistic in quantifying the group features. However, the results obtained thus far suggest certain interpretations that can be improved and extended to be applicable to more complex scenarios.

(4) In general, the term 'group' encompasses two meanings. The first refers to 'social groups', such as family units that consist of people with social ties. The second meaning of 'group' refers to people moving together due to a common goal, such as task-oriented groups, with no reference to social ties. In contrast to the stable relationship found in social groups, the relationship in task-oriented groups is temporary and may change dynamically over time. The 'groups' studied in this paper can partially but not fully capture the two meanings given above. We focused only on crowd evacuation dynamics involving social groups in an 'evacuation mode'. However, it would be interesting to explore the connection and transition between the social interaction mode and the evacuation mode. A future study on this subject is expected.

6. Conclusions

A crowd consists of both lone individuals and a large proportion of social groups. Group behaviour therefore cannot be ignored when simulating pedestrian crowd motion. In this study, a novel grouping method was implemented based on the SFM. A system of new parameters was developed to describe group characteristics, including the group harmony coefficient, the group cohesion coefficient and the group proximity coefficient. The proposed group model can reproduce the

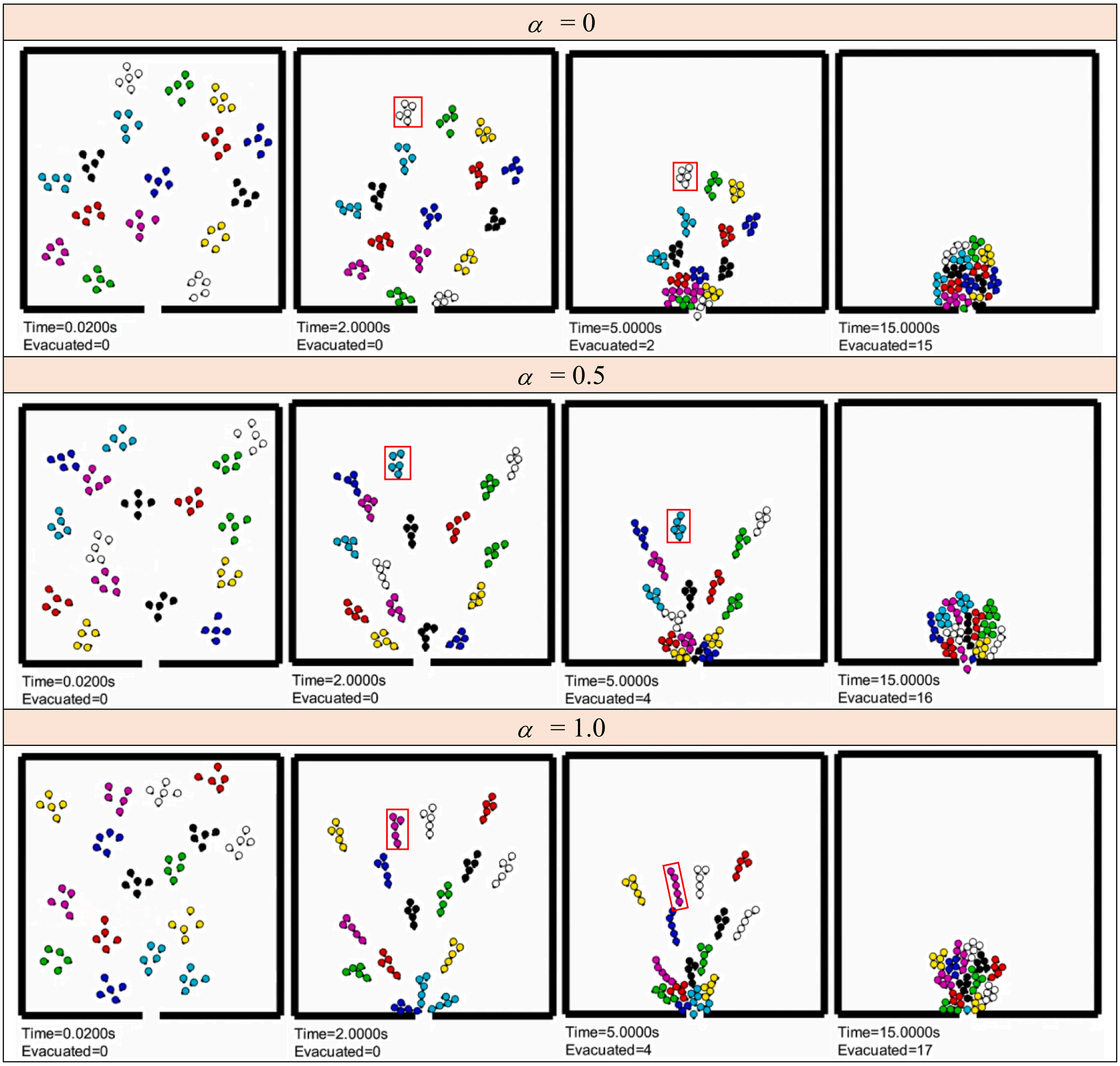


Fig. 12. Illustration of group shape during evacuation with various values of α (0, 0.5, 1). Group of five is taken as an example.

results of two group evacuation experiments. The overall evacuation performance and local group features were analysed, and the main results are discussed below.

(1) The group effect was positive for overall crowd evacuation time. A crowd composed of individuals tended to require more time than a crowd composed of groups in all simulated evacuation scenarios. A larger group had a shorter evacuation time when the exit width was 2, 3 or 4 m (rather than 1 m). When the exit width was 1 m, the advantage belonged to a larger group with a slower desired speed or a smaller group with a faster desired speed.
(2) The flow intermittence around exits of various widths was analysed. The average time interval remained nearly unchanged over time (approximately 0.84 ± 0.059 s, 0.27 ± 0.042 s, 0.19 ± 0.041 s and 0.17 ± 0.037 s for the exit widths of 1, 2, 3 and 4 m, respectively). The evacuation process with a narrow exit was notably slower, less smooth and fluctuating. Enlarging the exit from 1 to 2 m facilitated the overall evacuation significantly, whereas the promoting effect was not substantial when the exit was larger than 2 m.
(3) The group shape was approximated as a rectangle. The aspect ratio and normalised area were the two key components for evaluating local group features. It was found that a group would form a rectangle oriented along the moving direction during evacuation. The existence of a group leader tended to increase the aspect ratio. Larger groups seemed to have a smaller aspect ratio but required more space per person during evacuation. The stable normalised areas for groups of four, five and eight were 0.12, 0.14 and 0.18 m^2 per person, respectively.

The group model developed in this study can simulate group behaviour in a pedestrian crowd and accurately reproduce experimental results. The important findings for groups give us new insights in optimising crowd evacuation strategies in emergencies. For example, it is

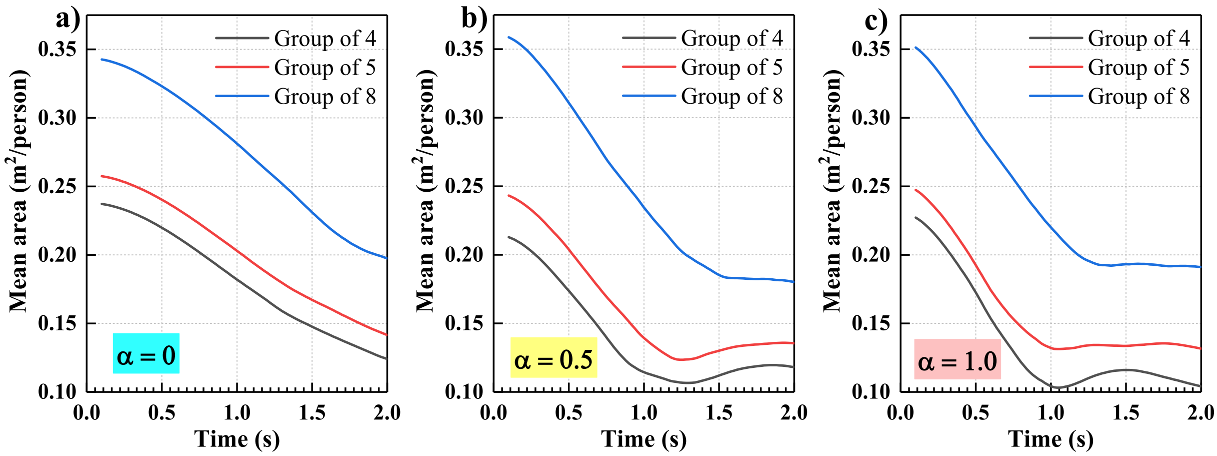


Fig. 13. Mean area of group rectangles with various values of α.

suggested that the group behaviours have a positive influence on evacuation when the space is large and has a wide exit, from a view of minimizing the overall evacuation time. Although this study revealed some critical features of social groups in an evacuation, it should be recognised that group behaviours are indeed very complex. Deep questions must be answered, such as who will emerge as a leader and with what kind of personality; how smaller groups will form a larger group and, in turn, how a larger group will split up into smaller groups; how different navigation rules of pedestrians through the exits will influence the group pattern. We will attempt to address these questions related to social group dynamics in future work.

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