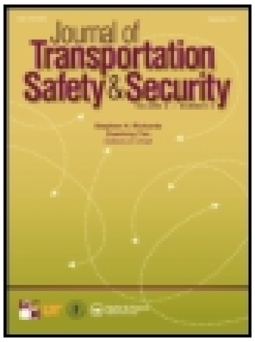

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Empirical investigation of child evacuation under non-emergency and emergency situations

Liang Chen[a], Tie-Qiao Tang[b], Ziqi Song[c], Ren-Yong Guo[d], and Hai-Jun Huang[d]

[a]Beijing Key Laboratory of Traffic Engineering, Beijing University of Technology, Beijing, China;
[b]School of Transportation Science and Engineering, Beihang University, Beijing, China;
[c]Department of Civil and Environmental Engineering, Utah State University, Logan, Utah, USA;
[d]School of Economics and Management, Beihang University, Beijing, China

ABSTRACT

In this study, we conducted a series of experiments to investigate child behavior during self-evacuation and guided evacuation under non-emergency and emergency situations. The properties of child flow dynamics are obtained through analysis of the experimental video recordings. It is found that under a non-emergency situation, the evacuation processes are orderly, and group and waiting behavior can be observed. Under an emergency situation, the evacuation processes become disorder, and running and pushing behaviors can be observed. Our analyses showed that the exit use is imbalanced under an emergency situation and that the guidance of teachers plays a positive role in the exit choice of children during an emergency evacuation process. The emergency degree has significant effects on the exit choice of children in self-evacuation. Our results also showed that the average evacuation time of children, flow rate, and average headway of the exit are less affected by the guidance of teachers and more affected by the emergency degree. The guidance of teachers affects some children's individual evacuation time. The findings can assist in improvements in the daily management and evacuation strategies for children, as well as the development and validation of child simulation models.

KEYWORDS

Child experiment; evacuation behavior; non-emergency; emergency

1. Introduction

The efficiency and safety of pedestrian evacuation from a public facility or building have become a significant research topic in the transportation science and public safety science fields (Haghani & Sarvi, 2018; Lovreglio, Ronchi, & Borri, 2014, Lovreglio, Kuligowski, Gwynne, & Boyce, 2019; Nagatani & Nagai, 2004; Vermuyten, Beliën, De Boeck, Reniers, & Wauters, 2016; Wu, Xu, Jia, & Qin, 2018). The majority of previous studies, which have been undertaken for a couple of decades, have focused on

CONTACT Tie-Qiao Tang tieqiaotang@buaa.edu.cn School of Transportation Science and Engineering, Beihang University, Beijing 100191, China.

exploring adult evacuation (Shi et al., 2009). Various observed self-organization phenomena, including arching blocking, faster-is-slower effect, and herding behavior during evacuation, have been studied extensively (Cao, Fu, Wang, Zeng, & Song, 2018; Gao, Qu, Li, Long, & Huang, 2014; Helbing, Farkas, & Vicsek, 2000; Kinateder, Comunale, & Warren, 2018; Lu, Chan, Wang, & Wang, 2017). However, research conducted in the area of child behavior during evacuation is limited.

Children from 0 to 14 years of age represent 16.8% of the population in China (National Bureau of Statistics of China, 2019). Children are considered a vulnerable population in society, and they typically need assistance during evacuation. Studies describing the behavior of children during evacuation have highlighted that age is a critical factor that affects evacuation dynamics (Fang, Jiang, Li, Qi, & Chen, 2019; Li, Zhang, Xia, Song, & Bode, 2019, Li, Zhang, Yang, Song, & Yuen, 2020; Zheng, Guo, Peeta, & Wu, 2020). Children's limited cognitive, psychological, and physical capabilities may lead to the possibility of unpredictable decision making when compared to adults. Hence, it is essential to conduct additional studies to develop a more comprehensive understanding of child behavior during evacuation.

Recently, researchers have begun to study child behavior during evacuation. Similar to studies on the evacuation of adults, child behavior during evacuation has been studied from two perspectives, that is, empirical studies (Cuesta & Gwynne, 2016; Hamilton, Lennon, & O'Raw, 2017) and simulation models (Klüpfel, Meyer-König, & Schreckenberg, 2003; Li et al., 2017). In terms of empirical studies, many studies focus on the review of evacuation drills, which take place in actual buildings. For example, Larusdottir and Dederichs (2011, 2012) presented data on 16 full-scale evacuation experiments made in 10 daycare centers. Kholshchevnikov, Samoshin, Parfyonenko, and Belosokhov (2012) provided evacuation data collected from eight kindergartens between 2008 and 2010. Cuesta and Gwynne (2016) presented data collected from five evacuation drills between 2011 and 2014 involving preschool, primary, and secondary schoolchildren from the same school. Najmanová and Ronchi (2017) presented data collected during two semi-announced evacuation drills conducted in the same preschool institution. Hamilton et al. (2017) described data from 12 full-scale evacuations of four primary schools. Fang et al. (2019) conducted an experiment on children evacuating from a kindergarten building, finding that the guidance of teachers, stairs or steps, and congestion on the transition platform have a significant influence on the children's evacuation process. Generally, these studies focused on measuring the travel speed on horizontal planes and stairs, as well as pre-evacuation time, total evacuation time, route use, and exit selection. The results obtained from these studies indicate that child behavior during evacuation differs from adult behavior, and the movement abilities of children are highly age-dependent. Furthermore, Ono and Tatebe (2004) conducted a survey on children's behavior during evacuation in Brazil and compared their results with data from Japan. Kholshevnikov, Samoshin, and Parfenenko (2009) provided the results of a questionnaire survey on fire victims and staff actions in cases of fire, and the results indicated that deaths of children and teenagers in fire fatalities in buildings where mass crowds had gathered might be due to poor staff training in fire safety. Daamen and Hoogendoorn (2012) conducted a group of experiments to investigate emergency door capacities for crowds consisting of children. Li et al. (2020) performed controlled laboratory experiments to investigate the dynamics of preschool children from three to five years of age passing through normal bottlenecks of different widths under high movement motivation. Gunter et al. (2020a, 2020b) investigated the evacuation flow of a school bus by conducting laboratory experiments with children. With respect to simulation models, researchers used parameters—especially pre-evacuation time, travel speed, route use, and flow rate through bottlenecks measured from the evacuation drills—as input data for simulation models (e.g., STEPS, Pathfinder, MassMotion) in order to assess the capability of these models to represent the movement of children (Capote, Alvear, Abreu, Cuesta, & Hernando, 2012; Cuesta, Abreu, Ancona, & Alvear, 2013, Cuesta, Ronchi, & Gwynne, 2015, Cuesta et al., 2017). These studies contributed to the understanding and quantification of children's behavior during evacuation.

In the abovementioned studies, children are naturally divided into groups (classes). These macroscopic properties of child movement measured from the evacuation experiment drills (e.g., travel speed, flow rate, density, and pre-evacuation time) are important elements in understanding child behavior, as well as in developing flow-based models to predict child movement dynamics and plan escape routes during evacuations. However, such properties only provide insights into some phenomena, such as congestion formation and jam transition. It is difficult to provide clear evidence and reasons behind those phenomena (Shahhoseini & Sarvi, 2019; Shi et al., 2016). Compared to those studies, we here investigate child evacuation behaviors under non-emergency and emergency situations from macroscopic and microscopic perspectives. Through the analysis of microscopic properties (e.g., headway through exits, individual evacuation time, and local interaction among children), we can gain insights into the possible causes of these global phenomena. And both microscopic and macroscopic properties are crucial in the development and verification of simulation models that intend to reproduce child behavior during evacuation. Besides, the aforementioned studies mainly focused on child behavior during guided evacuation, while self-evacuation experiments are rare, probably because of the risks they present. However, in reality, child evacuation without assistance is also observed in some situations because of the lack of staff. In addition, through the analysis of self-evacuation experiments of children, the natural behavior of children during evacuation can be observed.

In summary, although there have been some empirical and simulation studies conducted on child behavior during evacuation, the level of understanding of child behavior during evacuation is still relatively limited, and few studies have examined the microscopic and macroscopic properties of child movement during self-evacuation and guided evacuation under non-emergency and emergency situations. To gain greater insight into the understanding of child behavior during evacuation, in this work, we conducted a series of experiments on child behavior during self-evacuation and guided evacuation under non-emergency and emergency situations. Through the analysis of the experimental video recordings, exit choice, evacuation time, flow rate, headway at exit, as well as effects of emergency degree and teacher's guidance are obtained. The article is structured as follows: the next section presents a description of the experiments. The detailed results from the experiments are then analyzed. The discussion and conclusions are presented in the final section.

2. Experiments

2.1. Experiment setup

The experiments were performed in a classroom of the Lehai Primary School in Xiamen, Fujian, China, in June 2017. A total of 52 children (31 male and 21 female) ranging from 9 to 11 years of age and one teacher participated in the experiments. The children belonged to the same class in grade 3, and the average age was 10.04 years. They were familiar with the classroom layout since they had been studying in this classroom for two months. The school conducts one evacuation drill every year. Therefore, to some extent, they were also familiar with the evacuation procedure. In addition, the experiments were performed with the consent of participants' families and the school.

The classroom layout is shown in Figure 1. Two exits are located on the north wall close to the west and east walls, respectively. Each exit is 0.8 m wide. A lectern and 52 pairs of chairs and desks are placed in the classroom. The lectern and the desks are denoted in the schema by light gray rectangles, and the initial positions of the children are denoted by green circles and are numbered from 1 to 52.

Since the goal of our experiments was to investigate child behavior during self-evacuation and guided evacuation under non-emergency and emergency situations, the participants were asked to perform four sets of

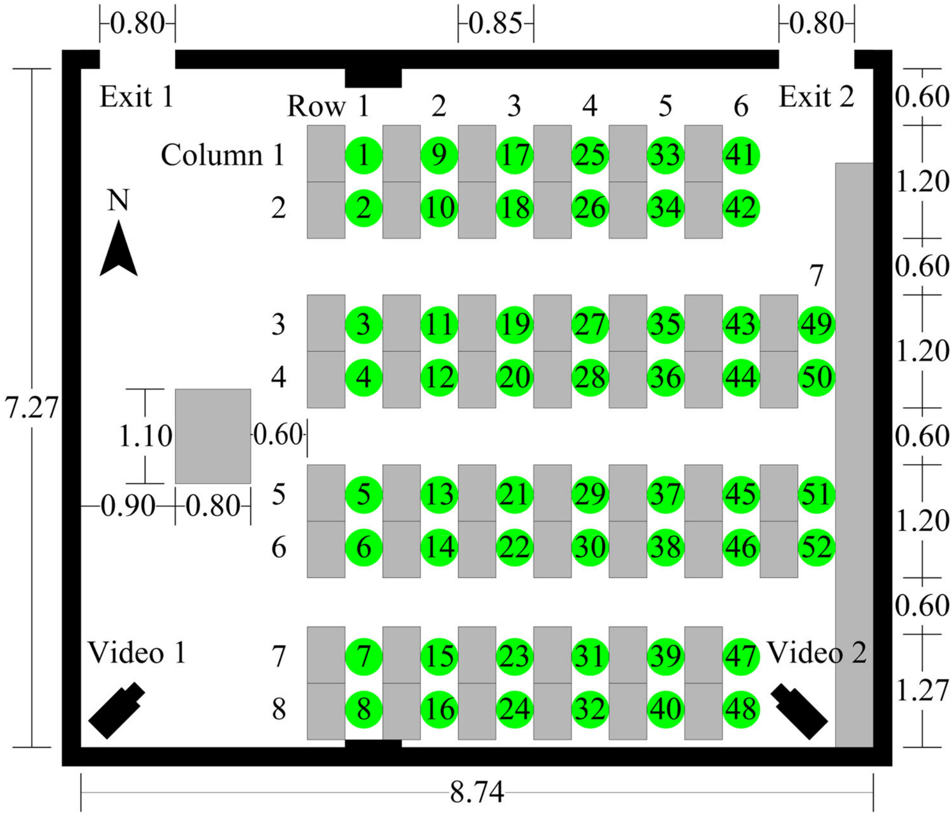

Figure 1. Classroom layout and two video camera locations (unit: m).

evacuation experiments: (1) self-evacuation under a non-emergency situation (SN), (2) self-evacuation under an emergency situation (SE), (3) guided evacuation under a non-emergency situation (GN), and (4) guided evacuation under an emergency situation (GE). As for the four sets of evacuation experiments, we provide the following explanations:

1. Self-evacuation under a non-emergency situation is the process by which the children imitate leaving the classroom in their daily activities at school and the teacher waits outside the classroom for children (i.e., there are only children in the classroom during evacuation). In this evacuation process, children cannot run.
2. Self-evacuation under an emergency situation is the process by which the children imitate leaving the classroom in evacuation drills conducted each year at school and the teacher waits outside the classroom for children. In this evacuation process, running is allowed.
3. Guided evacuation under a non-emergency situation is the process by which the children imitate leaving the classroom in their daily activities

at school and the teacher manages the evacuation in the classroom. In this evacuation process, children cannot run and the teacher provides instructions to children. The teacher's instructions will be described in detail in Section 2.2.

4. Guided evacuation under an emergency situation is the process by which the children imitate leaving the classroom in evacuation drills conducted each year at school and the teacher manages the evacuation in the classroom. In this evacuation process, running is allowed and the teacher provides instructions to children.

2.2. Experimental procedure

Four sets of evacuation experiments were conducted over two days, and each set of evacuation experiments was repeated three times to ensure adequate sample size. Thus, a total of 12 experiments were conducted with the 52 children in the same classroom. The initial positions of the children in each experiment were the same as usual. The experiments SN and GE were carried out in the first morning and afternoon, respectively. The experiments SE and GN were carried out in the next morning and afternoon, respectively. This, to some extent, reduces the interaction of the different evacuation types. As for the role of the teacher in these experiments, we provide the following explanations:

1. Before each evacuation process, for ethics and safety reasons, the teacher repeated the rules of the experiment with the students (i.e., during the evacuation under a non-emergency situation, children cannot run; during the evacuation under an emergency situation, children can run). The evacuation command was also given by the teacher. The evacuation command under a non-emergency situation was "Leave the classroom as usual," while under an emergency situation it was "Leave the classroom quickly." After each evacuation, the teacher organized them to return to the classroom.
2. In the self-evacuation process, the teacher stood outside the classroom and gave the evacuation command through the window. This would, to some extent, ensure that the children behave naturally and remove the teacher's impacts. Note that for ethics and safety reasons, self-evacuation is not completely out of the control of the staff. The evacuation process was supervised by two teachers via camera, and the teachers could immediately stop it if an emergency occurred.
3. In the guided evacuation process, the teacher stood by the lectern and gave the evacuation command in the classroom. The teacher keeps order to avoid running among children during evacuation under a non-

emergency situation and urges children to move quickly during the evacuation under an emergency situation. The teacher also gave a special instruction, that is, "You can go to exit 2," to children when many children gathered at exit 1.

Once the command to evacuate was given, all children stood up from their seats and moved toward the exits. Two video cameras capture the children's movements and behavior during the evacuation process, as shown in Figure 1. The first video camera was used to record the child outflow from exit 1, and the second video camera was used to record the child outflow from exit 2.

3. Results

The video recordings were collected at a frequency of 25 frames per second and were analyzed using VideoStudio X9 software. Let i represent the ith evacuation process in each set of evacuation experiments. For example, Figure 2 shows child evacuation from the classroom in experiments SN 1 at 10 sec, SE 1 at 7 sec, GN 1 at 10 sec, and GE 1 at 7 sec, respectively. A detailed description of the experimental results will be introduced in the following sections.

3.1. General observations

Under a non-emergency situation, the processes of both self-evacuation (SN) and guided evacuation (GN) are orderly, as shown in Figure 2(a and c). In general, there are no running, pushing or hitting behaviors. However, we observe that some children exhibit group behavior and waiting behavior in a group in experiments SN and GN. The children marked by red circles in Figure 2(a) and 2(c) represent those with group behavior. During the evacuation process, the group member waits for friends in the place where friends will pass through, and then everyone moves toward the exit together. Such group behavior is a stochastic behavior, since the children with group behavior do not exhibit group behavior in every experiment. Furthermore, some children near exit 1 move toward exit 2 after the teacher gives instruction during the evacuation process in GN experiments. This results in different movement directions among children in the local area. However, the evacuation process is still orderly. The reason for this phenomenon may be that the children can avoid conflicts with other children by altering directions of movement as they are walking.

Under an emergency situation, the processes of both self-evacuation (SE) and guided evacuation (GE) are disorderly, and physical contact between

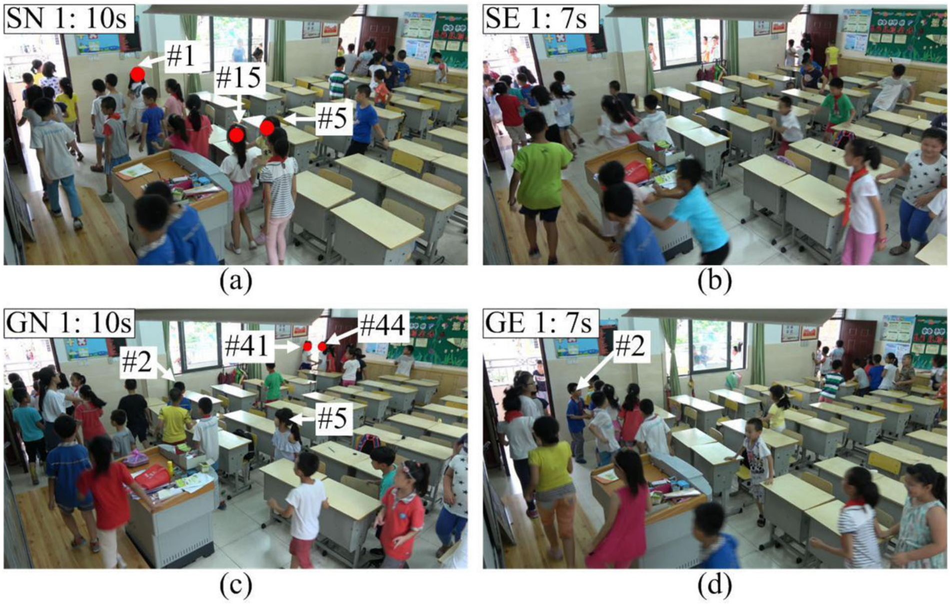

Figure 2. Photographs of evacuation in experiment (a) SN 1 at 10 sec, (b) SE 1 at 7 sec, (c) GN 1 at 10 sec, and (d) GE 1 at 7 sec, where the children marked by red circles represent those with group behavior.

children is rather obvious, as shown in Figure 2(b and d). More generally, running and pushing behaviors are exhibited. The children use their arms to push children in front of them when they are running (see Figure 2[b and d]). As for GE experiments, we still observe that some children exhibit pushing behavior despite the management of the teacher. Some children also changed their exit choice after the teacher gave the instruction. However, these behaviors result in a block during the evacuation process (see Figure 2[d]). This contributes to the disorderly evacuation process of GE experiments when compared to SE experiments. The reason for such results could be due to the running and pushing behavior exhibited under an emergency situation. It is hard for children who are running to change direction to avoid other children with different directions of movement. They may even push each other, which results in a block. The block leads to a sudden decrease of velocity within a fixed area, which increases the risk of crowd turbulence (Dias, Sarvi, Shiwakoti, Ejtemai, & Burd, 2013). Such crowd turbulence may result in stampedes or inefficient evacuation.

3.2. Exit choice

Exit choices of children in these experiments are recorded. The number of children evacuating from exit 1 and exit 2 is shown in Figure 3. The results

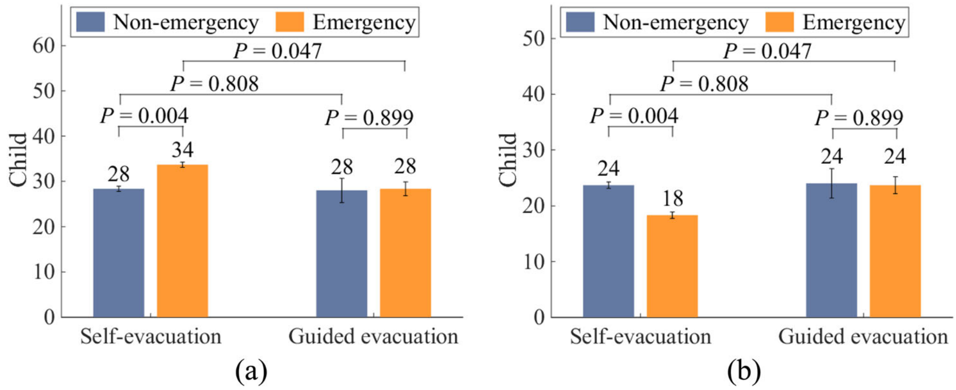

Figure 3. Number of children evacuating from (a) exit 1 and (b) exit 2. Data are mean± SD.

are the average values of the three repeated evacuations in the four sets of experiments. To examine the influence of emergency degree and teacher's guidance on the exit choice, paired-samples *t* tests are conducted (see Figure 3). From Figure 3, we can conclude the following:

1. In self-evacuation, there is a certain difference between the number of children choosing each exit under a non-emergency situation and an emergency situation. In guided evacuation, the number of children evacuating from each exit under a non-emergency situation is approximately equal to that under an emergency situation. The test results show that the number of children choosing each exit is statistically significant with emergency degree in self-evacuation ($p = 0.004$) and it is not statistically significant with emergency degree in guided evacuation ($p = 0.899$). This indicates that emergency degree has significant effects on the exit choice of children in self-evacuation, while it does not have significant effects on the exit choice of children in guided evacuation. The findings reveal that in self-evacuation some children change their exit choices under an emergency situation when compared to a non-emergency situation, and the teacher's guidance causes the number of children evacuating from each exit under an emergency situation to become similar to that under a non-emergency situation.
2. Under a non-emergency situation, the number of children evacuating from each exit in self-evacuation is approximately equal to that in guided evacuation. The number of children choosing exit 1 is slightly greater than that choosing exit 2. Under an emergency situation, the number of children choosing exit 1 is also slightly greater than that choosing exit 2 in guided evacuation. However, the differences are quite significant in self-evacuation. An imbalanced use of exits was observed in self-evacuation under an emergency situation. The test results show that the number of children choosing each exit is not statistically significant with teacher's guidance under a non-emergency situation

($p = 0.808$) and it is statistically significant with teacher's guidance under an emergency situation ($p = 0.047$). This indicates that teacher's guidance does not have significant effects on the exit choice of children during evacuation under a non-emergency situation, while teacher's guidance has significant effects on the exit choice of children during evacuation under an emergency situation. The reason may be that when compared to a non-emergency situation, some children change their exit choices under an emergency situation, which results in an imbalanced use of exits. Therefore, the teacher plays a positive role in the exit choice of children during an emergency evacuation process. However, under a non-emergency situation, exit use is nearly balanced during the evacuation process. Thus, the teacher plays a weak role in this case.

To further investigate the exit choice of children, we extract the number of children evacuating from each exit in each column. Figure 4 shows the percentage of children evacuating from exit 1 and exit 2 in each column in these experiments. The results are the average values of the three repeated evacuations in the four sets of experiments. From Figure 4, we can conclude the following:

1. The changing trends in the percentages are similar as the column increases in experiments SN, GN, and GE. The percentages of children evacuating from exit 1 in columns 1 through 4 are not greater than 50%. This indicates that more children whose initial positions are in the seats in columns 1 through 4 choose exit 2. This is reasonable because there are more seats near exit 2. The percentages of children evacuating from exit 1 in columns 5 through 8 are greater than 50%. This indicates that more children whose initial positions are in the seats in columns 5 through 8 choose exit 1, despite the fact that many seats are closer to exit 2. The reason may be that the seats in the last row are next to the wall. If the children in columns 5 through 8 want to evacuate from exit 2, they will travel through the aisles occupied by seats. When children leave their seats, many of them push their chairs back under the desks, and there is space for children to move. However, it is still inconvenient for children to cross these aisles. Therefore, these seats affect the exit choice of children.
2. In self-evacuation under an emergency situation (SE experiments), the percentages of children evacuating from exit 1 in columns 1 through 4 are approximately equal to that evacuating from exit 2, and the percentages of children evacuating from exit 1 in columns 5 through 8 are greater than 50%. This leads to relatively greater differences between the number of children choosing exit 1 and exit 2 in SE experiments. There are two possible reasons for this result. One possible reason may be that

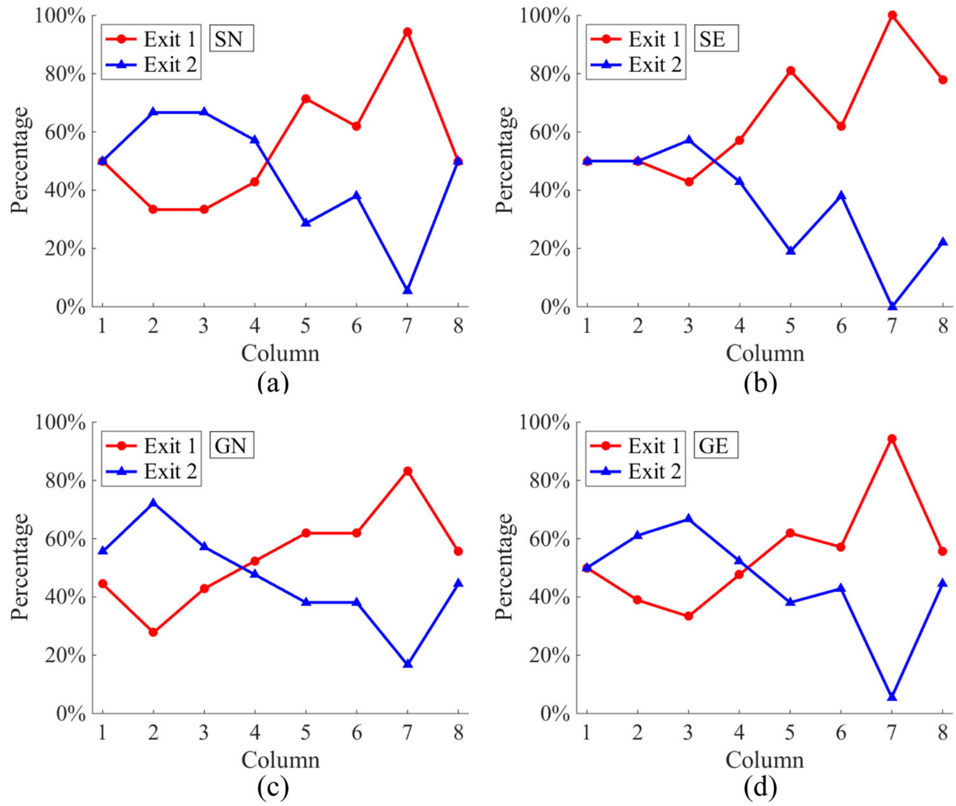

Figure 4. Percentage of children evacuating from each exit in each column in (a) SN, (b) SE, (c) GN, and (d) GE experiments.

the impacts of obstacles on the exit choice of children under non-emergency and emergency situations are different. More children will choose exit 1 as their evacuation exit under an emergency situation, which results in an imbalanced use of exits. Another possible reason may be the running and pushing behavior under an emergency situation. If the children want to exit through the aisles occupied by seats, they need to slow down their running speed. However, others behind the children might push them to keep running. The imbalanced use of exits represents the interactional outcome of both reasons. However, with the management of the teacher in GE experiments, there is less pushing behavior and fewer children choosing exit 1 as their evacuation exit when compared to SE experiments. Thus, the differences between the number of children choosing exit 1 and exit 2 are slight in GE experiments.

3.3. Evacuation time

A child's evacuation time is defined as the time that elapses between when the command to evacuate is given and the moment the child leaves the

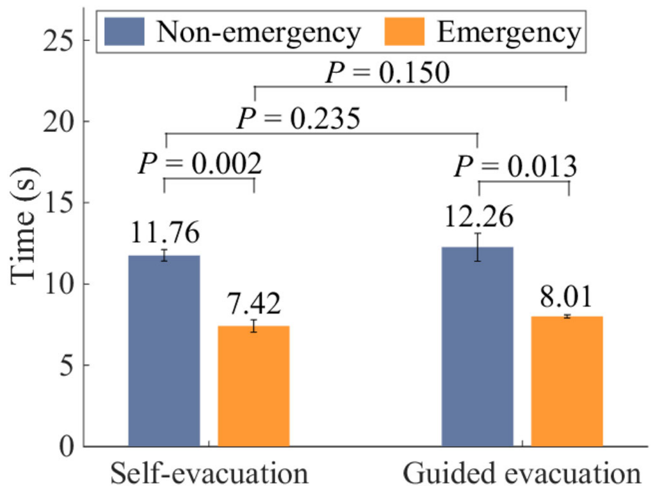

Figure 5. Average evacuation time of children. Data are mean± SD.

classroom. The average evacuation time of children in these experiments is shown in Figure 5. The results are the average values of the three repeated evacuations in the four sets of experiments. To examine the influence of emergency degree and teacher's guidance on the evacuation time, paired-samples *t* tests are conducted (see Figure 5). From Figure 5, we can conclude the following:

1. In both self-evacuation and guided evacuation, the average evacuation time of children under a non-emergency situation is greater than that under an emergency situation. The test results show that the average evacuation time of children is statistically significant with emergency degree in both self-evacuation ($p = 0.002$) and guided evacuation ($p = 0.013$). This indicates that emergency degree has significant effects on the average evacuation time of children. These results are not surprising since the children are running under an emergency situation.
2. Under both a non-emergency situation and an emergency situation, the average evacuation time of children in self-evacuation is approximately equal to that in guided evacuation. The test results show that the average evacuation time of children is not statistically significant with teacher's guidance under both a non-emergency situation ($p = 0.235$) and an emergency situation ($p = 0.150$). This indicates that teacher's guidance does not have significant effects on the average evacuation time of children. This is understandable. The teacher plays a weak role under a non-emergency situation. The teacher's guidance does not affect the exit choice or evacuation time of children during evacuation under a non-emergency situation. During an emergency evacuation process, the teacher's guidance plays a positive role in the exit choice of children.

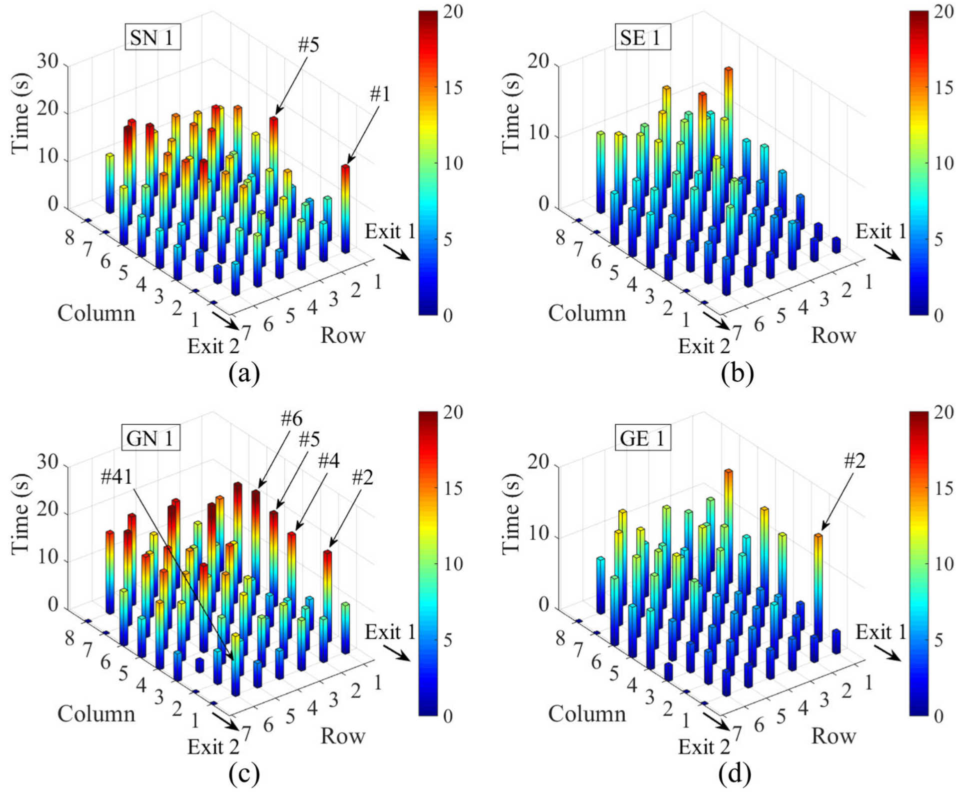

Figure 6. Individual evacuation time in experiments (a) SN 1, (b) SE 1, (c) GN 1, and (d) GE 1.

However, it just affects some children's exit choices and leads to a change in their individual evacuation time. It has no significant effect on the average evacuation time of children.

To further investigate evacuation time, the bar charts delineating the evacuation time of each child in experiments SN 1, SE 1, GN 1, and GE 1 are shown in Figure 6. From Figure 6, we can conclude the following:

1. For SE experiments, the evacuation time generally decreases as the column decreases, owing to the effect of distance to the exit, and the children in the middle generally face a longer evacuation time than those in other areas in every column (see Figure 6[b]). The other three sets of evacuation experiments show the same trend in terms of individual evacuation time. However, there are some outliers in the other three sets of evacuation experiments.
2. For SN experiments, the children numbered 1 and 5 have longer evacuation time than neighboring children in experiment SN 1 (see Figure 6[a]). The reason is that the children numbered 1 and 5 who engaged

in group behavior waited for their friends when the command to evacuate was given (see Figure 2[a]). They then moved toward the exit in a group. The waiting behavior in a group increases the evacuation time of the members.

3. For GN experiments, there are two reasons for the disorderly evacuation time. One is that group behavior exists in the evacuation process. The child numbered 41 whose initial position was closest to exit 2 waited for her friend in experiment GN 1 (see Figure 2[c]). This results in a greater individual evacuation time (see Figure 6[c]). The other reason is the teacher's guidance. The children numbered 2 and 5 changed their exit choices and moved toward exit 2 after the teacher gave the instruction. The longer route results in a greater individual evacuation time. In addition, one can observe that the children numbered 4 and 6 also have a longer evacuation time. The reason is attributable to the time spent on moving back chairs.
4. For GE experiments, the teacher's guidance is also the reason for the disorderly individual evacuation time. The child numbered 2 changed the exit choice and moved toward exit 2 after the teacher gave the instruction in experiment GE 1. This results in a block near exit 1 and a greater individual evacuation time (see Figures 2[d] and 6[d]). The block may also increase the risk of crowd turbulence. This demonstrates that in order to increase the safety and efficiency of child evacuation, it is important to avoid conflicts among children resulting from different directions of movement.

3.4. Flow rate of the exit

We now compute the exit's flow rate J, that is, the number of children who can go through the exit per unit time. The flow rate of each exit can be expressed as $(N-1)/(w(t_N-t_1))$, where N is the number of children evacuating from the exit, w is the width of the exit, and t_1 and t_N denote the evacuation time of the first child and the last child evacuating from the exit, respectively. The values are shown in Figure 7. The results are the average values of the three repeated evacuations in the four sets of experiments. To examine the influence of emergency degree and teacher's guidance on the flow rate, paired-samples t tests are conducted (see Figure 7). From Figure 7, we can conclude the following:

1. In both self-evacuation and guided evacuation, the flow rate of each exit under an emergency situation is greater than that under a non-emergency situation. The test results show that the flow rate of each exit is statistically significant with emergency degree in both self-evacuation

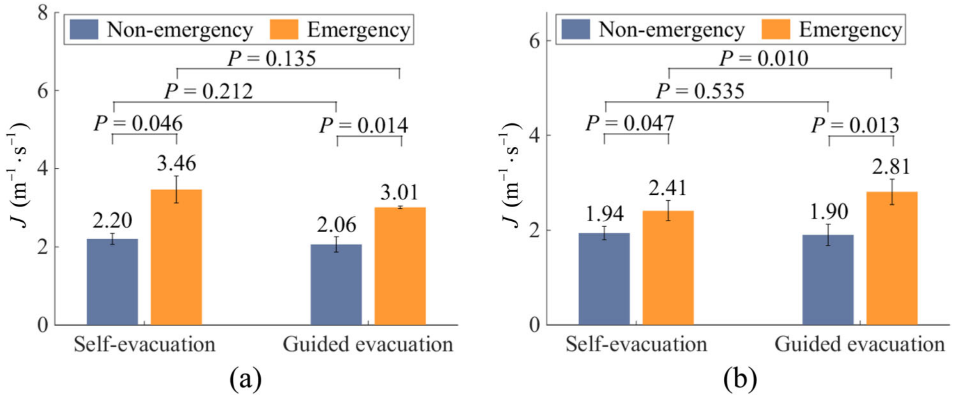

Figure 7. Flow rate of (a) exit 1 and (b) exit 2. Data are mean± SD.

(exit 1: $p = 0.046$, exit 2: $p = 0.047$) and guided evacuation (exit 1: $p = 0.014$, exit 2: $p = 0.013$). This indicates that emergency degree has significant effects on the flow rate of each exit. This is understandable since the children are running under an emergency situation.

2. Under a non-emergency situation, the flow rate of each exit in self-evacuation is approximately equal to that in guided evacuation. The test results show that the flow rate of each exit is not statistically significant with teacher's guidance under a non-emergency situation (exit 1: $p = 0.212$, exit 2: $p = 0.535$). This indicates that teacher's guidance has little impact on the flow rate of each exit under a non-emergency situation. Under an emergency situation, the test results show that the flow rate of exit 1 is not statistically significant with teacher's guidance ($p = 0.135$) while the flow rate of exit 2 is statistically significant with teacher's guidance ($p = 0.010$). This indicates that under an emergency situation, teacher's guidance has little impact on the flow rate of exit 1, while it has significant effects on the flow rate of exit 2. The reason may be that there are more obstacles near exit 2 when compared to exit 1. The children who selected exit 2 do not have the opportunity to run as fast as the children who selected exit 1. Under an emergency situation, no matter self-evacuation or guided evacuation, the flow rate of exit 1 is close to its capacity and the flow rate of exit 2 is lower when compared to exit 1. Therefore, the change in flow rate of exit 1 is relatively small with the change in the number of children evacuating from exit 1, while the flow rate of exit 2 increases with the increase in the number of children evacuating from exit 2.

In addition, the change in flow rate among different sets of evacuations can also be seen from the number of children left in the classroom at different evacuation times during the evacuation process. Figure 8 presents

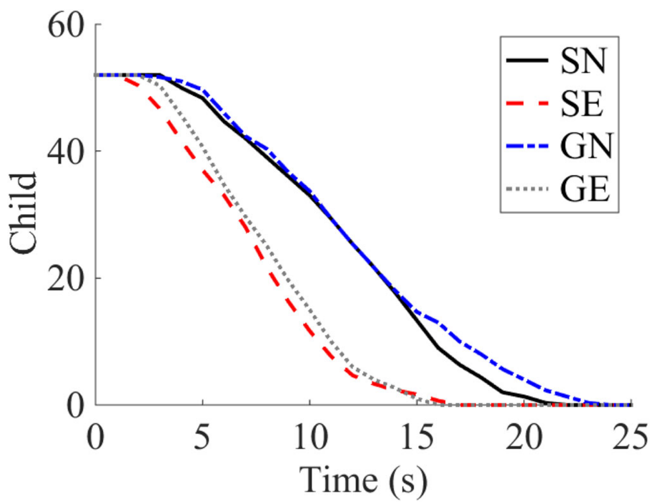

Figure 8. The number of children left in the classroom at different evacuation time.

the number of children remaining in the classroom over time for the four sets of evacuation experiments. The results are the average values of the three repeated evacuations in each set of experiments. We can observe that the lines for experiments SE and GE share a similar trend, and the lines for experiments SN and GN also share a similar trend. The downward slope of experiments SE and GE is steeper than that of experiments SN and GN during most of the evacuation process. This indicates that the flow rate of each exit under an emergency situation is greater than that under a non-emergency situation.

3.5. Headway

On average, the flow rate of each exit is related to the average headway $\langle\Delta t\rangle$ between evacuees via $J = w^{-1}\langle\Delta t\rangle^{-1}$. The headway between evacuees can be calculated through $\Delta t = t_{i+1} - t_i$, where t_i is the evacuation time of the ith child evacuating from the exit. The average headway of each exit is presented in Figure 9. The results are the average values of the three repeated evacuations in the four sets of experiments. To examine the influence of emergency degree and teacher's guidance on the headway, paired-samples t tests are conducted (see Figure 9). Comparing the flow rate and the average headway of each exit (see Figures 7 and 9), we can observe that as the average headway increases, the flow rate decreases. The average headway of each exit under an emergency situation is lower than that under a non-emergency situation. The test results also show that the average headway of each exit is statistically significant with emergency degree in both self-evacuation (exit 1: $p = 0.038$, exit 2: $p = 0.043$) and guided evacuation (exit 1: $p = 0.026$, exit 2: $p = 0.026$).

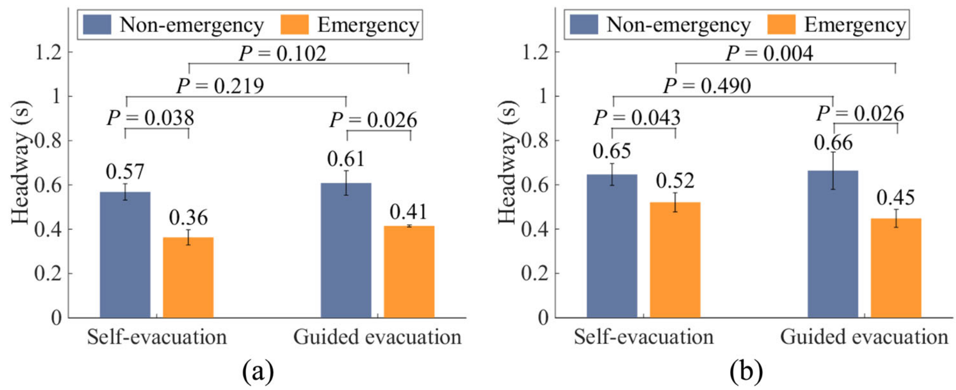

Figure 9. Average headway at (a) exit 1 and (b) exit 2, where the data are mean± SD.

Figure 10 shows the frequency distribution of headways of each exit. This reveals substantial differences in these distributions for different types of evacuations. Child flows in experiments SE and GE display a relatively sharp peak at a characteristic time, while child flows in experiments SN and GN do not present a very well-defined peak. On the other hand, child flows in experiments SE and GE include a region of very small headways $\Delta t \rightarrow 0$. Interestingly, these features are also observed in experiments SN and GN, as shown in Figure 10. This corresponds to quasi-simultaneous evacuation from the exit, due to the smaller size of the child.

4. Discussion and conclusion

Child behavior during evacuation is critical in fire safety management. Although a few studies on child behavior during evacuation have been undertaken, our understanding of child behavior during evacuation is still limited, and few studies have examined the properties of child movement during self-evacuation and guided evacuation under non-emergency and emergency situations. In this study, a series of experiments were conducted to investigate child behavior during self-evacuation and guided evacuation under non-emergency and emergency situations. By asking the participants to imitate the process of evacuation under different situations, four sets of experiments were performed.

Several properties of child flow dynamics were obtained from the group of experiments on child evacuation. The results are summarized as follows. First, under a non-emergency situation, evacuation processes are orderly, and group behavior and waiting behavior in a group can be observed in both self-evacuation and guided evacuation. However, under an emergency situation, evacuation processes become disorderly, and running and pushing behavior can be observed in both self-evacuation and guided evacuation. Second, emergency degree has significant effects on the exit choice

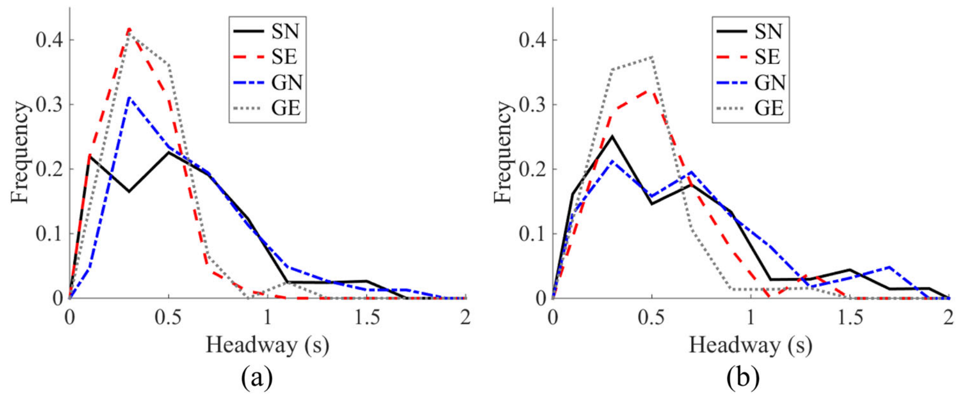

Figure 10. Frequency distribution of headways at (a) exit 1 and (b) exit 2.

of children in self-evacuation. In self-evacuation, the exit use is nearly balanced under a non-emergency situation, while the exit use is imbalanced under an emergency situation. Therefore, the teacher plays a positive role in the exit choice of children during an emergency evacuation process. Third, emergency degree has significant effects on the average evacuation time of children. The average evacuation time of children under a non-emergency situation is greater than that under an emergency situation since the children are running under an emergency situation. However, teacher's guidance affects some children's individual evacuation time. It has no prominent impact on the average evacuation time of children. Fourth, emergency degree has significant effects on the flow rate and average headway of each exit. The flow rate of each exit under an emergency situation is greater than that under a non-emergency situation since the children are running under an emergency situation. A reverse trend is observed for the average headway of each exit. As the flow rate of each exit increases, the average headway of each exit decreases. Teacher's guidance has little impact on the flow rate and average headway of each exit under a non-emergency situation. However, teacher's guidance has significant effects on the flow rate and average headway of exit 2 under an emergency situation because the change in the number of children evacuating from exit 2. Our findings, along with the existing empirical evidence provided by Fang et al. (2019), suggest that the guidance of teachers has a significant influence on the children's evacuation process. In addition, Fang et al. (2019) concluded that children would strictly obey the orders of teachers. However, it was shown that some children did not follow the guidance in our experiments. Children's inconsistent responses to the guidance of teachers led to opposite directions of movement and even a block during the evacuation process. A possible justification is a difference between the age of children in two studies (9 to 11 years old in this study and 5 to 6 years old in Fang et al., 2019).

Based on our findings, we offer three recommendations, as follows, to prevent the risk of accidents during child evacuation.

1. Child behavior: As noted in our study, group behavior and waiting behavior in a group are exhibited under a non-emergency situation, resulting in an increase of individual evacuation time. Additionally, running and pushing behavior exists under an emergency situation, resulting in a disorderly evacuation process and the risk of crowd turbulence. Thus, it is important to prevent such behaviors during evacuation. More evacuation drills should be conducted to acquaint children with the evacuation plan and to ensure that correct actions become a habit (Hammond, Cherrett, & Waterson, 2014).
2. Guidance: Children are considered one of the vulnerable populations in society, and typically they need assistance during evacuation. Thus, the teacher plays an important role in child evacuation at school. However, the teachers or other staff have poor training in fire safety and evacuation of schools (Hamilton et al., 2017; Kholshevnikov et al., 2009). As noted in our study, the guidance given by teachers on the spot leads to different movement directions among children in the local area due to the children's inconsistent responses to the guidance, despite the fact that the teacher plays a positive role in the exit choice of children during an emergency evacuation process. This is an important finding which we recommend be taken into consideration when devising a child evacuation plan. As found in our study, children's inconsistent responses to the guidance of teachers led to opposite directions of movement and even a block during the evacuation process. This may increase the risk of crowd turbulence, especially under an emergency situation. Therefore, it is important to conduct training for school staff to learn how to organize child evacuation effectively and safely.
3. Classroom layout: As seen from our study, the impacts of obstacles on the exit choice of children are different under different situations, which results in imbalanced use of exits in self-evacuation under an emergency situation. Therefore, it is important for planners and architects to consider the impacts of different architectural configurations on the safe evacuation of children.

The research described herein is focused on child evacuation from a classroom. These qualitative and quantitative characterizations obtained through analysis of the experiments can be employed for model configuration and validation and can also help to garner a more precise understanding of the child evacuation process. However, it should be noted that the children in this experiments are around 10 years old. Therefore, the results in this study can only be representative of a small segment of all children. The potential implications of learning effects (each set of evacuation experiments is repeated three times) and habitual behaviors (the children have been studying in this classroom for two months) are also not considered. In addition, this is only part of the total evacuation process. Other processes (i.e., pre-evacuation, movements on stairways) have a direct influence on the evacuation process. It is essential to gain a thorough understanding of the mechanisms of child movement patterns at buildings where many children congregate. In the future, the evacuation behavior of children of all ages and the different evacuation behaviors of children at different ages should be investigated by conducting comprehensive evacuation experiments. The children's interactions with teachers' instructions, as well as the mode of guidance, should also be investigated in the future. Nevertheless, the findings from this study may assist in the improvement of daily management and evacuation strategies for children, as well as the development and validation of child simulation models.

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ORCID

Liang Chen http://orcid.org/0000-0002-3582-294X

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