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Effect of exit location on flow of mice under emergency condition*

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The evacuation of crowds in a building has always emerged as a vital issue in many accidents. The geometrical structure of a room, especially the exit design has a great influence on crowd evacuation under emergency conditions. In this paper, the effect of exit location of a room on crowd evacuation in an emergency is investigated with mice. Two different exits are set in a rectangular chamber. One is located in the middle of a wall (middle-exit) and the other is at the corner of the chamber (corner-exit). Arching and clogging are observed in the flow of mice. The result based on the escape trajectories of mice shows a dynamic balance in the arch near the exit wherever the exit is located. We demonstrate that the occupant position in the arch has an effect on the escape sequence of mice. At a low stimulation level, the narrow middle-exit is more effective in increasing the flow rate of mice than the narrow corner-exit. However, the opposite result appears when the exit becomes wider. At a high stimulation level, the effect of exit location on flow of mice tends to be weakened. The results suggest that the specific level of stimulation needs to be taken into account when optimizing the evacuation efficiency of a crowd through the geometrical structure of a room.

Keywords: exit location, evacuation, mice, stimulation level

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1. Introduction

With the acceleration of urbanization and the increase of buildings in cities, the evacuation of pedestrians in disaster situations such as a fire in limited space becomes a widely studied topic. The exit design has a great influence on the evacuation under emergency conditions. However, the study of collective behavior of humans in this situation is extremely difficult[1] for the following reasons. First, the chaos of the scene under panic often results in recording failure, which does not help to acquire authentic data from real disasters. Second, creating a similar condition to a real emergency with experimental methods is almost impossible due to moral and legal constraints in human society. Third, the volunteers recruited for experiments are usually too relaxed to behave like affected people who are panicking. Although many mathematical models have been explored to simulate crowd evacuation,[2–10] physiological and psychological factors which affect the individual and collective behaviors are difficult to simulate.[11–13] Explaining the complex interaction between a person and the surrounding environments and that between two people requires combining knowledge of multiple disciplines. Therefore, researchers have been searching for more suitable alternative entities to humans in experimental studies of crowd evacuation.

Using non-human biological entities such as ants,[14–22] sheep,[23,24] mice,[25–33] and woodlice[34,35] has become a good choice to understand human behavior under emergency conditions. Among them, mice as a model organism widely used in medical and behavioral research, is shown to have good similarities to humans in physiological structure and stress reaction, especially under panic.[36,37] The results from the experiments on mice can provide an insight into the study of particle flow through a bottleneck and is opening a new field of crowd dynamics.

Shiwakoti *et al.*[8,38] compared the flow of ants through an exit at the corner with that in the middle of a wall. They found a higher evacuation efficiency of ants through the corner one and attributed it to the incoming direction of an individual. More studies have been conducted about the location of exit using mice. Wu *et al.*[32] designed a rectangular room (0.3 m × 1.5 m) for the evacuation of mice stimulated by smoke and found that changing the location of middle-exit from a wall of 0.3 m to another wall of 1.5 m can improve the evacuation efficiency of mice significantly. Chen *et al.*[31] studied the escape time of mice through a corner exit (without fixed short part in Fig. 1 in this article) and center exit (middle-exit in this article) at different levels of stimulus of smoke. They found that the center exit was more efficient in a low competitive evacuation condition, whilst the corner exit was more efficient in a high/medium competitive evacuation condition. Besides, Saloma *et al.*[25] explored the effect of separation distance by changing the locations of two exits using mice from a water pool to dry land. We should note that there exist many differences in the experimental design compared with the experiments above with smoke, such as the

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unit of exit width, stimulus type, and movement manner of the mice.

Although the results of numerical simulations and experiments above are available to investigate the effect of exit design on the evacuation process, many studies are neither comprehensive nor thorough, especially in the perspective of multiple disciplines. It greatly restricts the application of findings from these research to human society. Therefore, we explore the effect of exit location on the flow of mice under emergency condition in this paper. We refer to the exit in the middle of a wall as the middle-exit, and the exit near the end point of a wall as the corner-exit. This corner-exit is designed, as most doors of rooms in human society are generally set near the end point of a wall rather than in the absolute corner of a room. Smoke[27–29,31,33] generated by burning joss sticks is used as stimulus in the escape of mice.

A dynamic balance in the arch in front of the middle- and corner-exit is found through the escape trajectories of mice. We demonstrate that the occupant position in the arch has different effects on the escape sequence of individuals in two scenarios. Next, we compare the difference of escape time and mean flow rate of mice through the middle- and corner-exit and analyze the time interval, body position, and density map of movement of mice in four scenarios. We conclude that the effect of exit location on mouse flow is related to the exit width. Furthermore, we study the flow of mice at a high level of stimulus to explore whether such an effect still exists.

2. Materials and methods

The materials and methods were introduced by Zhang *et al.*[33] Some improvements have been made based on the prior design as indicated in the following.

2.1. Mice system

Naïve female ICR mice were purchased form Animal Model Research Center of Nanjing University, China. The license number is SCXK (Su) 2015–0001. 160 ± 4 mice participated in the experiment. Their age ranged from 8 weeks to 12 weeks. All mice were reared at 20–25 °C under a natural light–dark cycle. Their average body length, height, hip width, body weight were measured to be 9.63 ± 0.18 cm, 2.72 ± 0.11 cm, 3.07 ± 0.09 cm, and 21.6 ± 1.3 g, respectively.

2.2. Experimental setup

As shown in Fig. 1, the experimental equipment consisted of three parts: smoke generation zone, evacuation zone, and safety zone. In the smoke generation zone, a certain number of non-toxic joss sticks (25 g/bunch) used for sacrifice in China were put into a combustion reactor. The number of joss sticks (φ) within limits was used to quantify the stimulation level in the experiments.[29,31] The low stimulation level was created by one bunch of joss sticks ($\varphi = 1$) while the high stimulation level by four bunches of joss sticks ($\varphi = 4$). The video records showed that the mice neither lost their way nor lost their ability to escape when $\varphi = 1$ or 4. An air pump was set to provide oxygen and promote the spread of smoke into the chamber.

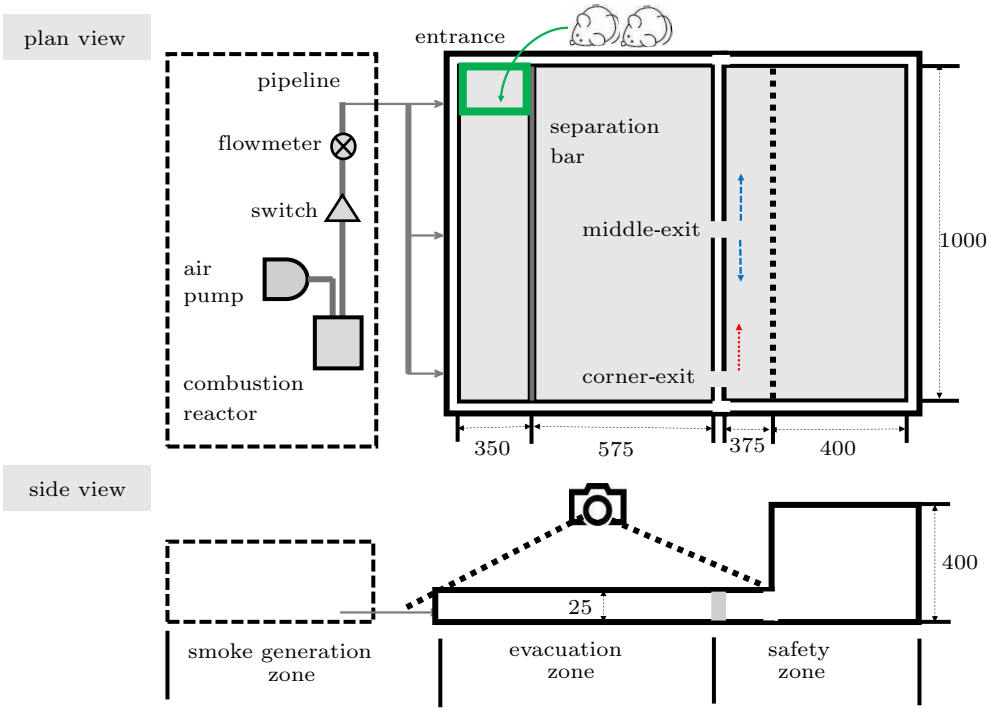


Fig. 1. Experimental setup (dimensions in units of mm). The wall between the evacuation zone and safety zone is divided into two parts by the middle- or corner-exit. With the increase of exit width as indicated by the dotted arrow, the corner-exit divides the wall into a fixed short part (2.5 cm) and a gradually shorter part, while the center of the middle-exit is fixed.

In the evacuation zone, the entrance was the landing point of mice into the chamber. A mobile separation bar was used to restrict the scope of activities of mice until the evacuation began. Two width-adjustable exits were set on the wall away from the stimulus. The exit width of 2 cm was defined as a unit width expressed as $w = 1$. This width allows one mouse to pass easily and prevent two or more to pass side by side. The width of the exit was set as follows: $w = 1$ (2 cm), $w = 1.5$ (3 cm), $w = 2$ (4 cm), $w = 3$ (5 cm), and $w = 4$ (8 cm). The depth of the exit was 2.5 cm. The heights of evacuation zone and part of safety zone were set to be 2.5 cm because this design can prevent mice climbing over others during escape, so the evacuation was restricted in a bi-dimensional plane.

In addition, the bottom and walls in the evacuation zone were made of aluminum alloy with good corrosion resistance and deformation resistance. The cover was made of highly transparent polymethylmethacrylate (PMMA). One camera (digital sampling rate = 25 frames per second) was used to record the process of evacuation.

2.3. Experimental methods

Mice always move to the exit that they are familiar with in a period under stress conditions.[31] To avoid the effect of memory of the exit location, we divided the mice into two groups: one group was named group-M for the scenario with middle-exit and the other was called group-C for the scenario with corner-exit. Two groups of mice were arranged to walk freely in the experimental chamber without stimulus several times in the first two days to become familiar with the arena. Then, training was conducted before formal test.[26,28,33] After several days of training, the mice gained the skills of minimizing potential injury in the escape.

The protocol of training or formal test is as follows.
(i) Open the middle- or corner-exit and lock its width.
(ii) Transfer mice from holding cages into the experimental chamber through the entrance.
(iii) 3 s later, put the burning joss sticks into the combustion reactor and open the air pump (220 L/h).
(iv) 15 s later, take the separation bar away and allow mice to escape from the evacuation zone to the safety zone (the open time of the separation bar is defined as zero-time).
(v) When most of mice have arrived at the safety zone except those stranded,[28,31,33] block the exit and cut off the smoke (the trial is finished).
(vi) Give the mice 15–20 min to have a rest and provide them with food and water. The still exhausted mice are replaced.
(vii) Between two trials, eliminate the smoke with a fan and remove the mice excrements. Wipe the chamber and dry it by fan.

Table 1 shows all treatment conditions. We conducted four repeated trials for each treatment condition. Each group of mice was subjected to 8 trials a day followed with a day off to regain their strength.

Table 1. Treatment condition for each group.

Group name	Exit category	Panic parameter	Exit width
Group-M	middle-exit	$\varphi = 1$	$w = 1, 1.5, 2, 3, 4$
Group-M	middle-exit	$\varphi = 4$	$w = 1, 1.5, 2, 3, 4$
Group-C	corner-exit	$\varphi = 1$	$w = 1, 1.5, 2, 3, 4$
Group-C	corner-exit	$\varphi = 4$	$w = 1, 1.5, 2, 3, 4$

2.4. Data analysis

Through the video-playing software under slow motion mode, we obtained the time series of the escaped mice. The mouse whose hip completely passed through the exit was regarded as an escaped one. In all trials, the number of stranded mice ranged from 0 to 8. Out of uniform and convenient data processing, the first 70 mice were counted. The position points and trajectories of the mice were captured by a self-programming software named TrackStat (Tracking and Statistics).

3. Results and discussion

The results about the middle-exit are obtained through analyzing the data from Ref. [33].

3.1. Arch formation

The characteristic features of escape panics were summarized by Helbing *et al.*,[3] such as physical pushing, uncoordinated moving through a bottleneck, arching and clogging, jamming, and herding behaviors. These features provide a criterion to evaluate whether a model of collective behavior is a good medium to study crowd dynamics under emergency conditions. In this research, we find that the mice in life-and-death situations present a series of features described above. In the following, we explain it by a typical scenario ($w = 1$, $\varphi = 1$) where only one mouse is allowed to pass through the exit.

After the mice are transferred from holding cages into the experimental chamber through the entrance, they walk randomly and are distributed uniformly in the space separated by the bar. Once suffering from smoke stimulus, they become anxious and escape immediately into the evacuation zone when the separation bar is removed. The results show that several mice herd into the corner in the scenario with middle-exit as shown in the red solid circle in Fig. 2(a). This phenomenon can be explained as follows. First, feeling safe in a corner and congregating around it are natural instincts of mice.[39,40] Second, the exit blocked by the mice arriving earlier makes it harder for others relying on visual spatial memory to locate the exit.[41,42] Third, mice exhibit the herding behavior,[3] despite the previous training. Some individuals follow others blindly and even walk in a wrong direction instead towards the exit in the middle of the wall as shown in the red solid circle in Fig. 2.

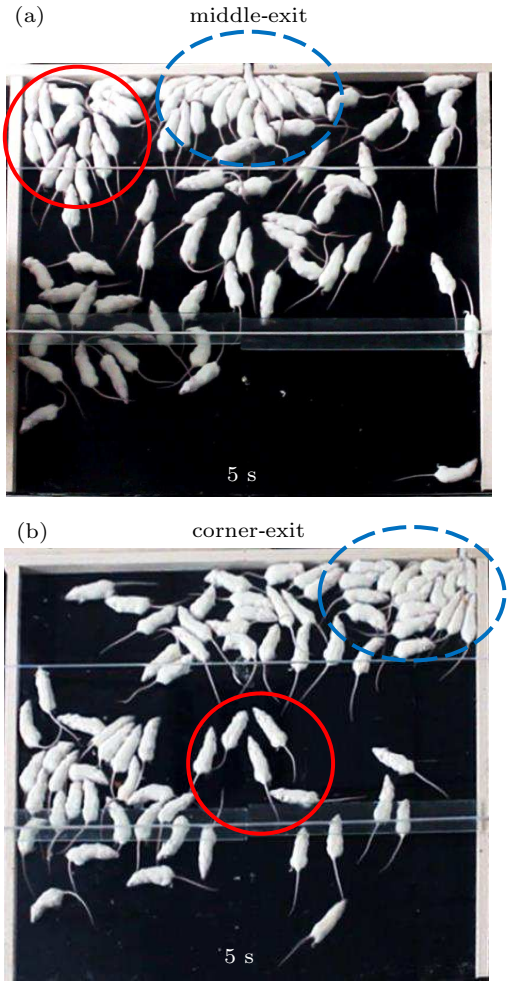


Fig. 2. Snapshots of mice escaping through the middle- or corner-exit ($w = 1$, $\varphi = 1$) at 5 s. Dotted circle represents mice running to the exit immediately with selfish evacuation behavior. In panel (a), the solid circle shows mice herding into a corner. In panel (b), the solid circle shows mice walking in a wrong direction by blindly following.

An arch is formed in front of the middle-exit in our experiments, as shown in the blue dashed circle in Fig. 2. In the scenario of the corner-exit, the arch is squeezed into sector shape. With the accumulation of individuals at the exit, clogging arises. In our record, some mice choose to wait at the exit while others walk away from the exit to search for an alternative route to escape, which means that there is a dynamic balance in the collection of mice in the arch.

To study the arch formation, we randomly capture the escape trajectories of some mice through the middle- or corner-exit ($w = 1$, $\varphi = 1$). As shown in Fig. 3, some mice (black trajectory) could escape to the exit in a nearly direct path and competed with others to struggle for the chance to escape. This phenomenon reflects the selfish evacuation behavior[16] or impatient behavior[43] as reported in previous studies where water was designed to be the stimuli in the escape of mice.[25,26] Nonetheless, some mice preferred to move along the boundary of the chamber, which was called wall-seeking behavior[25] or wall-following tendency.[44] As a consequence, they lagged behind others from the beginning.

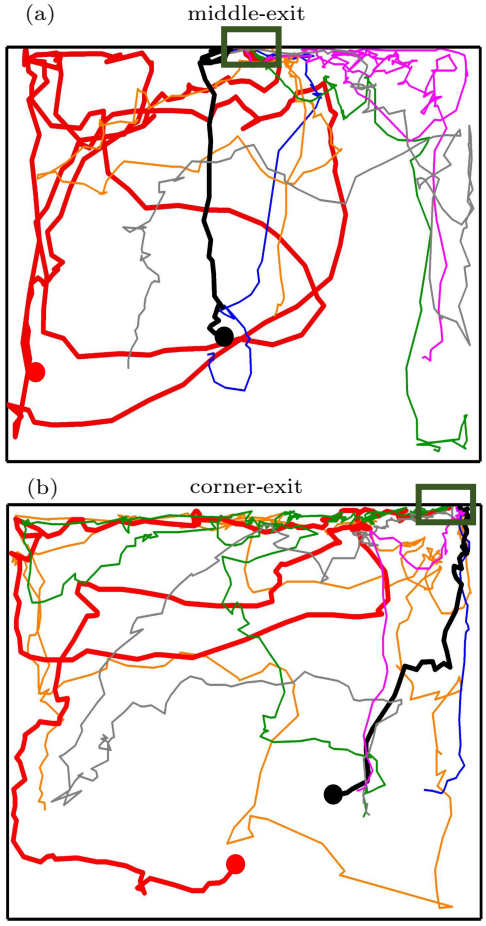


Fig. 3. Several typical trajectories of mice through the (a) middle- or (b) corner-exit ($w = 1$, $\varphi = 1$) in one repetition. The black trajectory shows a mouse moving to the exit in nearly direct path while the red trajectory shows a mouse with wall-seeking behavior.

3.2. Escape sequence in the arch

Although the arching and clogging phenomena near the exit have been reported many times, the details of individual behavior in the arch near the exit are still unclear. The frequency distribution of burst size and time interval (time lapse or headways)[23,24,28,29,32] and the density evolution[33] of the crowd near the exit were studied based on macroscopic analysis, ignoring individual characteristics and the relations among them. In this section, we compare the escape sequence of mice in the arch near the middle- and corner-exit in one typical scenario ($w = 1$, $\varphi = 1$).

We divide the arch into three regions by a certain angle as shown in Fig. 4. Near the middle-exit, the arch is divided equally into Mid-A, Mid-B, and Mid-C. Near the corner-exit, the arch is divided into Cor-A, Cor-B, and Cor-C. It should be noted that the angle of the corner-exit is π /4, as it is not in the absolute corner of the chamber. The video frames show that wherever the exit is located, each region is able to accommodate two mice in the very front. Through the video under slow motion mode, an unfair chance for mice to pass through the exit is found. The mice in Mid-B even make room for those from Mid-A or Mid-C. Besides, the escape sequence is different between the two exit locations.

In this subsection, we collect the data in the period from the 11th to the 70th for the case of mice escaping through the exit when the arch maintains a steady shape. We record the escape time of each mouse and the region it came from as depicted in Figs. 5(a) and 5(b). To further investigate the priority of each region, a statistical analysis for frequency is conducted. As shown in Fig. 5(c), the results of T-tests indicate that the frequency of mice from Mid-A and Mid-C is significantly higher than that from Mid-B. We can conclude that near the middle-exit, the mice whose positions are closer to the wall or body along the wall are easier to escape from the evacuation zone. However, for the corner-exit, the frequency of mice from Cor-C is the highest of the three as shown in Fig. 5(d). Therefore, mice whose bodies are along the wall and towards the exit are at a dominant position when they pass through the corner-exit.

We speculate that the wall with stable and smooth surface is beneficial for mice to move forward along it. In contrast, the neighbors could resourcefully push them and even distort their bodies. For the corner-exit, the mice in Cor-C move forward along the wall and do not need to change their bodies' direction when passing through the exit, so they are in a dominant position.

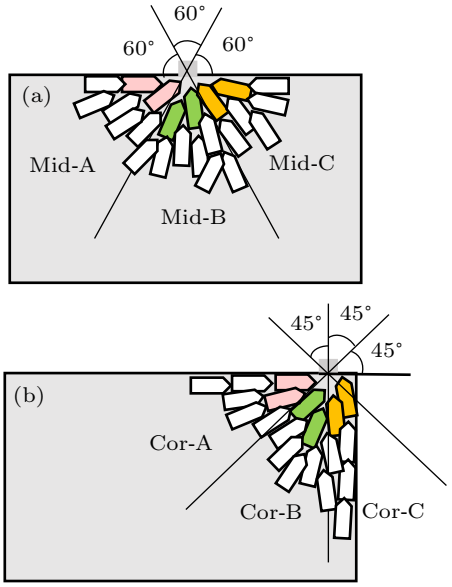


Fig. 4. Schematic diagram of regional division for each scenario: (a) middle-exit, (b) corner-exit. The colored bars in the chamber represent the mice in the very front.

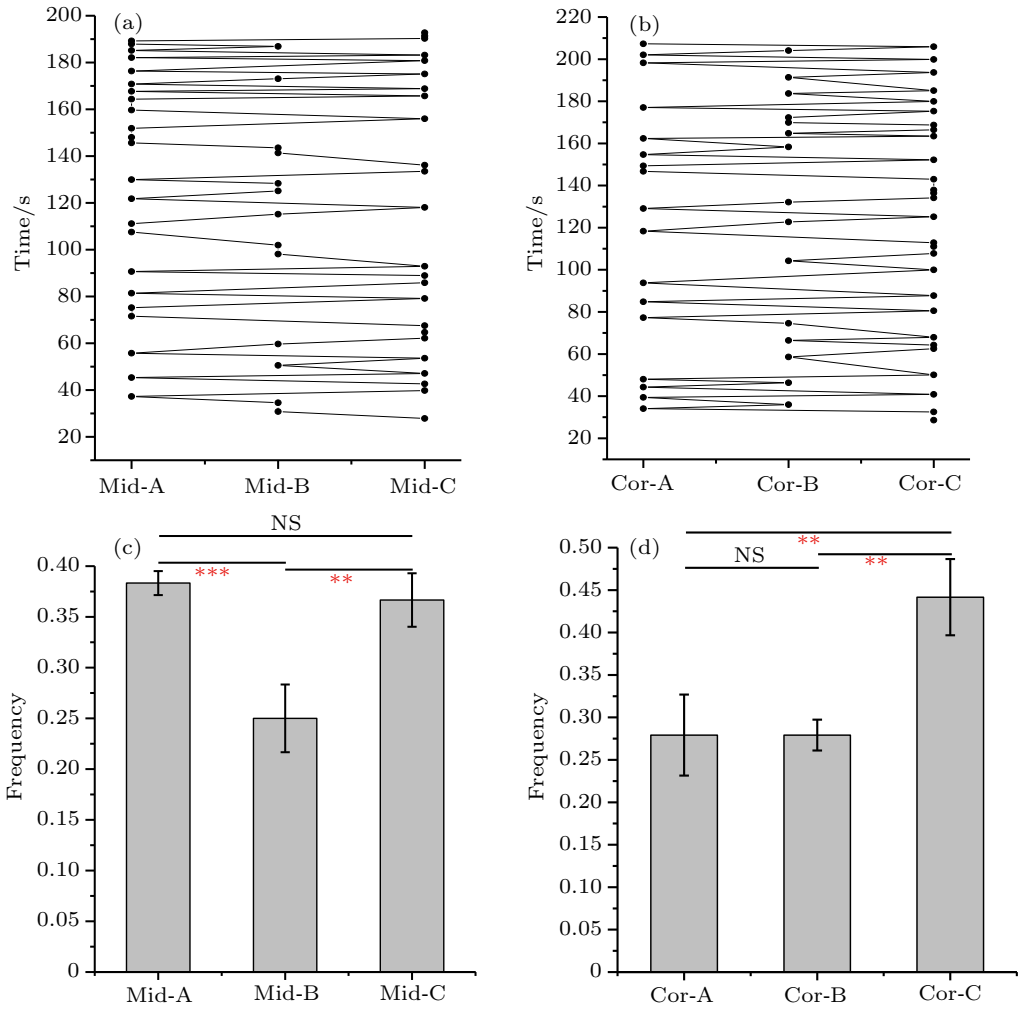


Fig. 5. Escape sequences of mice passing through exits in two scenarios. In panels (a) and (b), tandem dot represents a mouse belonging to a certain region escaping through an exit in one repetition. Panels (c) and (d) show statistical results of frequency in all repetitions. In T-test, *P*-values below 0.05, 0.01, 0.001 are indicated by one, two, three stars, respectively. NS stands for no significance.

3.3. Time evolution and mean flow rate

We have demonstrated that the arch is formed with dynamic balance in front of the middle- and corner-exit but the escape sequences and dominant positions in the arch are different between these two scenarios. In this subsection, we study the time evolution and the mean flow rate of mice passing through the middle- and corner-exit with different widths.

The individual mice are numbered as $i \in [1, N]$. The escape time (t) of each mouse (t_i) is analyzed with different exit widths ($\varphi = 1$). The total evacuation time is determined by the escape time of the 70th mouse (t_{70}). As shown in Fig. 6(a), the total evacuation time of mice escaping through corner-exit is longer than that from middle-exit when $w = 1$, 1.5, 2, or 3. Nevertheless, the opposite holds when $w = 4$. It can be demonstrated by the mean flow rate (J) calculated as

$$J = \frac{N-1}{t_N - t_1}, \quad N = 70. \tag{1}$$

T-tests are performed to compare the J values for mice passing through middle- and corner-exit with different widths as shown in Fig. 6(b). A critical value between $w = 3$ and 4 indicates that an optimum location design of exit is relative to the width of the exit.

The time interval (Δt) between two consecutive escaping mice can reveal the flow intermittency in the collective movement. In this subsection, we analyze the frequency distribution of Δt.

As shown in Fig. 7, when $w = 1$, two exits have similar frequency distributions of Δt. The Δt concentrates to 2–4 s, which means that severe clogs happen frequently in the flow of mice. When $w = 2$, several long intervals indicate that more clogs happen near the corner-exit than that near the middle-exit. However, when $w = 4$, an opposite scenario can be found.

We respectively analyze the positions of mice in the evacuation zone at different time points when $w = 2$ and $w = 4$ through tracking the snout of the mouse in the record.[45] As shown in Fig. 8, the mice herd into the corner wherever the exit is located as proposed in Subsection 3.1. We conclude that the mice's preferential movement to corner can relieve the pressure of high density near the narrow middle-exit while reducing the utilization of the wide middle-exit with higher door capacity.[33,46,47] However, the opposite holds in the flow of mice through corner-exit.

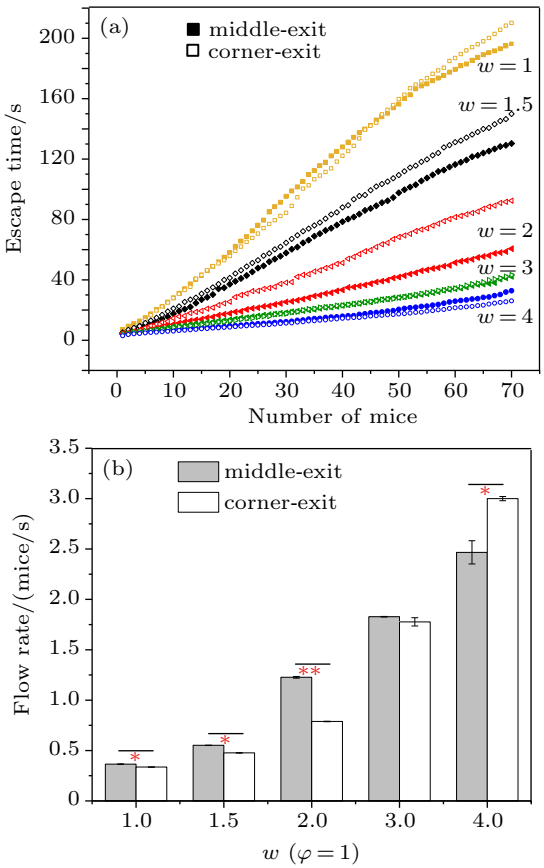


Fig. 6. (a) Time evolutions and (b) mean flow rates in different conditions. In T-test, P-values below 0.05, 0.01, 0.001 are indicated by one, two, three stars, respectively. Columns with no marked stars represent no significant difference between them.

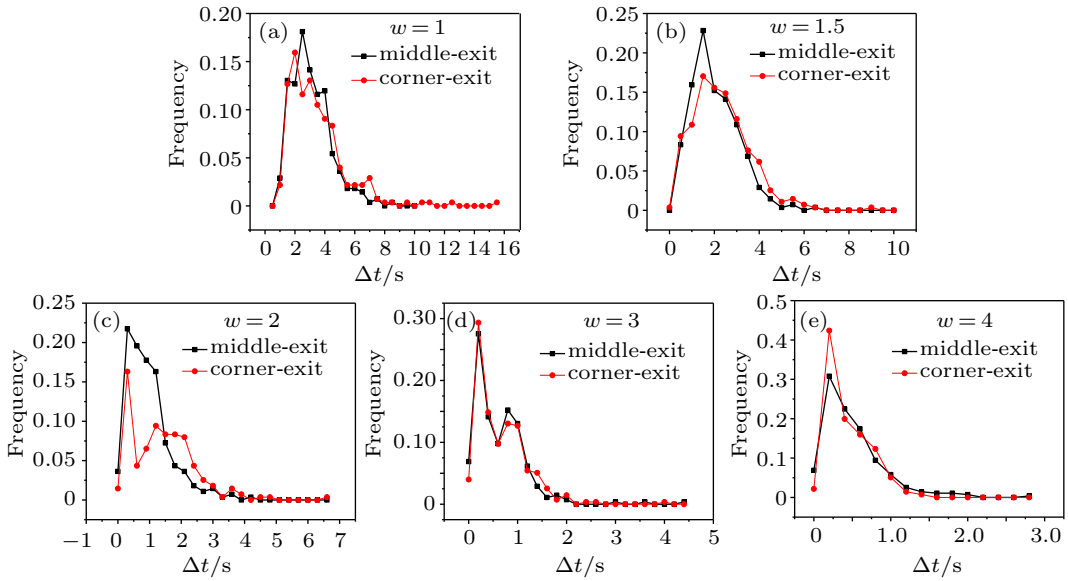


Fig. 7. Dependence of frequency on time interval in all repetitions (a)–(e).

To further depict the movement preference of mice in the whole process of evacuation, the hot area of movement is presented by the density map of the position of mice. The complete evacuation zone is divided into grids of 2 cm × 2 cm. We capture the positions of 20 mice randomly chosen by the time gradient of 0.2 s. Each position falling into a grid is recorded and depicted by the density map as shown in Fig. 9. When $w = 2$, a hot area of movement can be found not only near the middle-exit but also in the corner where no exit is located, while only one hot center can be found at the corner-exit. The density of positions in this hot area reaches above 22.5 mice/cm^2, which is 2.5 times that at the middle-exit (around 9.0 mice/cm^2). When $w = 4$, due to the high door capacity which allows more than four mice to pass through it side by side, most mice escape quickly without searching for an exit along the wall. Therefore, the density of positions in the hot area decreases to around 6.26 mice/cm^2 (middle-exit) and 4.26 mice/cm^2 (corner-exit), respectively.

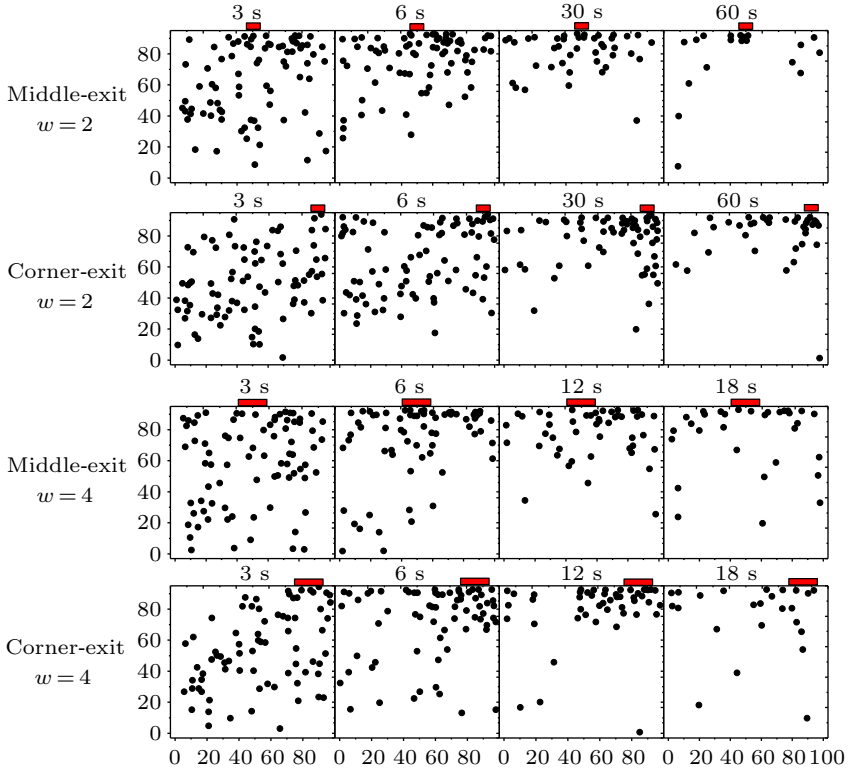


Fig. 8. Distributions of body positions of mice in the evacuation zone at different time points in four scenarios. Rectangle represents an exit in the wall and a square represents the position of the mouse.

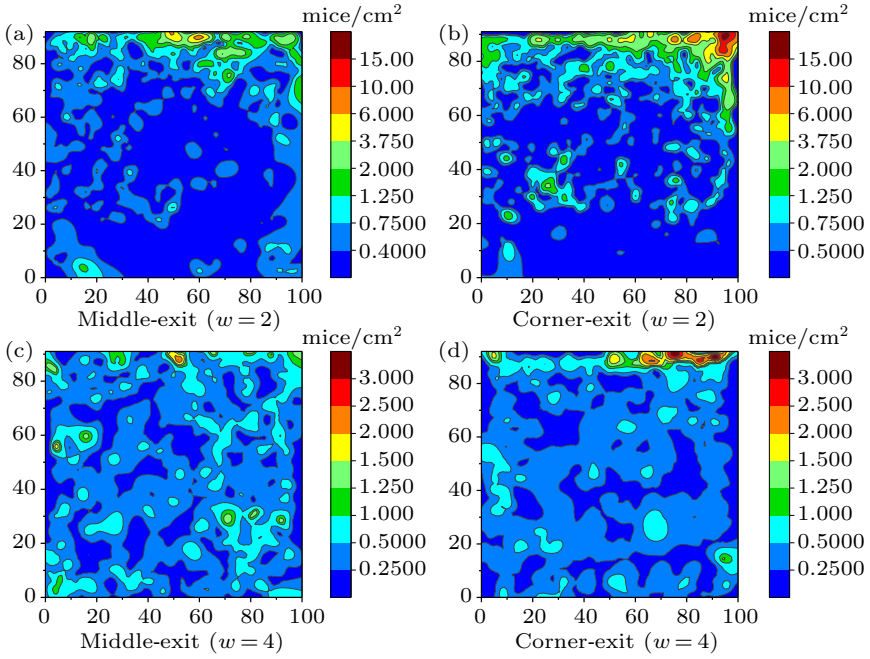


Fig. 9. Density maps over the complete evacuation zone in the whole process of mice evacuation in four repetitions of each scenario: (a) middle-exit ($w = 2$), (b) corner-exit ($w = 2$), (c) middle-exit ($w = 4$), (d) corner-exit ($w = 4$).

We conclude that both the exit location and the natural instinct of mice can influence the escape path and the density near the exit under emergency conditions, thereby determining the escape time evolution or mean flow rate of the crowd of mice.

3.4. Evacuation at high stimulation level

We have already demonstrated previously that the middle-exit is more effective than the corner-exit when the width is narrow, but not in the case of a wider exit at low stimulation level ($\varphi = 1$). Here, we study the effect of exit location at a high stimulation level ($\varphi = 4$) where the smoke concentration is high enough but not obviously damaging to mice. The escape time and the mean flow rate of mice are shown in Fig. 10(a). The T-tests are performed to compare the mean flow rate of mice through the middle-exit with that through the corner-exit. The results in Fig. 10(b) show that there are no significant differences among different locations of exit.

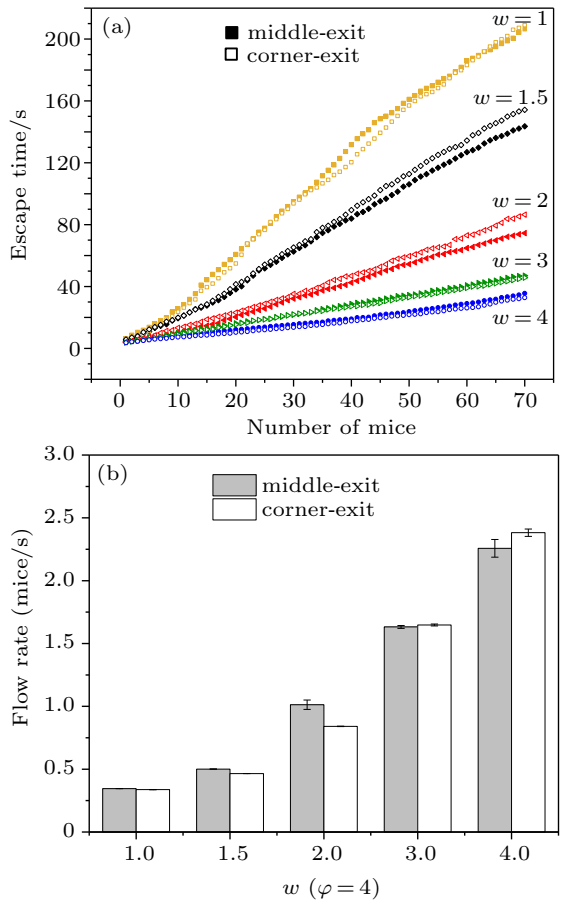


Fig. 10. (a) Escape time and (b) mean flow rates in different conditions. Columns marked with no stars are of no significant difference between them.

To compare the mean flow rates of mice in two stimulation levels, we define the middle-exit as the standard reference and introduce a relative ratio (R_J) of the mean flow rates in different conditions. R_J is calculated from the following equation:

$$R_J = J_C/J_M, \tag{2}$$

where J_C and J_M are the mean flow rates of mice passing through corner- and middle-exit, respectively. As shown in Fig. 11, when φ is 1 or 4, $R_J < 1$ and keeps away from the baseline with the increase of w from 1 to 2. However, R_J returns to the baseline when $w = 3$ followed by $R_J > 1$ when the exit becomes wider. Moreover, the results highlight that the effect of exit location on flow of mice tends to be weakened when φ increases from 1 to 4. We can speculate that the effect of exit location can be covered up by the level of emergency among mice.

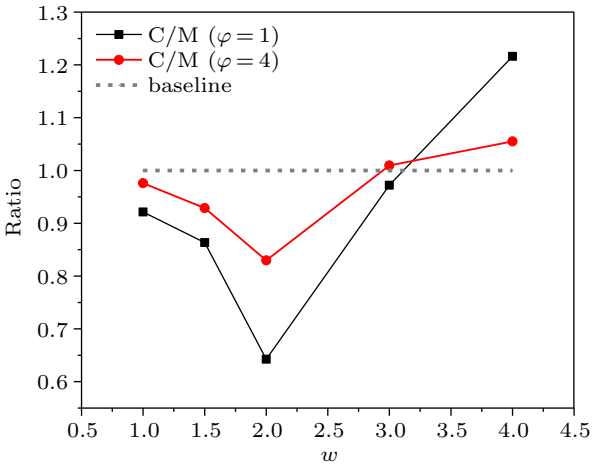


Fig. 11. Relative ratios of mean flow rate in different conditions. Baseline represents $J_C = J_M$.

Shiwakoti *et al.*[8] and Shiwakoti and Sarvi[38] explored the effect of the location of a single exit on the flow of Argentine ants stimulated by citronella and demonstrated that the corner-exit was more effective than the middle-exit. The width of their exit was 2.5 mm equal to the unit width ($w = 1$) in our study. They reported that ants escaping along both sides of the wall had to change their directions when they passed through the middle-exit, and thus resulting in conflicts with the ants moving straight towards the exit. That is, they explained the difference between the two exits in their experimental conditions through the ant's natural instinct including the wall-seeking behavior. Mice share the wall-seeking behavior with ants, but they can form an arch near the exit with obvious jamming or clogging, which is more appropriate in modeling human behavior. Besides, we note that our corner-exit is not in the absolute corner in a room, but the corner-exit approaches the absolute corner-exit as it becomes wider. It may be coincident with the results of Shiwakoti *et al.* that the corner-exit was more effective than the middle-exit.

Chen *et al.*[31] did a series of experiments on mice and reported that the center exit was more efficient in a low com-

petitive evacuation condition, but the corner exit was more efficient in a high or medium competitive evacuation condition. The seemingly contradictory results may be due to the following reasons: first, their corner exit has no fixed short part in Fig. 1 in this article, and is also different from the absolute corner-exit in the experiments of Shiwakoti *et al.*;[8,38] therefore, the body and moving directions of individuals in the arch are different; second, the quantitative method of stimulation itself and the division of degree of stimulation are inconsistent between two studies.

Wang *et al.*[48] explored the effect of exit location on pedestrians considering different exit widths. They set three exit locations, i.e., the exit in the middle, the exit in the corner, and the side exit (the center of the exit is located 1.0 m away from the side wall). The exit widths 0.6 m, 0.8 m, 1.0 m for adults can be expressed approximately by $w = 1, 1.5, 2$ in our study. Their results showed that the exit in the middle was significantly more effective with increasing mean flow rate of humans than the side exit and the difference gradually decreased as the exit became wider. It is consistent with our results to some degree. However, because of many differences between these two evacuation systems, understanding the collective behavioral similarities and dissimilarities under emergency conditions between mice and humans still needs further study.

4. Conclusion

The effect of exit location on evacuation under emergency conditions is investigated through a series of mice experiments in this paper. Two different exits, i.e. middle- and corner-exits are adopted to form a bottleneck in the evacuation of mice. The results based on the escape trajectories of mice show a dynamic balance in the arch near the exit wherever the exit is located. We further explore the individual information in the arch and find that the occupant positions of mice in front of the exit have an effect on their escape sequence. It can be confirmed that mice exhibit selfish behavior just like human under emergency conditions.

At a low stimulation level, the middle-exit is significantly more effective in increasing the mean flow rate of mice than the corner-exit when the exit is narrow. However, an opposite result appears when the exit becomes wider. We conclude that the exit location and the natural instinct of mice can influence the escape path and the density near the exit. Then, both the move path and the density in front of the exit further affect the escape time evolution and the mean flow rate of the mice.

Furthermore, we conduct a series of experiments on mice at a high stimulation level. The effect of exit location on flow of mice tends to be weakened, which indicates that the effect of some geometric structural factors could be covered up by designing the stimulation level. The results remind us to consider specific emergency conditions when optimizing the maximum outflow through adjusting the architectural elements.

This paper can deepen our understanding of collective behavior of mice under emergency conditions and contribute to the study of pedestrian evacuation dynamics through animal models in different architecture designs. Besides, understanding the behavioral similarities and dissimilarities among human and non-human species is rather significant to achieve optimal benefits and lowest casualties of rooms in an evacuation system.

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