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Children's evacuation behavioural data of drills and simulation of the horizontal plane in kindergarten

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ABSTRACT

The critical factors that impair the evacuation safety come from two aspects: anthropic and architectural design. The behavioural data on children's evacuation is limited. The quantitative dataset of this study was collected and derived from three evacuation drills which were carried out in a one-storey kindergarten (the children enrolled are 3–6-year-olds) in Dalian, China. The children's free walking speed was calculated as 1.05 ± 0.11 m/s, and the mean horizontal walking speed during the evacuation is confirmed as 0.86 ± 0.20 m/s. Then, the density, evacuation time and flow rate are analysed. The pre-evacuation time and evacuation behaviours in the classrooms are presented. At the same time, the parameters, including free walking speed and body dimensions, were entered into the Pathfinder, and a similar consistency was observed between the experimental results and the Pathfinder simulation results. The study can be a reference to kindergarten evacuation modelling, simulation, safety strategies and architectural layout design.

1. Introduction

The fire safety design of the buildings includes many aspects such as determining the location, the number of emergency exit doors and their diameters, stairway design, corridor design (Haghani, 2020). The human factor consists of, among others, age, physiological and psychological characteristics, walking speed, number of evacuees (Larusdottir & Dederichs, 2011, 2012; Lyzwa, 2018). The indicators of an efficient evacuation include factors such as movement time, service level, the flow rate at exit doors (Kurniawan et al., 2018; Ministry of Housing and Urban-Rural Development of the PRC, 2014). Children aged 3–6 years in the kindergartens are not fully capable of reacting to emergency cases independently. Therefore, the architectural design and construction practice of kindergartens should take children's immature physical capacity into account and ensure their safety. The standards, guidelines and specifications for architectural design have been highlighted in details in many countries, such as in the United States, the United Kingdom, Australia, and Japan (Hurley and Rosenbaum, 2016). However, evacuation studies concerning kindergarten children are much less than that of adults. Because of the closed-off management of kindergartens, it is very difficult to carry out experiments in kindergarten. Moreover, the flow rate, walking speed, and other essential factors are playing a decisive role in formulating the strategic decisions of evacuation (Hamilton et al., 2020; Larusdottir and Dederichs, 2012). In architectural design, fire safety test is a performance-based process stipulated in technical specification standards in many countries such as Japan, Singapore, Australia (SCDF, 2015; Tsujimoto, 2002; Beck, 1997). One of the constituent substantiations is evacuation data (Kurniawan et al., 2018). Therefore, it is very important and necessary to collect and analyse the data on children's evacuation behaviour.

This paper aims to explore the behaviours of children in classrooms among different ages during orderly pre-movement and evacuation; the difference between children's behaviour and that of adults during evacuation; and the setting of parameters in evacuation software. Therefore, a detailed data collection method is described for comparing each divided area/marked position. A new data-set that collected from the children's evacuation and pre-movement phase will be presented. Also, the simulated data are compared with the data from the drills.

1.1. Children walking speed in evacuation drills

The recent studies show that the walking speed of children during evacuation drills in kindergartens are different around the world. Taciuc and Dederichs (2014) compared the dataset of children's evacuation collected from several countries to describe specific behaviours in an indoor environment, such as walking speed on stairways with different

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gradients and widths. Fridolf et al. (2013) mentioned the *modelling speed* and *movement speed* to describe the difference of calculation of evacuation distance, which provides the method of the division of area for this study. Najmanová and Ronchi (2017) discussed the data collection method and analysed the horizontal and vertical travel speed of Czech Republic preschool children in 2016; they also stated that age and escape route were the critical factors impacted evacuation movement. So, this study fills the gap of children's evacuation behaviours in different age groups in China. Russian study (Kholshchevnikov et al., 2012) presented that the walking speed increased with age and analysed the relationship between population density and movement speed at the exit doors, stairs and other places in several schools and preschools from 1998 to 2007. In Brazil, the movement speeds of 6–14 years old were measured in corridors and on the stairs in three evacuation drills (Ono et al., 2012), the students evacuated in line, and pause or move forward following the teacher's instructions. Hamilton et al. (2020) analysed the effects of evacuation patterns such as the effect of adult companionship on modelling speed in 2019. In Denmark, Larusdottir & Dederichs (2011, 2012) compared the horizontal walking speed of children aged 3–6 with the speed of adults, they mentioned the effects of children's evacuation could be improved with regular training/drills, and behaviours of children are different from those of adults during evacuation. In China, the experimental study (Fang et al., 2019) on the walking speed of 5–6 years old children in the corridor and stairs was carried out to establish the relationship between the walking speed, flow rate and the density. However, there are few studies concerning other age groups. Li et al. (2020) shows that the walking speed, flow and density of children were different when passing the different widths of the bottleneck, which reflects the impact the architecture design would have on the evacuation behaviour of children.

It is concluded from the literature that the horizontal walking speed of children's evacuation is different from that in the vertical direction, and it is affected by many factors, such as teacher's leadership and guidance, evacuation mode, architectural design. Moreover, the speed varies significantly among different age groups.

1.2. Determination of speed parameter in evacuation simulation

Peng (2009) simulated a children's evacuation with a horizontal walking speed of 0.76 m/s, 0.40 m/s for going upstairs and 0.52 m/s for going downstairs. Wang (2014) input 0.4 m/s for walking speed and 0.28 m for the shoulder width in the simulation software to analyse children's evacuation in a kindergarten. Zhang (2014) stated that the larger the corner turning angle is, the lower the evacuation efficiency would be; and the evacuation is influenced by the density of evacuees based on the simulation results. These comparisons indicate that the kindergarten facilities and architectural design could affect the children walking speed during the evacuation and impact evacuation performance directly. Lyzwa (2018) compared the data from evacuation drills and FDS + Evac simulation, the speed parameter (maximum value was 1.07 m/s, minimum value was 0.72 m/s of 3–6 years old) was defined as the walking speed at low density. Cuesta et al. (2017) compared five computerized simulations with the mean walking speed of 6–16 years old children in the evacuation experiments carried out in Spain, which showed good consistency between observed and simulated curves. However, the simulated evacuation process is different in each of the simulations.

After reviewing the research on children's evacuation simulation, it is found that the range of simulation parameter settings for children is wide and the methods are varied. There is no fixed method, but it is necessary to set the parameters according to the data from children's actual evacuation drills.

2. Experimental design

In this study, the object is divided into three parts. The first part is the behavioural studies of the well-trained children during the pre-movement phase and travel phase. The second part is the analysis to the effect of the density on the walking speed and the flow rate of children, which is described with the time flow to reflect the children's behaviour during the evacuation, then compared with other literature. The third part is to present the simulation results of children's evacuation and compare them with the results of the drills. The comparisons will be used to verify whether Pathfinder is reliable for simulating children's evacuation.

Because the local government requires the kindergartens to perform evacuation drills on a regular basis, the children are familiar with evacuation procedures and routes. Therefore, the children's evacuation and the parameterization of a standard situation would be more accurate to enhance the precision of the simulation results (Cuesta et al., 2017; Najmanová and Ronchi, 2017; Othman and Tohir, 2018). The experiments of this study can provide relatively mature data of children's evacuation behaviour.

2.1. Evacuation drills

2.1.1. Experimental setup

The evacuation drill was carried out three times in a day-care one-storey kindergarten in Dalian, China. There are six classes in kindergarten (Fig. 1). They belong to three age groups with two classes in each group. There is a total of 115 children and 23 staff in the kindergarten during weekdays. The evacuation drill was carried out three times, at 10 am to 11 am on 3rd July, 3 pm to 4 pm on 5th August, and 10 am to 11 am on 9th August in 2019 accordingly. During the evacuation drills, it was sunny weather and with warm air temperature. In each evacuation drill, 101 children and 14 teachers who are healthy and fit participated in the experiment, and all drills were pre-announced. Total participants of the drills were 303 children and 42 teachers. According to the *Fire Safety Regulations of Educational Institutions in Dalian* (Dalian Education Bureau, 2015), at least one evacuation drill must be conducted quarterly to ensure that all children become familiar with the evacuation routes. All the evacuees were deemed as children because they move as groups (Lyzwa, 2018). The whole procedure (Fig. 2) of the drills was properly arranged. In order to prevent suffocation from smoke, children were instructed using towels to cover their nose and mouth. Then, everyone ran towards the classroom door and lined up orderly, and left their classroom following the teachers' instruction before passing through final exit (WS and WN) (Fig. 3).

2.1.2. Evacuation route plan

Fig. 1 shows the layout of this single-storey kindergarten. There are two emergency exits (North Exit and South Exit) at each end to the northern and southern sides. The North Exit is 1.5 m in width, and the South Exit is 1.8 m in width. Following the *Regulations on Pre-school, Elementary and Junior High School Safety Management* (Ministry of Education of the PRC, Ministry of Public Security of the PRC, 2006), the Dalian Fire Department approved the evacuation route plan and provided instructions of the evacuation onsite. Six classes were divided as A-1 and A-2 for 3–4 years children, B-1 and B-2 for 4–5 years children and C-1 and C-2 for 5–6 years children. In this study, the class A-1, A-2 and B-2 were evacuated through South Exit, which is Route 1. The class B-1, C-1 and C-2 evacuated through North Exit in Route 2 (Fig. 1).

2.1.3. Observations

In order to ensure children's safety and security in kindergarten, the People's Government of Liaoning Province (2006) requires kindergartens to install CCTV systems. Several cameras were installed on the roof and the ceiling of the kindergarten (Fig. 1). Certain data used in this study were collected from the CCTV system. Meanwhile, five additional cameras had been installed in designated areas: corridors, lobby, emergency exits, and corners, to record the entire process of the evacuation drills and provide detailed information about children's walking

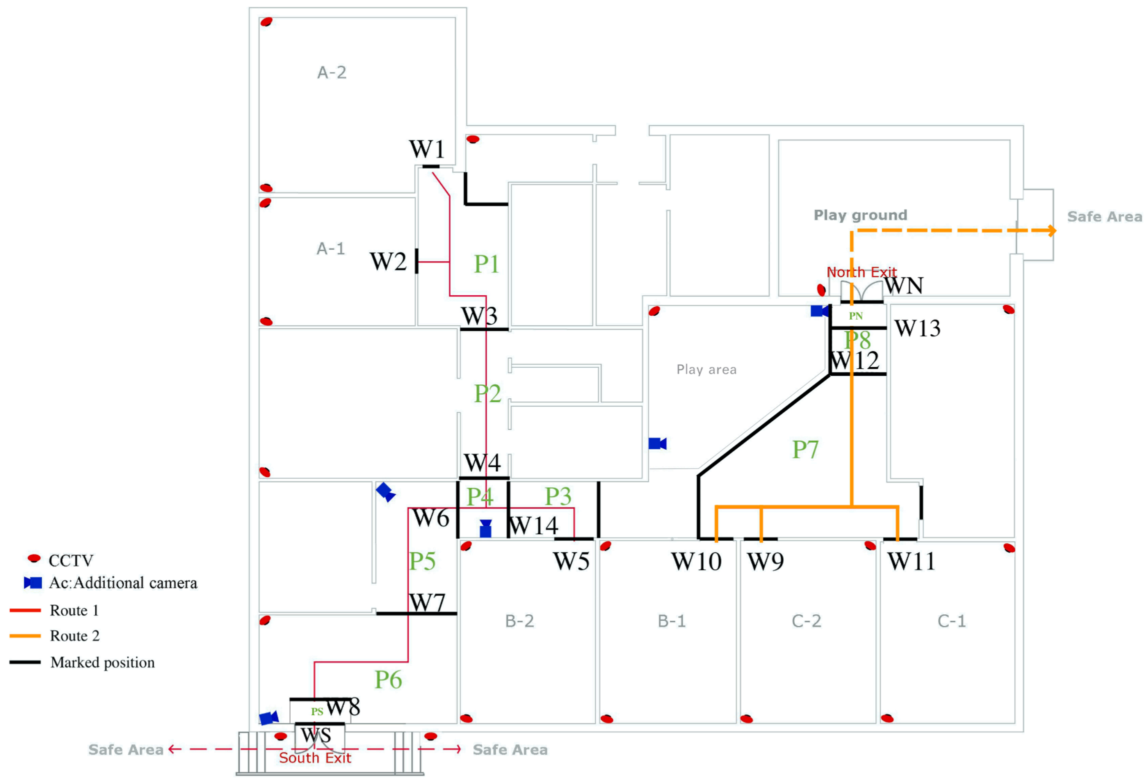


Fig. 1. The floor layout of the kindergarten, camera locations and evacuation routes.

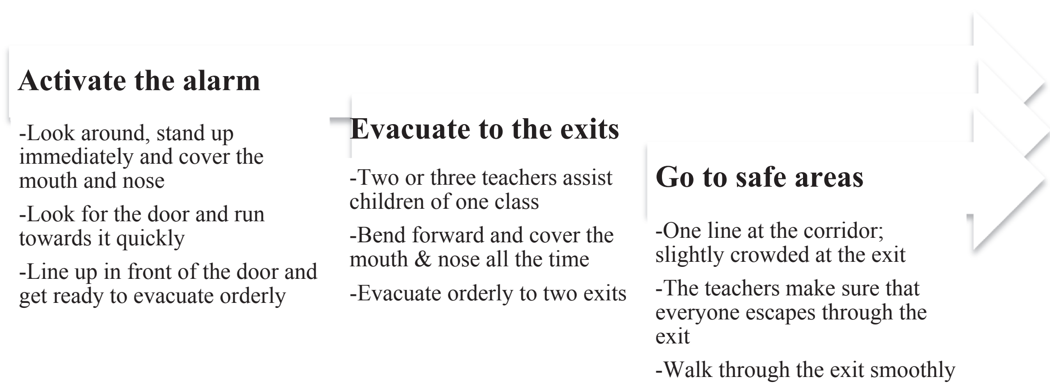


Fig. 2. The evacuation procedures.

speed, hesitation, retreat and other abnormal behaviours. The additional cameras were deployed to record the scenes at the corridor and exit doors. Following the behavioural data collection method (Cuesta and Gwynne, 2016; Larusdottir & Dederichs, 2011, 2012; Othman and Tohir, 2018), the images were obtained from video footages via software, and information was collected.

2.2. Data collection

2.2.1. Marked positions and divided area

The two evacuation routes are analysed separately. Route 1 includes 17 children and 2 teachers in class A-1, 21 children and three teachers in class A-2, and 16 children and 2 teachers in class B-2. There are ten marked positions: W1, W2 and W5 are the doors of each class evacuated by this route; during the evacuation, the north and east classes intersect at W4 and W14; the corridor turns at W6 and W7 to the lobby, which could cause congestion; W8 is the end of the lobby; WS is the south exit.

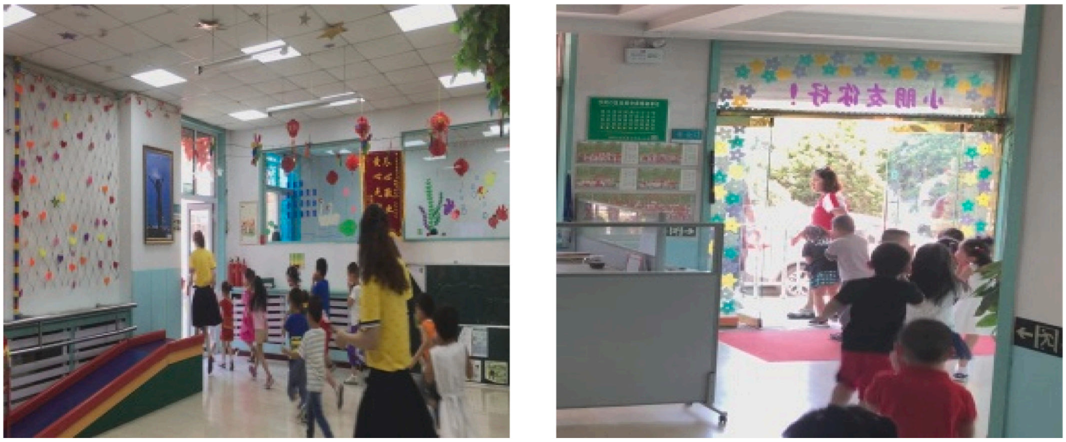
There were 17 children and 2 teachers in class B-1, 16 children and three teachers in class C-1, and 14 children and 2 teachers in class C-2. They all used the evacuation Route 2. Six marked positions are shown on Route 2. The position of W9, W10 and W11 are the doors of each class evacuated by Route 2, and they will all gather at W12 and W13, then escape to the outdoor through north exit WN.

The distances between the marked positions are presented in Table 1. Also, the movement areas enclosed by the main signs are PS, PN and P1-P8 areas (Table 2).

2.2.2. Measurement data

After analysing the video footages of the three drills, the time of each image was collected with frequency of every 0.4 s. The following data are collected and observed:

(a) The movement time and pre-movement times.
  - **Movement time**: starts from the first child left the classroom door to the time when all evacuees arrived at the exits (WS & WN);



(a) North Exit. (b) South Exit.

Fig. 3. The scene of the evacuation drills.

Table 1
The distance between the marked positions.

Marked positions	Route 1									Route 2				
	W1-W3	W2-W3	W3-W4	W4-W6	W5-W14	W14-W6	W6-W7	W7-W8	W8-WS	W9-W12	W10-W12	W11-W12	W12-W13	W13-WN
Distance (m)	6.62	3.72	5.40	2.02	2.92	1.94	4.38	3.96	1.00	6.95	7.99	6.08	2.00	1.00

Table 2
The area of each divided area.

	P1	P2	P3	P4	P5	P6	P7	P8	PS	PN
Area (m^2)	15.21	9.02	6.00	3.73	13.22	8.83	29.36	4.38	2.00	2.00

– **Pre-movement time**: starts from the alarm activated to the first child left the classroom door (Kholshchevnikov et al., 2012; Larusdottir, 2014; Hamilton et al., 2017).

(b) The pre-movement period is divided into two stages according to the children's behaviour: Recognition time and Response time. They are gathered by analysing the CCTV footage of the classroom (Fig. 4).

– **Recognition time**: the fire alarm activates, the children put down their toys and look around;

– **Response time**: Stand up, walk to the front of the classroom with classmates and look for the teachers' instruction, and then line up following the teachers' order. In the period, the children get together to form a group. When the teacher confirmed that all the children are running towards the line with help from the other teacher, they will start exiting the room. So the Response time may run past the end of the pre-movement period.

(c) The free walking speed and horizontal walking speed.

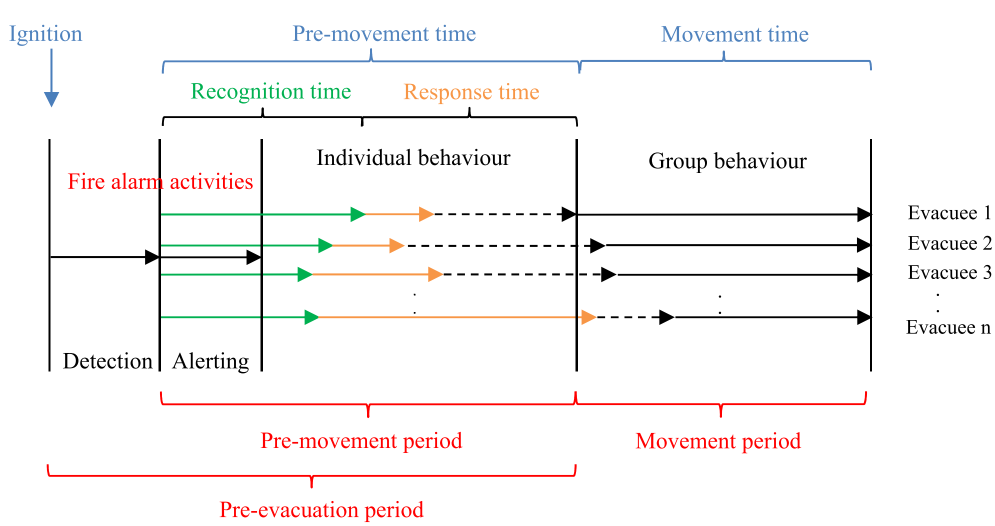


Fig. 4. Timeline of children's behaviour in the pre-movement and movement period.

– The **free walking speed** is the speed of children who are not disturbed or stopped, which is the determination of simulation parameter (speed of the agents) (Thunderhead Engineering, 2015). Free walking speed in different age groups at a low density (D < $0.5p/m^2$) is defined similar to German study (Lyzwa, 2018). In this study, 63 children were selected for an evacuation experiment. The experiment was at the clear aisle which is low density of children in a free movement scenario. From the west side of the aisle to the east side, these children were evacuating against the wall. The free walking speed was calculated by using the walking distance and time, which was also divided under three age groups for statistical analysis.
– **Horizontal walking speed** is the average walking speed of occupants from the classroom to the final exit, accounting for evacuation behaviours such as congestion, stoppages, etc.

2.2.3. Density

Density D of children in each divided area is determined by the mean of the instantaneous density at each moment during their stay in the area (Fig. 5), which is the number of occupants in each divided area in one second (person/m^2). However, the physical space occupied by children is different from that of adults (Predtechenskii and Milinskii, 1978), the density (person/m^2) should multiply the body ellipse area at 0.04 m^2 of children (Hamilton et al., 2020). Then, it is converted from p/m^2 to m^2/m^2.

2.2.4. Simulation set

This study uses Pathfinder as a simulation software because it is widely used in safety design in China. The limitation of most evacuation simulation software is that only adult behaviours are parameterized. It means that the software is only applicable to children whose evacuation behaviours are mature and similar to that of adults. In Pathfinder's Steering mode, the evacuation routes were set according to the drills, and the motion correcting interval in the simulation was set to 0.1 s. The free walking speed without interference, which avoid the random events such as obstruction, turning back and congestion, may appear in the actual situation in evacuation drill. The software will automatically allocate environmental elements, for example, avoiding obstacles (Thunderhead Engineering, 2015). Since the teachers were leading the children during evacuation drills, they interact with each other (Klupfel et al., 2003; Ono et al., 2012; Hamilton et al., 2017), so the walking speed of the teachers is defined the same as the children's. Relevant data of the teachers and the children are set in terms of the Chinese body dimensions standard. The teacher's height was set as 1.65 m, and shoulder-width was 0.40 m, and the height of children was set as 1.07 m, and shoulder-width was 0.26 m (National Health Commission of the PRC, 2009). The definition of movement time in simulation is consistent with that in the experiment.

3. Results and discussion

3.1. Pre-movement

3.1.1. Pre-movement time

Table 3 shows the pre-movement time of each class in the three drills. Compared with other literature (Hamilton et al., 2017; Cuesta and Gwynne, 2016; Lyzwa, 2018; Najmanová and Ronchi, 2017), the pre-movement time is relatively short. A-1 and B-1 class have the same number of children and teachers, and the mean pre-movement time differs by 1.7 s, indicating that pre-movement time might related to the age of children. After analysing the mean value of the pre-movement time in the three age groups, it shows that the older the children, the less the pre-movement time.

3.1.2. Behaviours in the classrooms

There are 2–3 teachers in each class. The children are divided into 2–3 groups and sit at the desks (Fig. 6). When the fire alarm started, the children put down the toys, look around (Recognition time). Following the teachers' instruction, the children stood up, pulled out the handkerchief from pockets and lined up by the door (Response time). It is shown that the classrooms are small, and the play area is not far from the classroom door (Fig. 6).

It is shown in Fig. 7 that the time it took the children to exit the classrooms are different among the three age groups in the experiments. The mean time required for the last child in A level classes to leave the door is 16.1 s, and 90% of the children spend 4–6 s of Recognition time, the mean Recognition time was 5.3 s. The mean time of the last child in B level classes to escape from the class door is 13.5 s, and the mean Recognition time is 4.2 s. In C level classes, the mean time for the last child to leave class is 11.4 s, and 80% of the children spend 2–4 s of Recognition time, and the mean Recognition time was 3.6 s. In summary, the mean Recognition time was 4.4 s, and the mean Response time was 9.3 s.

According to the data, the time it took A level classes to exit the classroom is the longest, and it is more dispersed, which is very different from the B level classes and the C level classes. The Recognition times of the younger children are close, indicating that the younger children had a more concentrated response when the alarm started, they found teachers' help directly. However, the elder children look around to confirm the reaction of their peers before deciding whether to stand up. The Response time of 3 years old children was relatively dispersed. It was observed by CCTV that it took them longer to move from where they were to the front of the classroom.

Base on the data, it shows that many influential factors can affect the

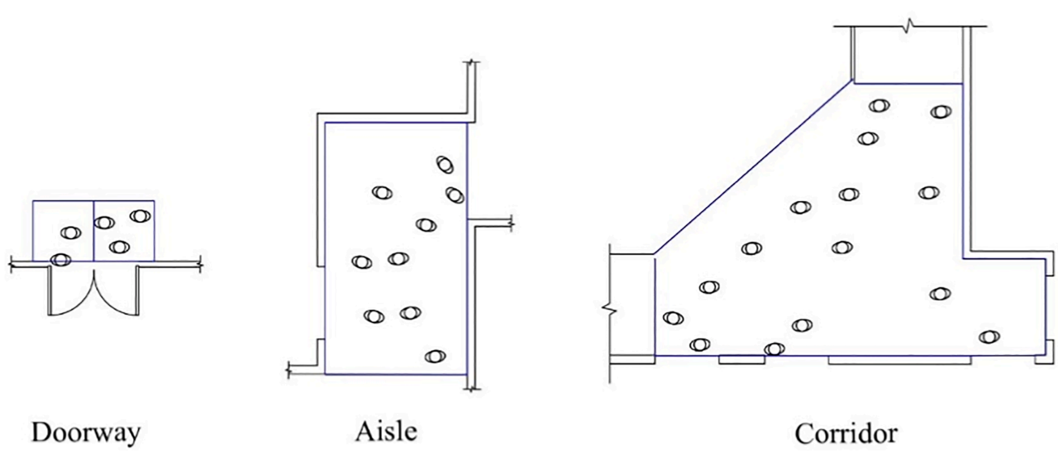


Fig. 5. The density reference area.

Table 3
Pre-movement time.

	Class	Age (yrs old)	No. of children (n)	No. of Adults (n)	Pre-movement time (s)				
					Drill 1	Drill 2	Drill 3	Mean	
Current study	A1	3–4	17	2	14.8	14.4	13.2	14.1	14.4
	A2	3–4	21	3	17.2	13.6	13.2	14.7	
	B1	4–5	17	2	12.4	12.8	12.0	12.4	12.5
	B2	4–5	16	2	13.2	12.4	12.0	12.5	
	C1	5–6	16	3	12.0	11.6	11.2	11.6	11.8
	C2	5–6	14	2	11.6	13.2	11.2	12.0	
	Total	3–6	71	14	–			12.9	
Cuesta and Gwynne (2016)	–	6–12	–					21.8	
Hamilton et al. (2017)	–	4–12	–					18.5	
Lyzwa (2018)	–	0–6	–					60	
Najmanová and Ronchi (2017)	–	3–4	–					46	
		5–6	–					20	

Fig. 6. Behaviours in the classrooms.

time, including the behaviours in the pre-movement phase and the children's movement in the classrooms. The children's condition at the moment is another curial factor, which comprises children's age, reaction speed, and behaviour, whether they are well trained, and the children's activities before evacuation. Moreover, the state of object factors come into play, such as the arrangement of desks and chairs in the classroom, children's location and the distance from the classroom door, the number of children and teachers in the classroom, and evacuation method (whether escaping in a line, covering mouth and nose).

3.2. Walking speed

3.2.1. Free walking speed (unaffected walking speed) during an experimental evacuation

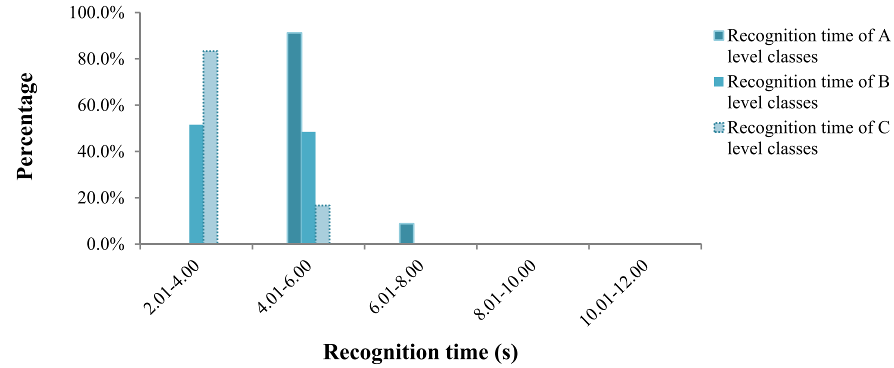
Table 4 shows that the mean free walking speed is 1.05 m/s, which is in the range of Lyzwa's (Lyzwa, 2018) study (0.72 m/s-1.07 m/s). Also, the value is less than that of adults (1.20 m/s-1.30 m/s) in low densities (Hurley et al., 2016; Larusdottir, 2014). The free walking speed is higher than the parameters (0.92 m/s; 0.80 m/s) of children evacuation simulation mentioned in previous literature (Tang et al., 2019; Tian, 2018) in China.

3.2.2. Horizontal walking speed

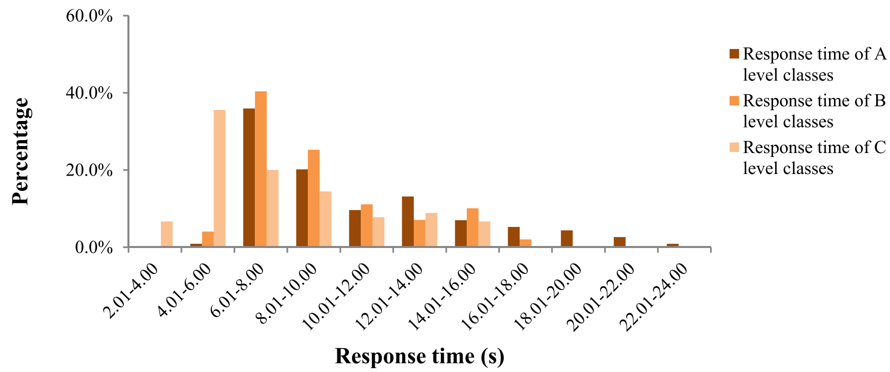
Table 5 shows the horizontal walking speed of children, which is in different areas and varies from age to age. The different value of the mean of horizontal walking speed between A level classes and B level classes is 0.02 m/s, and it is 0.05 m/s between B level classes and C level classes. The mean walking speed of all children aged 3–6 years was 0.86 m/s. Shown in Fig. 8, the speed of 60% of children aged 3–4 years is between 0.80 and 0.90 m/s, and the distribution is concentrated. The speed of 27% children aged 4–5 years is between 0.80 and 0.90 m/s, and 23.4% of them is between 0.90 and 1.00 m /s. The speed of 23.3% children aged 5–6 years ranged from 1.20 to 1.30 m /s. It can be seen that the distribution of the horizontal walking speed becomes more dispersed with the increase of age.

3.2.3. Comparison with literature reviews

Table 6 presents the comparison between current study and literature. The mean horizontal walking speed (0.86 m/s) is almost the same as that of Larusdottir & Dederichs (Larusdottir and Dederichs, 2011a, 2011b) (0.84 m/s). In the Japanese study, some 5-year-olds were faster than the current study's because they were running during the evacuation (Furukawa, 2013). Also, the walking speed in Shanghai's study (Fang et al., 2019) was lower than that of this study, which was also conducted in China. According to the figures in their article, because the children were not evacuated in a line, congestion occurred during the evacuation. The density is higher than the current study, which could influence the speed. As previous research (Klupfel et al., 2003; Ono et al., 2012; Hamilton et al., 2017) mentioned, the teachers have a great influence on the evacuation speed. The children in this study were



(a) The Recognition time distribution.



(b) The Response time distribution.

Fig. 7. The time distribution of children movement in the classrooms.

Table 4
The free walking speed of children in different age groups.

Age	No. of Children	Free walking speed			
		Mean	SD	95% Confidence Interval	
(years old)	(n)	(m/s)	σ(m/s)	Max.(m/s)	Mini. (m/s)
3–4	21	0.9125	0.0474	0.9341	0.8909
4–5	22	1.0900	0.0501	1.1122	1.0678
5–6	20	1.1530	0.0519	1.1773	1.1287
Total/Mean	63	1.0508	0.1098	1.0793	1.0224

Table 5
Horizontal walking speed in each age group.

Age (yrs old)	Density (m^2/m^2)	Sample No. (n)	Horizontal walking speed (m/s)		
			Mean	SD	95% Confidence interval Min./Max.
3–4	D = 0–0.040	417	0.8512	0.1244	0.8393/0.8632
	D = 0.0401–0.080	265	0.8190	0.1158	0.8050/0.8330
	D = 0.0801–0.120	2	0.8217	0.0165	0.6736/0.9697
	D = 0–0.120	684	0.8400	0.1184	0.8308/0.8486
4–5	D = 0–0.040	248	0.9005	0.1976	0.8758/0.9252
	D = 0.0401–0.080	133	0.7963	0.2478	0.7538/0.8388
	D = 0.0801–0.120	12	0.8556	0.3948	0.6048/1.1065
	D = 0–0.120	393	0.8638	0.2281	0.8412/0.8865
5–6	D = 0–0.040	113	1.0162	0.2094	0.9772/1.0553
	D = 0.0401–0.080	146	0.8277	0.3323	0.7734/0.8821
	D = 0.0801–0.120	11	0.8883	0.3297	0.6668/1.1098
	D = 0–0.120	270	0.9091	0.3004	0.8731/0.9451
3–6	D = 0–0.120	1347	0.8606	0.2025	0.8498/0.8715

required by the local government to evacuate in line during the evacuation. As faster children have to wait in line, however, the congestion was less likely to occur.

3.2.4. Speed-density relationship

In each divided area, the maximum density value was 0.120 m^2/m^2, which occurred in the PN area in each drill. The mean density of the whole area in the three drills was 0.034 m^2/m^2. According to Table 7, during the three drills, the density value of each area is between 0 and 0.120 m^2/m^2, and it is relatively low. Because the children were evacuated in lines, there was less congestion.

In the corridor/aisle area, the mean density in the turning area of P4 is the highest (Table 8), and the maximum value of density is 0.097 m^2/m^2 in Drill 2, when class B-2 and two A level classes met. Because the corridor is narrow, the turning area quickly became crowded. In P4 area, the children's mean speed is low while A level classes have the lowest speed (0.82 m/s). In the lobby area (P8), the density of P8 reaches the maximum (D = 0.091 m^2/m^2) at 11 s. Since the area from each classroom door to W12 is spacious, the children of the three classes entered the P8 area smoothly, which is less than 3.0 m away from the 1.5 m-wide North Exit, and the evacuees are gathered here, this area has a high density. The mean density value of Route 2 is higher than that of Route 1, the mean density was the highest in PN, and the mean speed was the lowest. According to the data analysis of the three drills, the children's walking speed is different in each area. Therefore, the influence of density is inconclusive. As higher density conditions did not occur due to the evacuation procedures, such a finding is common in evacuations of children in controlled circumstances.

3.2.5. Comparison of speed-density relationship with adults'

The maximum speed of the children in A level and C level classes was

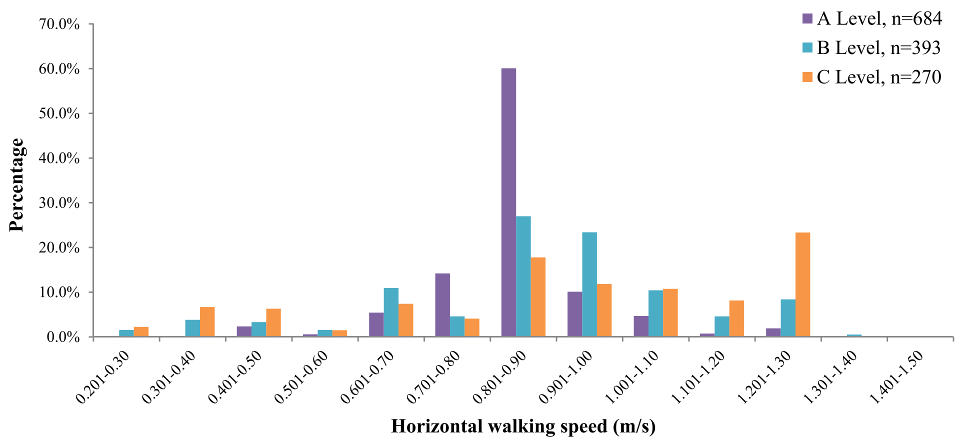


Fig. 8. Distribution of children's horizontal walking speed.

Table 6
Comparison of horizontal walking speed with literature reviews.

Study	Age (yrs old)	Sample No. (n)	Walking speed (m/s)
Dalian, China (Current)	3–4	684	0.84
	4–5	393	0.86
	5–6	270	0.91
Shanghai, China(Fang et al., 2019)	5–6	206	0.81
Russia(Kholshchevnikov et al., 2012)	3–4	34	0.78
	4–5	31	0.85
	5–7	39	0.86
Denmark(Larusdottir and Dederichs, 2011a, 2011b)	3–6	–	0.84
Czech Republic (Najmanová and Ronchi, 2017)	3–4	42	1.02
Ireland (Hamilton et al., 2017)	4–12	755	1.46
Japan (Furukawa, 2013)	3–4	28	1.07
	4–5	33	1.47
	5–6	54	1.68

1.25 m/s, which occurred in several areas. The maximum speed of the children in B level classes was 1.31 m/s with a density of 0.015 m^2/m^2, which occurred in P6 area of Drill 2.

The study of the relationship between walking speed and density can give a reasonable quantitative evaluation of human behaviour during the whole evacuation process. According to the literature that studies the adults' evacuation behavioural data, the density of the evacuees has a significant impact on the speed (Cuesta and Gwynne, 2016). By analysing the speed and density data of the children's evacuation, the relation between walking speed and density is established, shown in formula (1).

$$S = 0.928 - 1.6788D \tag{1}$$

The D value of density in this experiment is low. The speed is slowly decreasing as the density increases (Fig. 9). This phenomenon is consistent with the speed-density relationship of adults given in SFPE (Gwynne and Rosenbaum, 2016). However, it can be seen in formula (1) and Fig. 9, the children's speed of all age groups is lower than that of adults at the same density. Compared with B level classes and A level classes, the speed of children in C level classes is close to that of adults. It indicates that the evacuation behaviour of children in the C level (5–6 yrs old) is similar to adults because they are taller, faster and more coordinated with each other under the teachers' guidance during the evacuations.

3.3. *Flow rate*

The flow rate is the number of people passing through a clear width

Table 7
The mean walking speed and density in each area.

Marked position	Age (yrs old)	No. of children (n)	Density (m^2/m^2)		Walking speed (m/s)	
			Mean	95% Confidence interval Min./Max.	Mean	95% Confidence interval Min./Max.
P1	3–4	114	0.023	0.021/ 0.025	0.8604	0.8497/ 0.8710
P2	3–4	114	0.036	0.033/ 0.040	0.8527	0.8424/ 0.8630
P3	4–5	48	0.021	0.019/ 0.023	0.9471	0.9144/ 0.9799
P4	3–4	114	0.042	0.038/ 0.045	0.8178	0.8008/ 0.8348
	4–5	48			0.8641	0.8392/ 0.8891
P5	3–4	114	0.022	0.020/ 0.024	0.8642	0.8528/ 0.8757
	4–5	48			0.9452	0.9096/ 0.9808
P6	3–4	114	0.029	0.027/ 0.032	0.8694	0.8451/ 0.8938
	4–5	48			0.8996	0.8508/ 0.9485
P7	4–5	51	0.019	0.017/ 0.021	0.9225	0.8697/ 0.9752
	5–6	90			0.9995	0.9578/ 1.0411
P8	4–5	51	0.048	0.044/ 0.052	0.8249	0.7345/ 0.9153
	5–6	90			0.8883	0.8242/ 0.9524
PS	3–4	114	0.042	0.038/ 0.046	0.7737	0.7357/ 0.8117
	4–5	48			0.7537	0.6975/ 0.8100
PN	4–5	51	0.057	0.052/ 0.063	0.7565	0.6541/ 0.8589
	5–6	90			0.8395	0.7651/ 0.9138

(Hamilton et al., 2020) in a unit of time (second). The maximum flow rate obtained in the three experiments was 4.615 p/m·s, which occurred in the PN area of Drill 3.

3.3.1. *Flow rate at the marked position*

The flow rates at the marked positions in the two routes are shown in Table 8. Because the boundary layer is not considered when children evacuated, the width of each marked position is the clear usable width (Hamilton et al., 2020). The flow rate is lower in W7 due to its width (2.88 m), the density of P5 was not too high to fill the clear width at the

Table 8
Flow rate at the marked positions and the density of divided areas.

Area	Marked position	Width (m)	Drill No.	Flow rate (p/m·s)		Density (m^2/m^2)	
				Mean	95% Confidence interval Mini. /Max.	Mean	95% Confidence interval Mini. /Max.
Corridor/aisle	W3	1.54	Drill 1	0.9972	0.8368/1.1577	0.020	0.017/0.024
			Drill 2	1.2140	0.9422/1.4858	0.024	0.021/0.028
			Drill 3	1.1169	0.8910/1.3427	0.024	0.020/0.028
	W4	1.54	Drill 1	0.9307	0.7661/1.0954	0.032	0.027/0.038
			Drill 2	1.0739	0.8931/1.2548	0.039	0.033/0.045
			Drill 3	1.2140	0.9170/1.5110	0.038	0.031/0.045
	W6	1.70	Drill 1	0.9698	0.8220/1.1175	0.039	0.034/0.043
			Drill 2	1.1765	0.9531/1.3999	0.043	0.036/0.050
			Drill 3	1.1385	0.9720/1.3051	0.044	0.038/0.049
	W7	2.88	Drill 1	0.5724	0.4896/0.6553	0.020	0.018/0.023
			Drill 2	0.6076	0.5177/0.6976	0.023	0.019/0.026
			Drill 3	0.6496	0.5234/0.7759	0.024	0.020/0.027
	W8	2.00	Drill 1	0.8243	0.6762/0.9725	0.026	0.023/0.029
			Drill 2	0.8714	0.7375/1.0054	0.030	0.025/0.034
			Drill 3	0.8971	0.7376/1.0565	0.033	0.029/0.037
	W12	2.14	Drill 1	1.2016	0.9040/1.4992	0.020	0.016/0.024
			Drill 2	1.2016	0.8549/1.5483	0.019	0.015/0.024
			Drill 3	1.0971	0.8273/1.3669	0.018	0.014/0.022
	W14	1.98	Drill 1	0.6494	0.5126/0.7861	0.021	0.017/0.025
			Drill 2	0.6494	0.5126/0.7861	0.023	0.019/0.026
			Drill 3	0.6494	0.5126/0.7861	0.019	0.016/0.023
	W13	2.00	Drill 1	1.1250	0.7770/1.4730	0.050	0.043/0.056
			Drill 2	1.2857	1.0017/1.5697	0.048	0.041/0.056
			Drill 3	1.0000	0.7097/1.2903	0.044	0.038/0.051
Exit	WS	1.60	Drill 1	1.0033	0.8482/1.1583	0.040	0.033/0.047
			Drill 2	0.9776	0.8049/1.1502	0.041	0.034/0.047
			Drill 3	1.1553	0.9261/1.3846	0.045	0.037/0.052
	WN	1.30	Drill 1	1.5382	1.1608/1.9157	0.059	0.049/0.070
			Drill 2	1.5975	1.1954/1.9995	0.058	0.046/0.070
			Drill 3	1.5382	1.1902/1.8862	0.055	0.046/0.064

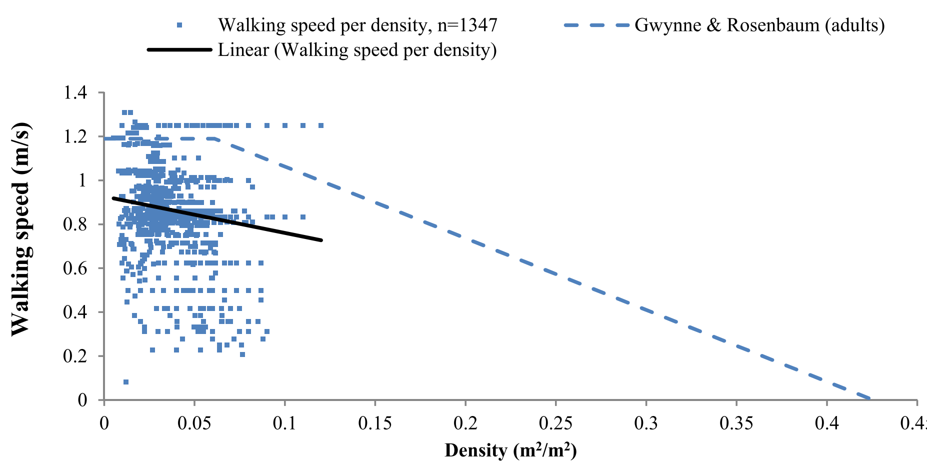


Fig. 9. A comparison of walking speed-density between the children and the adults.

same time. Also, it has a greater influence on the convective rate under the condition of low density (D $\leq$ 0.120 m^2/m^2 because of the children's small body size. It is similar to the analysis of other literature (Larusdottir, 2014; Capote, 2012). The occupants are narrower and can fit through exits much easier than adults. Moreover, each divided area is based on the function of the building. The density is lower in P7, and the different geometric shapes of the area also have a great impact on the flow rate.

3.3.2. Comparison of flow rate-density relationship with adults'

According to the evacuation behavioural data in this study, the relationship between flow rate and density of the children is shown in formula (2).

$$F = 120.6*(0.2686 - D)D \quad (2)$$

Fig. 10 shows that the flow rates first increase and then decrease, which is similar to adults (Gwynne and Rosenbaum, 2016). However, according to the experiment data, the curve in this study is obviously higher than the adults' curve, which is similar with other literature (Hamilton et al., 2020; Larusdottir and Dederichs, 2012). At the same time, the maximum flow rate obtained in this paper is 4.615 p/m·s, which is more than 3 times the maximum of adults. This is because the children's smaller body size occupies less space. Children have no sense of boundaries, it makes several children easier to pass through at same time.

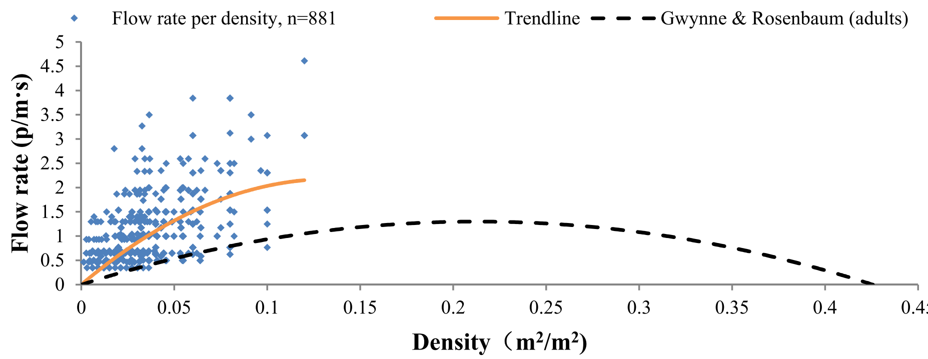


Fig. 10. Comparison between the children flow rate-density with adults'

3.3.3. *Density and flow rate at the exits*

The density of the two exits areas is shown in Table 8. At WS of the PS, the maximum density occurred in Drill 3. In the PN area of WN, the maximum density occurred in Drill 1. The density of PS area at WS is almost between 0.04 and 0.06 m^2/m^2, and the density of PN area at WN is mostly between 0.06 and 0.08 m^2/m^2. Both exit areas are low in density ($D \leq 0.120$ m^2/m^2). The low density might be the result of the orderly evacuation guided by the teachers, which reduced congestion.

In Fig. 11, the flow rate at WS is mostly between 0.501 and 1.00p/m·s, and at WN, the flow rate is mostly between 0.501 and 1.50p/m·s. The distribution histogram of the flow rate at two exits are showing a different shape. WS histogram is unimodal, while WN is a bimodal histogram, which is relatively steady. It suggests that two processes occurred at WN. Fig. 11(b) shows a zero probability for a flow rate between 1 and 1.5. The flow rate was lower for a while and suddenly became higher for a period at WN. At WS, because the B-2 is close to WS, they arrived in the PS area first. Then A-1 and A-2 arrived successively. Because the three classes met at P6 and PS for only a short period, the density was low and caused no congestion. However, children of B-1, C-1 and C-2 classes were evacuated to the exit at the same time. Since the width of WN is only 1.3 m, there was a higher density at P8 and PN, the flow rate was higher.

3.4. *Simulation*

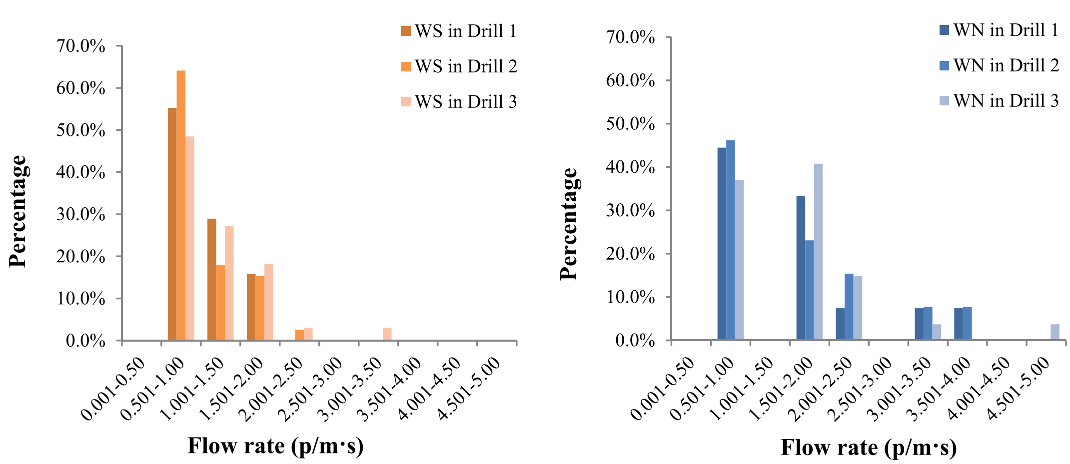
3.4.1. *Comparison of movement time*

The free walking speed was calculated (1.05 m/s) and entered. The movement time of the simulation is 57.3 s, which is basically consistent with the experiment. The movement time of the three drills was 62.0 s, 55.2 s and 52.4 s respectively, and the movement time of the Drill 3 was the shortest. The curve regression of evacuees and time is calculated by using simulation data. Fig. 12 shows that the curve data obtained by the drills and the simulation data are in good agreement. The curves are linear, indicating that the evacuation path is barrier-free and relatively continuous. The movement time of the Drill 1 is greater than the simulated time, and the movement time of the Drill 2 and Drill 3 is shorter than that of simulation. The input speed parameter is a fixed value, and there is no teachers' instruction or changes in children's psychological status in the simulation. So the differences are more obvious between simulation and drills in areas prone to congestion. In the drills, the teachers' guidance reduced the congestion. It would no doubt harmonise the flow of children, however, there is no evacuation guidance from conductors in the software. This may cause the movement time of the simulation different from the drills.

3.4.2. *Comparison of flow rate*

Table 9 shows the mean flow rate at each exit in the simulation. Fig. 13 shows the probability distributions of flow rate at two exits in drills and simulation. The flow rate of the two exits in the simulation is concentrated in 0.501–2.00 p/m·s. The maximum flow rate was 3.125 p/m·s at WS, the maximum flow rate was 4.615 p/m·s at WN.

Looking at the overall situation of the three experiments, the flow rate distribution of the two safety exits is dispersed, and the maximum value of the flow rate is higher than that in the simulation, which reflects the random events in the drills.



(a) Probability distribution of flow rate at WS. (b) Probability distribution of flow rate at WN.

Fig. 11. Probability distribution of flow rate at two exits.

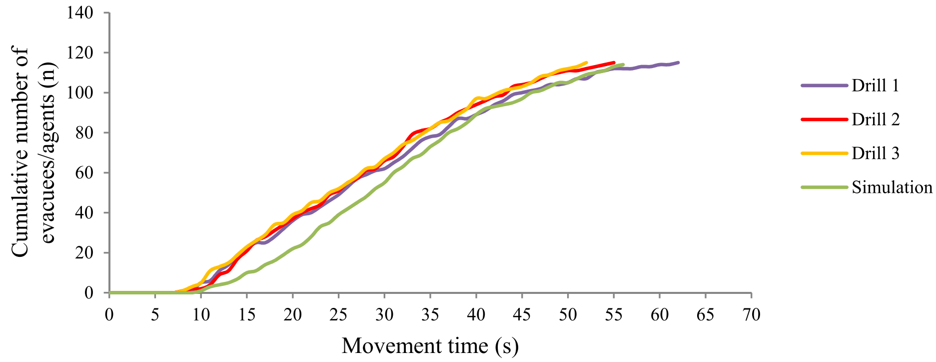
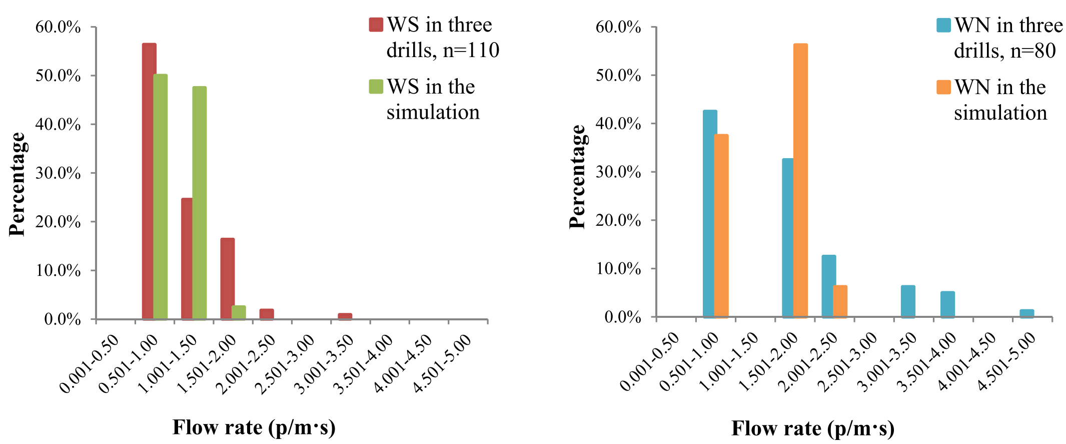


Fig. 12. Movement time comparison between experiments and simulation.

Table 9
The time of the last child/agent passing through the exits and the mean flow rate.

Exit	Width (m)	Movement time (s)				Mean flow rate (person/m·s)	
		Drill 1	Drill 2	Drill 3	Simulation	Drills	Simulation
WS	1.60	62.0	55.2	52.4	57.3	1.0398	0.9531
WN	1.30	40.0	41.2	39.6	40.4	1.5574	1.2980



(a) Probability distributions of flow rate at WS. (b) Probability distributions of flow rate at WN.

Fig. 13. Probability distributions of flow rate of drills and simulation at the two exits.

4. Summary

4.1. Recommendations

According to the floor layout and the classes' arrangement in the kindergarten, we would recommend that the kindergarten had better switch the A level classes with Class C level classes, considering the walking speed of different age groups. Because switching the classes can reduce the distance that A level classes have to cover during an evacuation. The speed data were collected from children's movement at a horizontal space. Therefore, the travel speed on stairs was not included in this study. One of the mandatory provisions for the kindergartens architectural design in China is that the stories of a building cannot be more than three. Although single-storey kindergartens are common, multi-storey buildings are popular in cities. It is also necessary to compare the behaviour data of children of different ages. Therefore, it is necessary to research on behavioural data of children's movement on stairs. A comparative study of the children's behavioural data in different age groups is also valuable.

4.2. Limitations

This study does not take the time of the children putting on outerwear into consideration because the evacuation drills were conducted in summer. In addition, the evacuation drills in this study were carried out under announced preparation in advance, so the pre-movement time could be different if it is unannounced or conducts in winter. Therefore, in the future, it is necessary to conduct evacuation drills in other methods and seasons to expand the pre-movement data.

By analysing the research methods and research scope of the paper, the limitations are put forward as follows:

(a) The way of dividing the areas and marking the positions could be improved.
(b) The design of the experiments is subject to the local by-laws and regulations (i.e., orderly queuing; covering their mouths & noses). It is reasonable to question, whether the children can queue up in an orderly manner during a real situation. They may rush to safety before getting a handkerchief in pre-evacuation.

(c) As the Fire Department provided instructions to pupils/teachers in advance concerning the evacuation. This situation would not occur with respect to real incidents and could have improved the evacuation performance.
(d) In this study, only the children's evacuation behaviours that happened inside the building are analysed. In the future, we should also pay attention to the behaviour that happened outside the building, such as outdoor steps. Since the exit is a bottleneck, the density outside the exit door may be more relevant to the flow than the density approaching the exit.

4.3. Conclusions

In this study, the children of three age groups had a free walking speed (unaffected speed) of 1.05 m/s at low density during an experimental evacuation. In three evacuation drills, the training of evacuation procedure is fairly mature, mean of the horizontal walking speed is 0.86 m/s and the children are conscious of taking necessary actions during an emergency scenario. The movement time and pre-movement time decrease as age increases. This may be related to the different ability to follow teachers' commands among various children's age groups. Younger children may need more training to familiarize themselves with the evacuation procedures, such as covering their mouths and noses, evacuating in line. Moreover, the Recognition time (mean 4.4 s) and Response time (mean 9.3 s) of children were varied greatly.

The mean flow rate at each marked position was 0.572–1.598 p/m·s; the mean density of each divided area was 0.018–0.059 m^2/m^2, which were influenced by the geometry of divided area, width of position/exits, evacuation method, etc. In this study, the 3–6 years old children's density-speed relationship curve was compared with that of adult', the two curves are similar in shape, and the speed decreases with the increase of density. However, the children's curve decreases more steadily. It could be because the impact of density on children's speed is less than adults. The curve of density-flow rate shows that the children's behaviour is different from that of adults, which is similar to other literature (Hamilton et al., 2020; Larusdottir and Dederichs, 2012). At the same density, the flow rate is higher than that of adults. The movement time of three drills (mean 56.5 s) is similar to the simulation results (mean 57.3 s), indicating that Pathfinder is suitable for the simulations.

This study expanded the applicability of the software and increased the reliability of children evacuation simulation. The children followed the teacher's instructions and always evacuated in line, so the teachers' guidance can lessen the impact of the children's behaviours on movement time, which is the same as in previous literature (Taciuc and Dederichs, 2014; Baharudin et al., 2018). Therefore, the more evacuation drills and training, the higher the accuracy of the simulation results will be. Moreover, the walking speed parameters in this study can be used as a reference for future researches on children's behaviour. It can also optimize the safety design of kindergarten buildings, such as the width of the corridor and exit, the size of stairs, the length of the hallway (Gwynne & Galea, 1999). This study provides a reference for kindergarten architectural design and fire safety code revisions.

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