Assessing school evacuation movement characteristics: children and adolescents speed and flow over stairs and through exit doorways

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Abstract - The available theories of evacuation movements are primarily founded on data gathered from adults, making them potentially unsuitable for children, especially in schools. Consequently, it is necessary to undertake further research to collect data on how children move during evacuations to understand their unique characteristics and disparities compared to adults. In this context, this paper aimed to explore the movement of school children and adolescents as they moved over stairs and through exit doorways during evacuations. The evacuation drill involved 295 school children and adolescents, whose behavior was closely monitored using a series of cameras. During the drill, their movement patterns, including flow and speed, were analyzed over stairs and through doorways. The observations revealed that children exhibited frequent interactions and contact with one another, unlike adults, who tend to maintain personal space. The findings of this study indicated that the average traveling speed over stairs was comparable to previous research, although female adolescents had a lower average speed compared to other groups. The speed and flow of participants passing through doorways were found to vary depending on their age and differed from estimates based on adult data. This study highlights that existing evacuation models fall short of adequately accounting for the dynamics of children, indicating the need for further research to improve the generalizability of evacuation models.

Keywords: stairs, vertical speed, children, school, evacuation, doorways

Introduction

Designing safe evacuation routes in buildings has a determinant effect on the overall success of fire safety strategies. The success of the design relies on accurate information about building evacuation characteristics, allowing for up-to-date codes and standards or performance-based design methods widely applicable to the public. In the latter case, estimating human behavior and movement characteristics on various egress components has been key to the approach's success. As a result, empirical methods for estimating occupant speed and flow have been developed[1], which are incorporated in available models and simulations for performance design use. These applications are growing thanks to advances in computing technologies.

Concerns over the validity of methods for different public groups have always been subject to research. Preliminary studies on crowd movement characterized pedestrian dynamics in buildings, such as flow velocities and rates, illuminating important parameters affecting evacuation times[2],[3]. Different evacuation components have been characterized through unannounced or quasi-

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announced evacuation drills, including pre-evacuation delay time[4,5]. Movement speeds and flow rates over horizontal surfaces such as corridors, straight and spiral stairs[6,7,8], and near and through exit doorways[9]. Further efforts have expanded information and data to other groups of occupants, such as elderly and disabled people[10,11,12]. The findings highlighted several important factors in determining evacuation behaviors, including building configurations, environmental conditions, and occupant characteristics, which ostensibly impact mass movement and total evacuation times. Some studies have also addressed the role of occupants' attire on movement speeds over different components of egress routes[2,13]. In contrast, others have argued that the same level of attention should be given to occupants' physiological and behavioral aspect, such as emotions, in addition to their mechanistic properties[14,15].

However, many of these studies concentrated on adults' movement during fire evacuations, and limited information is available about children's movements in schools. Children and adolescents constitute a considerable part of our societies, and they are the most vulnerable to emergency conditions such as fires[16]. Unlike adults, children's mental processing and decision-making functions may not be necessarily similar, and they may respond differently to fire cues. Additionally, their physiology is still growing and immature, resulting in different movement capabilities compared to adults. Cultural differences from one region to another can alter the perception of risks and urgency for evacuation, ultimately impacting evacuation behaviors and children's movement properties. Also, evacuation procedures can significantly influence the behavior of evacuees, especially immature children, resulting in different evacuation behavior scenarios. Therefore, assuming similar evacuation behavior of adults and children may lead to misinterpretations and movement miscalculations, particularly in schools where most building occupants are children and underage.

Available data on school evacuations has mainly been collected through evacuation drills. A series of evacuation drills in schools in Russia showed that children's age, the school's geometry, familiarity with stairs, and supervision by adults are influential factors in their vertical traveling speed[17]. The vertical speed of school children over stairs was measured through a series of evacuation drills implemented in primary schools in Ireland, where the authors found that the vertical speed of pupils changes proportionally with their ages[18,19]. They also noted the effect of handrail usage on the vertical speed of children in schools. Najmanova and Ronchi studied the traveling speed of pre-school children on stairs and horizontal surfaces in schools. They concluded that children's age, familiarity with escape routes, and environmental conditions determine their movement speed[20,21]. A series of evacuation drills in Brazilian schools with children of ages ranging from 6 to 14 years were carried out to investigate their movement characteristics[22,23]. The authors concluded that teachers' behavior and instruction during evacuation are crucial factors in characterizing the movement of adolescents and children in schools. Larusdottir conducted a series of evacuation drills and monitored children of different age groups in Danish schools and daycares[24,25,26]. The author monitored the motions of children aged 1to 15 years over spiral and straight stairs and through doorways. The study showed significant differences in speed and flow of children compared to adults. Studies on school children in Spain showed that children have higher movement speeds than adults[27]. Similar results were reiterated by Fang et al.[28] and Yao and

Wu[29,30]regarding the role of adults' guidance on children's movement characteristics. It was also found that children's movement through doorways is different from that of adults[31].

The main takeaway from previous studies on the dynamics of children's evacuation in schools unanimously highlights the differences between their movements and the estimations provided by available methods prescribed for adults. Additionally, evacuation characteristics can vary from region to region due to cultural differences, which can directly influence evacuation behavior, particularly among school children. This limitation necessitates further studies on children's evacuation behavior from different regions to expand our current understanding of school evacuations and contribute to the data on school children's evacuations. These two facts have motivated the current research to collect evacuation movement data on school children and compare their characteristics with other research findings.

Our objectives are twofold: first, to expand the available data on children and adolescent movements during evacuations in the schools, and second, to broaden the data by sampling from underrepresented parts of the world. In this paper, we presented the results of a quasi-announced evacuation drill conducted in a K-12 school in Muscat, Oman, assessing the movement of children and adolescents over stairs and through exit doorways.

Methods

Evacuation Site and Procedure

The evacuation drill was conducted in a school located in Muscat, Oman. The school serves pupils of all ages, from pre-school to grade 12. Pre-school classes are held in the basement, and the levels increase as they move toward the third floor. Only students over 7 were included for this study, and pre-school children were excluded for safety reasons. On average, each floor had over ten classrooms, accommodating 15-20 students with mixed gender profiles in each class.

The school is located in a four-story building with a total student population of over 300 across all levels. Figure 1 provides floor plans for the ground and first floor of the school. The ground floor consists of a large academic affairs office located in the center, separating classrooms on the east and west sides of the floor. The first, second, and third floors have similar layouts, with additional classrooms, conference rooms, and laboratories located in the center compared to the ground floor. A football pitch on the west side of the building is designated as the assembly point for all staff and pupils during emergencies. The staff-to-student ratio, as addressed by the school administration, was 1/21, and the drill primarily relied on students' self-evacuation, with minimal instructions provided by the classroom instructor to evacuate towards the corridors.

The building had three exits: one known as the main exit, locate on the south side, one exit on the west side of the building facing the football pitch; and the third exit, located on the east side of the building, opposite the west exit, facing a corridor that goes around the building and leads to the football pitch. Each exit is connected to stairs that pass through to the 3rd floor. For this study, only the east and west exits were used for occupant evacuation, and the main exit remained closed based on the school evacuation plan. Figure 2 provides geometrical details of the exits and stairs.

The evacuation drill was scheduled for a Thursday, the last working day of the week in the country, at 11 AM when all students attended their classes. Only the school management office had information about the date and time of the semi-announced drill, and the research team arrived one hour before the drill to minimize contact with students and staff. The drill involved all students on the first, second, and third floors evacuating the building after hearing the fire alarm controlled by the investigation team. The egress routes included the east and west side stairs, and students had to evacuate the building through the east and west exit doors.

The authors obtained a consent letter from the school director regarding the evacuation drill and permission to use the information for research purposes. Ethical clearances were also obtained from the research and ethics committee of the first author's institute. Additionally, the Civil Defense Authority was informed about the drill, and a representative from the authority oversaw the process.

Data Collection

Six cameras were used on the stairs and exit doors. Two cameras were positioned above the landing on each stair between the ground and first floors to monitor the movement of participants. The other two cameras are mounted at and near the exit doors to record exit flows. The cameras were set up half an hour before the drill while all students were inside the classroom to prevent any students from noticing the evacuation drill. Also, two handheld cameras were used to record students' movement during the evacuation and one camcorder used by school management to record the drill. Table 1 presents participants' characteristics, including their age range and grades. The pupils were categorized into two groups: children aged 7 to 12 and adolescents aged 13 to 17. The categorization was based on the presentation of results from previous works with similar or nearly similar groupings[17,27], and the aim was to make the results relevant for comparison purposes. Also, evidence suggests that decision-making and locomotion skills undergo critical changes at the age of 12[32,33]which corresponds to age categorization provided by the National Institute of Health[34]. The children and adolescents were marked based on their clothes to facilitate data processing by video editors for speed calculations, which will be presented in the paper.

Density

Occupant density over stairs and in front of doors has been calculated and presented using two approaches. The first approach is based on the number of people in reference areas within a defined duration, and it is presented in units of persons/m^2. In this case, the average number of people in the reference area at the beginning and end of the duration was used. The mathematical formulation for density as persons/m^2 is given by equation (1):

$$D_i = N_a/\Delta A \qquad (1)$$

Where N_a denotes the average number of participants in the reference area, and ΔA is the area of reference area measured in m^2. Reference areas were calculated over stairs and in front of doorways, as shown in Figure 2. The projection of the stair flight was calculated based on the horizontal length of the stairs and the slope of the stairs, which was measured on-site as 30 degrees using the following equation[2]:

$$L' = L.\cos \alpha \qquad (2)$$

Where L represents the horizontal projection of the stairs calculated using the thread and rise dimension given in Figure 2, and α represents the slope of the stair, which was measured as 30°. For doorways, the width of the doorway (1.48 m) and the landing depth of 1 m were taken as the reference area, as shown in Figure 2.

In the second approach, density was calculated based on the occupied projection area over stairs and in front of doorways, and it is presented as density in m^2/m^2. Average values provided by Predtechenskii and Milinski[2] for children and youth used in this study. In this case, an average value of 0.048 m^2 (with a range of 0.04-0.057 m^2) was used for children, and an average of 0.078 m^2 (with a range of 0.068-0.09 m^2) was used for adolescents, respectively. For adults, an average value of 0.1 m^2 [2,35] was used.

Speed Calculation

Evacuee speeds over stairs and near the exit doors were calculated using video editing software Filmora 12 at a frame rate of 25 fps and a resolution of 1920×1080. The total number of frames that a target evacuee passes through the reference area was calculated and then converted to their speed using the following correlation:

$$S\left(\frac{m}{s}\right) = \frac{L}{(Fr_{i1} - Fr_{i2}) \times 1/FR} \qquad (3)$$

The speed is measured in meters per second. $Fr_{i1}$and Fr_{i2} denotes the frame number of the target evacuee at the entrance and exit from the reference area, respectively. FR represents the frame rate of the video review, which was set as 25 frames per second. For the near door area, the distance on the landing before the doorway was measured as 1 m, and the width of the door was noted as 1.48 m. The same approach was applied to calculate the participants' speed and flow through doors, with a slight difference. Participants' speed was calculated with the length of the reference area and equation (3).

Flow Calculation

Flows over stairs were calculated as the product of speed and density, calculated by the above correlations, and divided by the effective width of the component as follows:

$$F = (SD_i)/W_{eff.} \qquad (4)$$

Which is measured in persons per second per meter of effective width (Persons/s/m). The effective width ($W_{eff.}$) was determined using values provided in the SFPE guide[1] for the boundary width of stairs and doorways. In this case, the effective width for stairs was calculated as 1.10 m. It is important to note that average densities at the beginning and end of the frames were used for flow calculations. The flow of participants through doors was calculated by counting the number of people passing through the doorways during a specific time for continuous flows of participants and using the average density of the beginning and end of the counting frames, presented as Persons/s. The calculated values were then divided by the effective width of the doorways, which was taken as 1.18 m, considering the recommended 0.15 m for the boundary width. The decision to apply the boundary width was based on a comprehensive review of videos, where it was observed that most participants moved over stairs or through exit doors while maintaining a distance from the edge.

Measurement Uncertainties

Uncertainty for density (Persons/m^2) is calculated relative to the uncertainty of counting the number of people on the reference area (±11.8%) and the uncertainty relative to the measurement of the reference area itself (±1.90%), resulting in a total uncertainty of ±1.80%. In the case of occupied density (m^2/m^2), the uncertainty depends on the measurement of the reference area (±1.9%) and the mean value for individual occupied projection area (±15.9%), resulting in a total uncertainty of ±8.9% for the occupied density measurement. For participant velocity, the uncertainty is calculated relative to the frame count (±1.80%) and the velocity uncertainty relative to the length measurement (L) (±0.6%), resulting in a total uncertainty of ±1.20% for velocity measurement. In flow measurement, the uncertainty is a combination of uncertainties calculated for density (Persons/m^2), velocity, and length measurements, resulting in a total uncertainty of ±1.2%.

Results

Behavioral Observations

Video observations revealed interesting aspects of school pupils' behaviors during the drill, which may not be commonly observed among adults. Figure 3 provides snapshots of these observations from the drill videos. In Figure 3a, one of the evacuees can be seen jumping over the last two stairs leading to the landing platform, using the handrail for assistance. This behavior can be explained as an act of excitement and is typically observed among schoolchildren. However, it only occurs when the density over the stairs is low enough to allow children to do so.

Figure 3b depicts a student who waits for his friends to come down the stairs, standing still for a few seconds and blocking the way for others descending. This behavior was also observed among two girls in the other stairway during the evacuation. Similar behavior has been reported in other studies conducted in nursery school[26], where children waited for slower peers, resulting in congestion and blockage on stairways and near doorways. This behavior may be explained by social bonding, where people try to respond to cues as a group rather than individually[36].

In Figure 3c, one of the participants tries to unintentionally prevent his friend or classmate from going down the stairs, indicating a sense of competition to reach the landing first. Figure 3d shows a student attempting to sneak through the side of an older student who appears to be moving slower. Common behaviors observed among both female and male children and adolescents were only those seen in Figure 3b and 3d. The other two behaviors recorded among male pupils in Figures 3a and 3c were not observed among their female counterparts. The impact of these behaviors on overall evacuation behavior and uncertainties is difficult to estimate. However, the uncertainties added to movement predictions by these behaviors of children require further consideration in future studies.

Total evacuation time

Figure 4a provides the flow rate of participants evacuating from the building through the eastern and western exit doors. The figure also presents the total counts of evacuees versus time during the evacuation period. A total of 295 school students evacuated from the building through the eastern and western exits during the drill. However, the number of students who chose the western exit was 20 students higher than those who selected the eastern exit. This choice may be attributed to the proximity of the west exit to the designated assembly point. The drill was concluded after the school fire wardens ensured that no one remained in the classrooms and floors, and they counted the students at the assembly point. Once the drill ended, the fire warden and their teacher instructed the students to return to their classes.

Regarding the eastern exit, there is an initial peak flow of 4 persons per second through the door, which continues until the end of the 229-second evacuation. However, the pattern is different for the western exit, where a peak flow of 5 persons per second is achieved in the middle of the evacuation, approximately 100 seconds after the start of the drill. The total evacuation through the western exit lasted for 307 seconds. The number of evacuees who used the western exit was slightly higher than those who used the eastern exit, likely because the western exit was closer to the designated assembly point at the football pitch. Figure 4b shows the cumulative arrival time of evacuees versus their order of arrival at the exits.

Mean traveling speeds over stairs

The mean speeds and standard deviations were calculated for the children and adolescents who participated in this study. Table 2 summarizes the mean flight speeds over stairs for both age groups. The mean speed was determined for children as 0.84 ± 0.06 m/s, with insignificant differences observed between females (0.89 ± 0.06 m/s) and males (0.80 ± 0.06 m/s). However, there is a notable disparity in the mean speed of adolescents between female and male participants. The mean flight speed for adolescents was calculated as 0.73± 0.05 m/s, with a mean speed of 0.85± 0.05 m/s for males, while it was reduced to 0.58 ± 0.01 m/s for female adolescents.

For this study, evacuees were categorized into two groups: those who partially or fully used handrails during their flight over stairs and compared with those who used the handrail. The mean velocity for the group assisted with handrails, consisting of 40 evacuees, measured as 0.81 ± 0.06 m/s. The maximum and minimum speeds recorded in this group were 1.40 m/s and 0.31 m/s, respectively. Those without handrail assistance had a mean speed of 0.76 ± 0.08 m/s, with maximum and minimum speeds of 1.72 m/s and 0.31 m/s, respectively.

Speeds over stairs and through doorway

For movement speed over stairways, both groups show a reduction in speeds proportionally with increasing density, presented as Persons/m^2. Figure 5a demonstrates that female adolescents had lower speed profiles over stairs in different densities, which aligns with the previously discussed mean speed findings. Three different estimations were used to capture the trend of changes in speeds for densities below 2.2 Persons/m^2. The estimations by Kholshevnikov et al. method for children aged 6-15 years fitted an exponential trend rather than a linear correlation. In all cases, the decreasing trend of speeds versus the number densities of children and adolescents is captured with the trends. However, the one for Gwynne and Rosenbaum[1] (SFPE guide - adults) is speculated to lead to total congestion over stairs sooner than the other two, whose current speed does not follow that trend.

Figure 5b shows a scatter plot of speed data for children and adolescents in front of exit doorways. A notable difference is observed between the speeds estimated by the Gwynne and Rosenbaum correlation[1] (for adults) and the speed data obtained in this study. The Gwynne and Rosenbaum correlation[1] defines the maximum speed during free movement (lowest density) as 1.4 m/s, while the maximum speed recorded in the current data barely reaches 1.09 m/s. Additionally, the slope of the trend defined for adults in the Gwynne and Rosenbaum correlation[1] suggests a full stop speed (zero speed) can be extrapolated at a much lower density compared to that of children and adolescents.

Figure 5b also includes two trends provided by Kholshevnikov et al.[14], which describe movement behaviors near doorways for children. The authors categorized children's dynamics into different modes during unimpeded free movement along evacuation routes, including comfortable, quiet, active, and increased activities. For the purposes of comparison, this study considers only the active and quiet modes. The data in Figure 5b aligns better with the quiet mode than the active mode. This is consistent with the observations from the videos, where the majority of participants exhibited quiet motions near the doorways.

Figure 6a presents speed measurements over stairs plotted against occupied density as m^2/m^2. The speed data is compared with two other estimations, using the Najmanova and Ronchi correlation[21], recently introduced for 3-6-year-old infants, and the one presented by Predtechenskii and Milinskii[2] for youths. Figure 6a reveals the discrepancies in movement characteristics over stairs between children and adolescents compared to those obtained for infants of less than 6 years, for densities less than 0.16 m^2/m^2. The slope of Predtechenskii and Milinskii[2] predictions for youths shows a better agreement with the slope change of the current data versus density, though it underestimates the maximum speed over stairs. By extrapolating the trends, full congestion for infants (under six years old) appears to occur at a much lower density than the one suggested by the current data slope.

The differences in population speed are more evident in Figure 6b, where the speed data near exit doorways is presented versus occupied density (m^2/m^2). Maximum speed and the slopes of speed changes are better captured by the predictions of the Predtechenskii and Milinskii[2] correlation for youth, though the values are slightly overestimated. The correlation presented for infants predicts full congestion of flow (nearly zero speed) at much lower densities than what appears with the slope change of the current data.

Flow over stairs and through doorways

Figure 7 provides scattered data of specific flow obtained for children and adolescents over stairs and through doorways, plotted against density as persons/m^2. Figure 7a shows that most of the flow data for children ranges from 0.2 to 2 persons/s/m, while the concentration of flows recorded for adolescents drops to 0.2 to 1.5 persons/s/m. According to Table 2, the average flow rate is calculated as 0.83 persons/s/m^2 for children and reduced to 0.58 persons/s/m^2 for adolescents. The flow rates over stairs are compared with predictions by Fang et al.[28] correlation for infants of 5-6 years old and estimations introduced by the Gwynne and Rosenbaum correlation[1] for adults with different stair dimensions. The data appears to agree well with the trends and data of both populations for low densities (less than one person/m²). However, flow values are underestimated for data at or near a density of 2 persons/m².

Figure 7b presents the flow through doorways calculated for both populations. Flow data shows a higher maximum flow of around 5 persons/s/m for adolescents and children, with a few exceptions that reached around six persons/s/m for adolescents. For children, higher flows through the exit doors were recorded with larger densities than the ones recorded for adolescents. Two trends were used for comparison purposes: one based on the correlations presented by Larusdottir[26] for children of different age groups ranging from 6-15 years and the other from Najmanova and Ronchi[21] for infants ranging from 3-6 years old. The comparison could not reveal any conclusive difference between the patterns due to the wide flow of data distribution across different densities.

Figure 8 depicts flows measured over stairs and through exit doorways in relation to occupied densities (m^2/m^2). A clear distinction between flow data over stairs for children and adolescents sorted by their occupied density is evident. Children exhibit higher flows than adolescents within the same range of densities, although this difference is most pronounced for densities of less than 0.1 m^2/m^2. Conversely, adolescents exhibit a slower change in flow across a wide range of densities, extending up to approximately 0.16 m^2/m^2. For comparison, three correlations have been employed, including the one presented by Najmanova and Ronchi[21] for infants aged 3-6 years and two trends provided by Predtechenskii and Milinski for children and youths. The data presented here deviates from the trend predicted by the Najmanova and Ronchi[21] correlation but aligns with the trends estimated by the Predtechenskii and Milinski correlations. The correlation for youths demonstrated better predictive accuracy regarding the slope of changes, as the one for children underestimated the trend observed in the data collected in this study.

Flows through the exit doors are presented versus occupied densities in Figure 9b. Flows are distributed across various densities, ranging from approximately 0.5 to 5 persons/s/m. In contrast to Figure 7b, flow data for children and adolescents covers a broader spectrum of densities, extending up to 0.18 m^2/m^2. Predictions from the three correlations provided in Figure 8a are also included here for exit door flow. Due to the spread of the data, the trends do not align with the current data, and drawing any conclusions would be premature.

Discussion

The movement characteristics of children and adolescents were investigated during an evacuation drill at a school. The observations of pupils' behavior captured by cameras unveiled unique behaviors exhibited by school pupils during evacuation. These behaviors included waiting for a friend or friends on stairs, jumping over stairs when crowd density is low, moving down faster than friends by obstructing their paths, or moving shoulder to shoulder without maintaining personal distance. These behaviors differ from those typically described for adults, including their privacy distance or body buffer zone, as introduced by Fruin during evacuations. Furthermore, the influence of culture on these behaviors and the body buffer zone among children should not be overlooked.

The mean speeds reported for flights over stairs align closely with previously documented values in the literature concerning school children and adolescents. Hamilton et al. reported a mean speed over stairs of 0.92 m/s, with the speeds of boys and girls ranging 6 to 12 years old was noted as 0.91 and 0.92 m/s, respectively[19]. This corresponds to the same values reported by Cuesta and Gwynne[27] for primary and secondary school children (6 to 16 years) and a lower value of 0.57 m/s for preschoolers (3 to 6 years). Fang et al. recorded a speed of 0.63 m/s for children aged 5-6 years in a kindergarten setting[28]. Another study conducted a series of unannounced and semi-announced evacuation drills in schools, capturing the movement of pupils aged 5 to 12 years using cameras[18]. The average speed over stairs was noted as 0.78 m/s for children, with the lowest speeds recorded for young children and higher speeds observed for older children. Ono et al. noted a speed of 0.86 m/s for school children aged 6 to 14 years old[22,23].

The study examined the effect of handrail assistance on mean flight speeds over stairs by calculating participants' speed with and without handrail assistance. The results do not offer conclusive evidence regarding the impact of handrails on movement speed over stairs. Similar findings were reported by Peacock et al.[37] in their study on the effect of handrails on movement speed in adults. They found no significant difference in movement speed between individuals with and without handrail assistance.

This study found that the flight speeds of female children and adolescents were generally lower than those of male children and adolescents. This is consistent with previously reported findings on adult females from Saudi Arabia, who exhibited lower mean speeds over horizontal surfaces and stairs[13]. The authors explained the difference as being related to female attire (abaya), which might reduce their speed during descent over stairs. Predtechenskii and Milinskii[2] also addressed the impact of attire on evacuees' movement characteristics, alongside age and physical characteristics, as factors influencing density and, consequently, movement speeds. They measured the horizontal projection area of evacuees under different clothing and movement scenarios, as presented in their report. The results presented in this study again underscore the importance of attire in determining the movement characteristics of school evacuees. More importantly, the impact of culture and its decisive role in shaping evacuation behavior and movements must be considered. This was not the scope of the current study, and special methodologies should be designed to address this issue in the future.

Speed data have been presented against number densities and occupied area densities for movement over stairs and in front of exit doorways. Speeds proportionally decreased with increasing densities in both cases. The rate of change in speed was found to be different from that of adults in all cases, which aligns with previous studies that have identified similar characteristics[17,19,21]. Moreover, the slope of the speed-density relationship differed significantly from that observed for infants when the results were plotted against occupied area densities. This finding implies a distinction between the movement of infants and that of children and adolescents over stairs and near exit doors, which may be attributed to two possible reasons. The locomotion ability of infants is the weakest compared to other groups, making it hard for infants to abreast movements at higher densities. The peculiar behavior of infants and its effect on their mass movement in high densities have been explained in Najmanová and Ronchi’s recent work[21].

Therefore, the possibility of near-zero movement in lower densities than children and adolescents' densities is not unusual. Also, infants' body sizes are smaller than other groups, allowing higher number of infants per 1 m^2, and at the same densities. It means infants may reach congestion number densities earlier than children and adolescents. Hence, a sharp decrease in slope of speed change for infants is not surprising.

Participant flow was calculated based on video observations and presented in relation to number densities and occupied area densities for movements over stairs and through the exit doors. The results with occupied area densities highlighted a distinction between the data for movements over stairs for the two studied groups, reemphasizing the relevance of the occupied area density method over the number density method for heterogeneous populations. In all the occupied area densities presented here, children exhibited higher flow rates than adolescents when moving over stairs. In addition to the differences in body size explained in the previous paragraph, this variation may be attributed to Fruin's definition[3] of the 'body buffer zone,' which can influence how individuals move abreast when descending stairs or passing through a doorway. Adults typically prefer to maintain their personal space and avoid physical contact with others during crowd movement, although the specific distances may vary across cultures. However, the concept of personal space and the practice of maintaining distance may not be as significant for children, who tend to have fewer concerns about avoiding contact with each other. Our observations of children descending stairs or moving through doorways in this study support the notion that there is a lack of personal space between children, while such space exists among adolescents. Contact between children occurred frequently without impeding their movement or slowing their speed. This lack of personal space implies a higher flow rate among children compared to adolescents at the same crowd densities and could explain the higher specific flows observed in this study.

The results also revealed a wide distribution of flow rate data points for children and adolescents passing through the exit doors. Broad distributions of flow at the exit doors were previously reported by Hamilton et al.[19] and Najmanová and Ronchi[21], with a large dataset collected for infants. The maximum range of flow rate distribution in this study was higher, reaching up to 5 persons per second per meter (Persons/s/m), compared to a previous study by Larusdottir[26] with the same age groups. Two factors may contribute to the variances observed here, including differences in door opening mechanisms and conditions of the doors during the drills. In the current study, both exit doorways were designed as double-leaf doors and left open during the drill. Both doors were held on the sides of the door frame without interacting with the participants. However, in Larusdottir's study[26], doors were a mixture of double and single leaves, and some doors were left locked during the drills. As the author noted, the locks were out of reach for children and required adult intervention to allow the children to pass through. Door leaf design and its condition during crowd movement have been previously addressed in other works[2,3], with the possibility of reducing effective width availability and, consequently, the flow capacity of doorways by up to 30%[9].

Limitations

This study has several limitations that should be clarified for readers. Foremost, it is important to note that the results presented here for speed and flow are only indicative and represent trends based on extrapolation of experimental data. Further statistical data should be obtained to validate the findings presented in this study. Furthermore, categorizing the samples into children and adolescents facilitated a clearer comparison of movement patterns. However, it is important to note potential variations in movement within each age group and across different ages (e.g. between 7 and 9), a factor not accounted for in this analysis and should be noted as a limitation of current study. Another limitation is that the data collected in this study were obtained in the context of evacuation drills, and their comparability to actual incidents should be considered. Moreover, when comparing the results of this study with those of previous studies, uncertainties may arise due to variations in factors such as staff engagement with children, guidance towards exit routes, and types of warning used. These differences can introduce further uncertainties in making direct comparisons between studies. In addition, the results presented here are the outcome of one evacuation drill in the school, and uncertainties associated with repeated trials are unknown. According to school management documentation, all children and adolescents were in normal physical condition. However, there might be a chance that some were reluctant to disclose information about their physical abilities completely, which could affect their movement speeds. Furthermore, some of the teachers had prior information about the drill, and it is uncertain whether they revealed the nature of the drill to the school pupils in the classrooms before it started. This could affect the sense of urgency and, consequently, their evacuation speed.

Conclusion

An evacuation drill was carried out to explore the movement of children and adolescents on stairs and near and through exit doors in a school. Participants varied in age from 7 to 17 years old and were divided into two groups of children (7 to 12 years old) and adolescents (13 to 17 years old). The participants' movement was observed using cameras mounted on stairs and near exit doors. The recordings were further processed to calculate participant densities, speeds, and specific flows over stairs and via exit doorways.

The study examined participants' travel speeds over stairs and near exit doorways, considering their population group and gender. Children had a higher mean speed than adolescents when traveling over stairs; this difference was statistically significant. Among adolescents, there was a significant gender-based difference in mean travel speed over stairs, with females being slower than males. For children, the mean travel speeds were nearly similar regardless of gender.

The analysis of speed-density profiles near stairwells and doorways yielded several key findings. Firstly, as population density increased, speeds over stairs and near doorways exhibited a decreasing trend. These findings align with previous studies involving other age groups, such as infants and adults. Notably, the rate of change in speeds was considerably lower than observed for infants provided by other works. Maximum speeds over stairs were recorded at 1.43 m/s for children and 1.37 m/s for adolescents, while minimum values were 0.41 m/s and 0.34 m/s, respectively. Near doorways, maximum speeds reached 0.94 m/s for children and 1.08 m/s for adolescents, with minimum speeds of 0.30 m/s and 0.37 m/s, respectively.

The flow-occupied area density profiles provided a distinct differentiation between children and adolescents in terms of their movement over stairs. Children exhibited higher flow rates compared to adolescents, with maximum flow rates reaching almost 2 persons per square meter for children and around 1.5 persons per square meter for adolescents. The flow rates for both age groups over stairs followed a different pattern compared to infants and adults, indicating an age-related influence on evacuation movement flow rates. For exit doorways, the flow rates varied widely, ranging from approximately 0.5 persons per square meter to 5 persons per square meter.

Evacuation movements in schools are intricate, influenced by distinctive behavioral and physical constraints that set them apart from the wider population. Future research should investigate how the unique behaviors identified in this study impact the uncertainties associated with measuring pupils' speeds and flows and the influence of cultural factors on evacuation behaviors, especially in underrepresented regions. This can be achieved through a well-designed methodology.

Data Availability

The data for the current work can be shared with the corresponding author upon request.

References

1. Gwynne SMV, Rosenbaum ER. Employing the hydraulic model in assessing emergency movement. In: *SFPE Handbook of Fire Protection Engineering*. ; 2016:2115-2151.

2. Predtechenskii VM, Milinskii AI. *Planning for Foot Traffic Flow in Buildings*. National Bureau of Standards; 1978.

3. Fruin JJ. *Pedestrian Planning and Design*. Elevator World Inc; 1971.

4. Lovreglio R, Kuligowski E, Gwynne S, Boyce K. A pre-evacuation database for use in egress simulations. *Fire Saf J*. 2019;105(May 2018):107-128. doi:10.1016/j.firesaf.2018.12.009

5. Fahy RF, Proulx G. Toward creating a database on delay times to start evacuation and walking speeds for use in evacuation modelling. *2nd Int Symp Hum Behav Fire*. 2001;(March):175-183.

6. Hoskins BL, Milke JA. Study of Movement Speeds Down Stairs. In: *SpringerBriefs in Fire*. Springer; 2013:81. http://www.springer.com/series/10476

7. Proulx G. Evacuation time and movement in apartment buildings. *Fire Saf J*. 1995;24(3):229-246. doi:10.1016/0379-7112(95)00023-M

8. Peacock RD, Reneke PA, Kuligowski ED, Hagwood CR. Movement on Stairs During Building Evacuations. *Fire Technol*. 2017;53(2):845-871. doi:10.1007/s10694-016-0603-5

9. Gwynne SMV, Kuligowski ED, Kratchman J, Milke JA. Questioning the linear relationship between doorway width and achievable flow rate. *Fire Saf J*. 2009;44(1):80-87. doi:10.1016/j.firesaf.2008.03.010

10. Kuligowski E, Peacock R, Wiess E, Hoskins B. Stair evacuation of older adults and people with mobility impairments. *Fire Saf J*. 2013;62(PART C):230-237. doi:10.1016/j.firesaf.2013.09.027

11. Adams APM, Galea ER. An Experimental Evaluation of Movement Devices Used to Assist People with Reduced Mobility in High-Rise Building Evacuations. *Pedestr Evacuation Dyn*. Published online 2011:129-138. doi:10.1007/978-1-4419-9725-8_12

12. Fujiyama T, Tyler N. An explicit study on walking speeds of pedestrians on stairs. *10th Int Conf*

Mobil Transp Elder Disabl People, Hamamatsu, Japan, May 2004. Published online 2004:1-10. http://discovery.ucl.ac.uk/1243/

13. Majed Almejmaj, Meacham B, Skorinko J. The effects of cultural differences between the west and Saudi Arabia on emergency evacuation—clothing effects on walking speed. *Fire Mater*. 2015;36:353-370. doi:10.1002/fam

14. Kholshevnikov V V., Shields TJ, Boyce KE, Samoshin DA. Recent developments in pedestrian flow theory and research in Russia. *Fire Saf J*. 2008;43(2):108-118. doi:10.1016/j.firesaf.2007.05.005

15. Kuligowski E, Averill JD, Kuligowski ED. *Stairwell Evacuation from Buildings: What We Know We Don't Know*.; 2009. doi:10.1007/978-3-642-04504-2

16. Bahmani H, Ao Y, Yang D, Wang D. Students' evacuation behavior during an emergency at schools: A systematic literature review. *Int J Disaster Risk Reduct*. 2023;87(October 2022):103584. doi:10.1016/j.ijdrr.2023.103584

17. Kholshevnikov V V, Samoshin DA, Parfenenko AP. Pre-school and school children building evacuation. *Proc Fourth Int Symp Hum Behav Fire*. Published online 2009:243-254. http://www.fireevacuation.ru/Archive_En/HBF_09.pdf

18. Hamilton GN, Lennon PF, O'Raw J. Human behaviour during evacuation of primary schools: Investigations on pre-evacuation times, movement on stairways and movement on the horizontal plane. *Fire Saf J*. 2017;91(February):937-946. doi:10.1016/j.firesaf.2017.04.016

19. Hamilton GN, Lennon PF, O'Raw J. *Toward Fire Safe Schools: Analysis of Modelling Speed and Specific Flow of Children During Evacuation Drills*. Vol 56. Springer US; 2020. doi:10.1007/s10694-019-00893-x

20. Najmanová H, Ronchi E. Experimental data about the evacuation of pre-school children from nursery schools, Part I: Pre-movement behaviour. *Fire Saf J*. 2023;138(March):103798. doi:10.1016/j.firesaf.2023.103798

21. Najmanová H, Ronchi E. Experimental data about the evacuation of pre-school children from nursery schools, Part II: Movement characteristics and behaviour. *Fire Saf J*. 2023;139(March):103797. doi:10.1016/j.firesaf.2023.103797

22. Ono R, Valentin M V, Vittorino F. Walking Speed Data of Fire Drills At an Elementary School. *Hum Behav fire - 2012*. 2006;(1):2-12.

23. Ono R, Valentim MV, Vittorino F. Method for collecting data of children descending movement on stairs in schools. *Fire Mater*. 2021;45(4):508-528. doi:10.1002/fam.2833

24. Larusdottir AR, Dederichs AS. A step towards including children's evacuation parameters and behavior in fire safe building design. *Fire Saf Sci*. 2011;(January 2011):187-195. doi:10.3801/IAFSS.FSS.10-187

25. Larusdottir AR, Dederichs AS. Evacuation of Children: Movement on Stairs and on Horizontal Plane. *Fire Technol*. 2012;48(1):43-53. doi:10.1007/s10694-010-0177-6

26. Lárusdóttir AR. *Evacuation of Children Focusing on Daycare Centers and Elementary Schools*. Technical University of Denmark; 2013.

27. Cuesta A, Gwynne SMV. The collection and compilation of school evacuation data for model use. *Saf Sci*. 2016;84:24-36. doi:10.1016/j.ssci.2015.11.003

28. Fang ZM, Jiang LX, Li XL, Qi W, Chen LZ. Experimental study on the movement characteristics

of 5–6 years old Chinese children when egressing from a pre-school building. *Saf Sci*. 2019;113(November 2018):264-275. doi:10.1016/j.ssci.2018.11.022

29. Yao Y, Lu W. Research on kindergarten children evacuation: Analysis of characteristics of the movement behaviours on stairway. *Int J Disaster Risk Reduct*. 2020;50(June):101718. doi:10.1016/j.ijdrr.2020.101718

30. Yao Y, Lu W. Children's evacuation behavioural data of drills and simulation of the horizontal plane in kindergarten. *Saf Sci*. 2021;133(May 2020):105037. doi:10.1016/j.ssci.2020.105037

31. Li H, Zhang J, Yang L, Song W, Yuen KKR. A comparative study on the bottleneck flow between pre-school children and adults under different movement motivations. *Saf Sci*. 2020;121(December 2018):30-41. doi:10.1016/j.ssci.2019.09.002

32. Giedd JN, Blumenthal J, Jeffries NO, et al. Brain development during childhood and adolescence: A longitudinal MRI study. *Nat Neurosci*. 1999;2(10):861-863. doi:10.1038/13158

33. Jiménez Díaz J, Salazar Rojas W, Morera M. Age and gender differences in fundamental motor skills (original version in English). *Pensar en Mov Rev Ciencias del Ejerc y la Salud*. 2015;13(2):1-16. doi:10.15517/pensarmov.v13i2.18327

34. National Institute of Health Style Guide. Age. US Department of Health and Human Services. Published 2022. https://www.nih.gov/nih-style-guide/age

35. Buchmueller S, Weidmann U. Parameters of pedestrians, pedestrian traffic and walking facilities. *IVT Schriftenr*. 2007;132(July):12-19. https://doi.org/10.3929/ethz-a-010025751

36. Kobes M, Helsloot I, de Vries B, Post JG. Building safety and human behaviour in fire: A literature review. *Fire Saf J*. 2010;45(1):1-11. doi:10.1016/j.firesaf.2009.08.005

37. Peacock RD, Hoskins BL, Kuligowski ED. Overall and local movement speeds during fire drill evacuations in buildings up to 31 stories. *Saf Sci*. 2012;50(8):1655-1664. doi:10.1016/j.ssci.2012.01.003

Table 1 *Children and Adolescents age and grade distributions participated in the evacuation drill*

Age [Years]	Grade	Number of Students	Category	Floor	Distribution
7-8	2nd	31	Children	Ground	10.5%
8-9	3rd	23	Children	Ground	7.7%
9-10	4th	26	Children	First	8.8%
10-11	5th	24	Children	First	8.1%
11-12	6th	17	Children	First	5.7%
12-13	7th	41	Adolescent	Second	13.8%
13-14	8th	32	Adolescent	Second	10.8%
14-15	9th	28	Adolescent	Second	9.4%
15-16	10th	21	Adolescent	Third	7.1%
16-17	11th	30	Adolescent	Third	10.1%
17-18	12th	22	Adolescent	Third	7.4%
Total		**295**	-		

Table 2 *List of mean speed and flow rates of children and adolescents over stairs.*

<table>
<tr><th></th><th colspan="2">Children</th><th colspan="2">Adolescents</th><th colspan="2">With Handrail</th><th colspan="2">Without Handrail</th></tr>
<tr><td rowspan="3">Mean Flight Speed</td><td colspan="2">0.84 ± 0.06 m/s</td><td colspan="2">0.73 ± 0.06 m/s</td><td colspan="2">0.81 ± 0.06 m/s</td><td colspan="2">0.76 ± 0.06 m/s</td></tr>
<tr><td>Female</td><td>Male</td><td>Female</td><td>Male</td><td>Max.</td><td>Min.</td><td>Max.</td><td>Min.</td></tr>
<tr><td>0.89 ± 0.06 m/s</td><td>0.80 ± 0.06 m/s</td><td>0.58 ± 0.01 m/s</td><td>0.85 ± 0.01 m/s</td><td>1.40 m/s</td><td>0.31 m/s</td><td>1.72 m/s</td><td>0.31 m/s</td></tr>
<tr><td>Mean Flow Rate</td><td colspan="2">0.83 Persons/s/m^2</td><td colspan="2">0.58 Persons/s/m^2</td><td colspan="2">-</td><td colspan="2">-</td></tr>
</table>

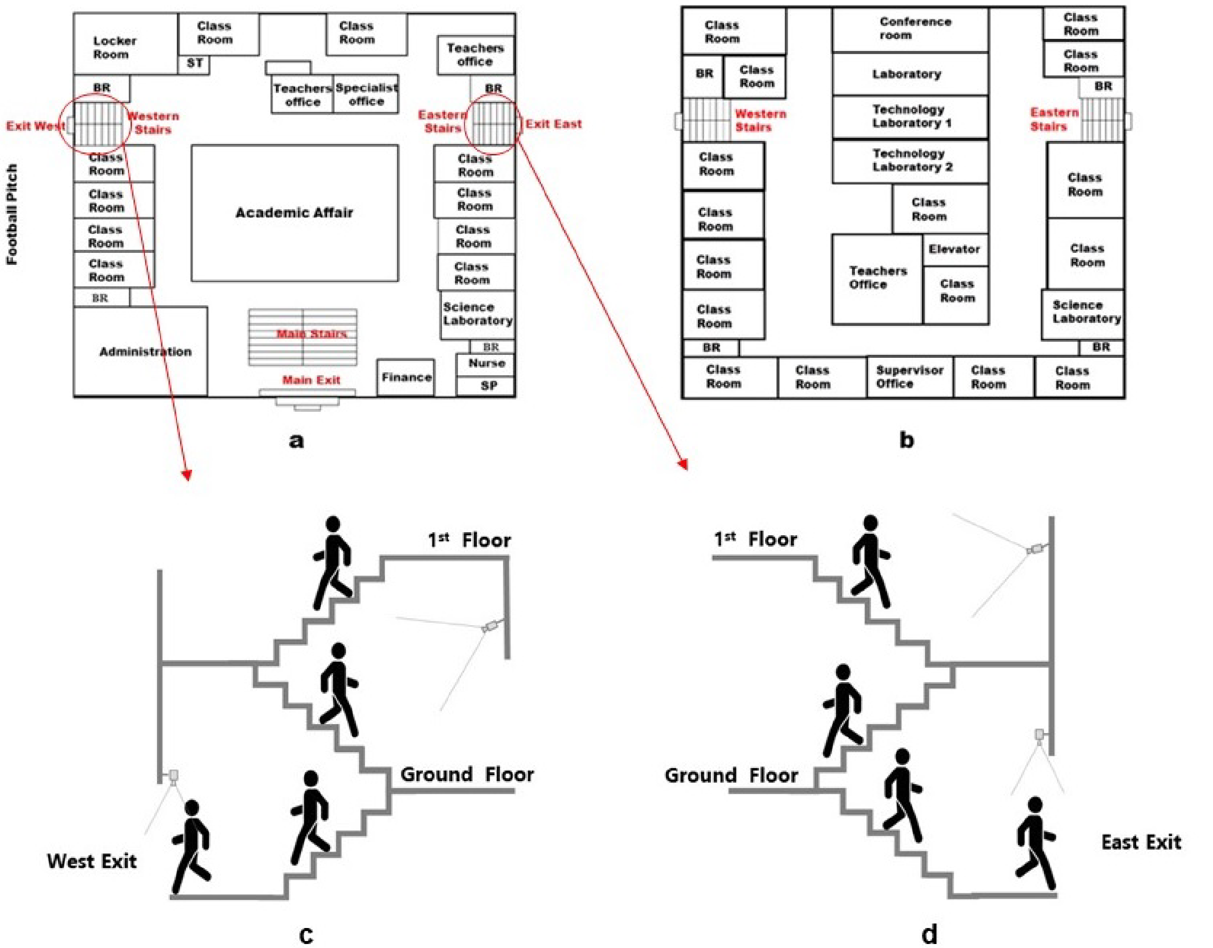

Figure 1 School building floor plan a) Ground floor; b) 1st, 2nd and 3rd floors; c) layout of cameras in the west stairs and exit door; d) layout of cameras in the east stairs and exit door

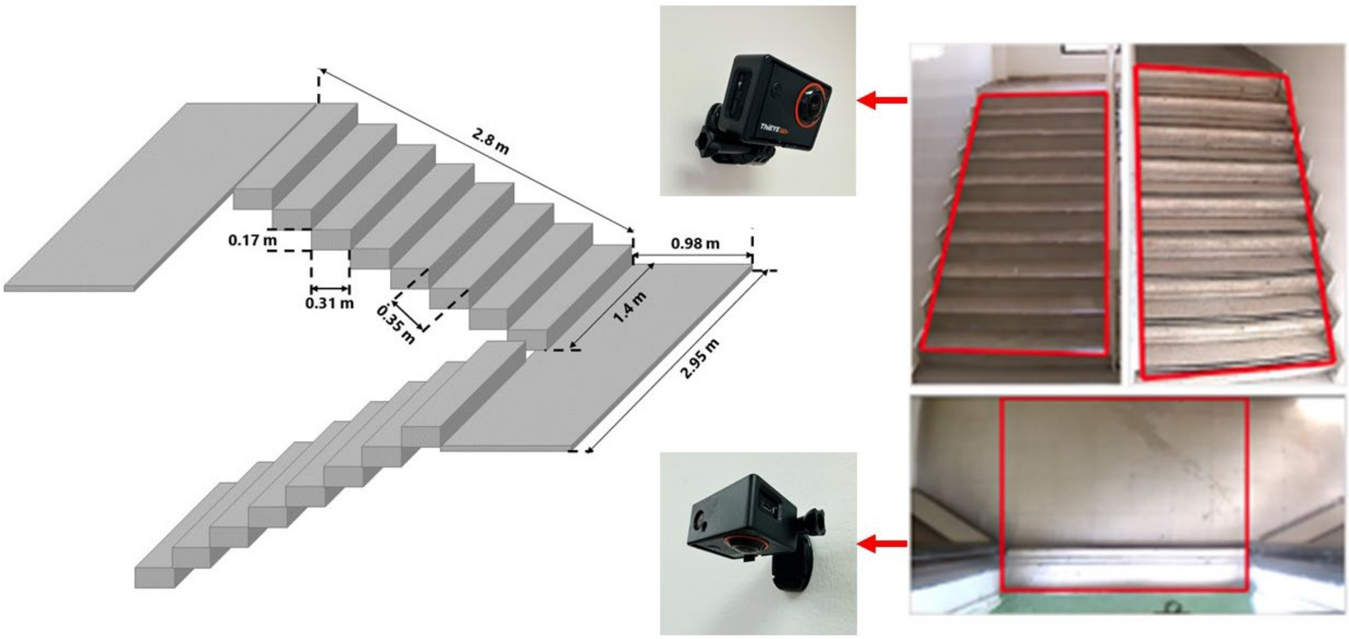

Figure 2 Stairs dimensions and pictures of depicted reference area on stairs and near doorways

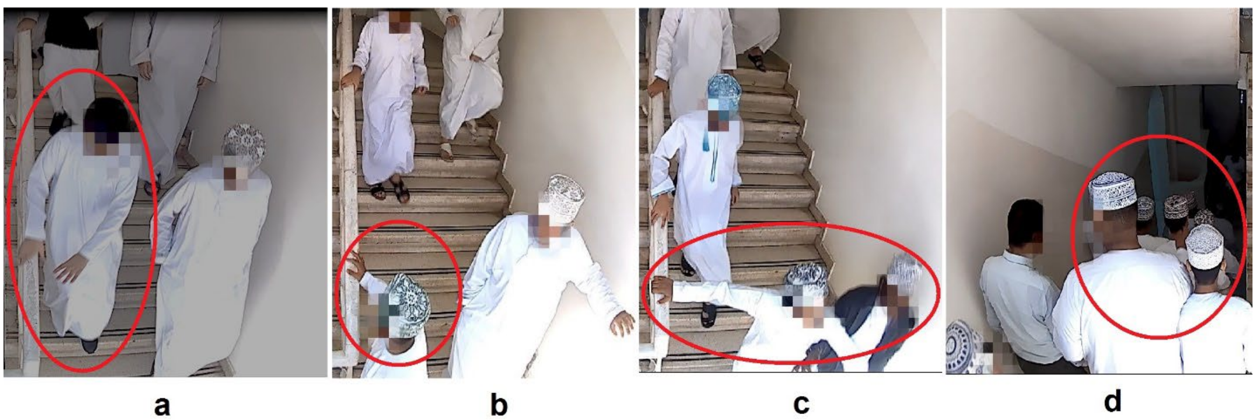

Figure 3 Snapshots of children's movement behavior over stairs (obtained from video surveillance)

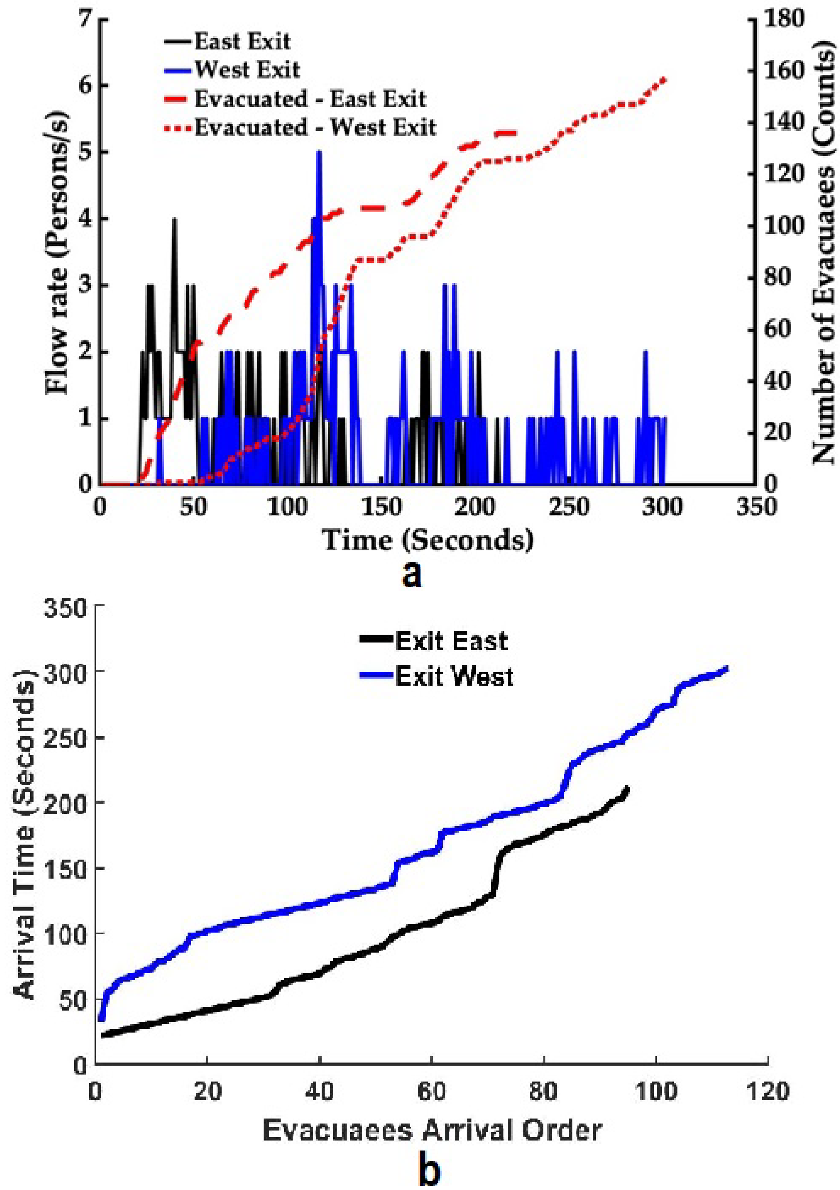

Figure 4 a) Calculated flowrates of children through west and east exit doorways and their evacuation times; b) Cumulative arrival time of evacuaees through west and east exits sorted versus evacuees arrival order.

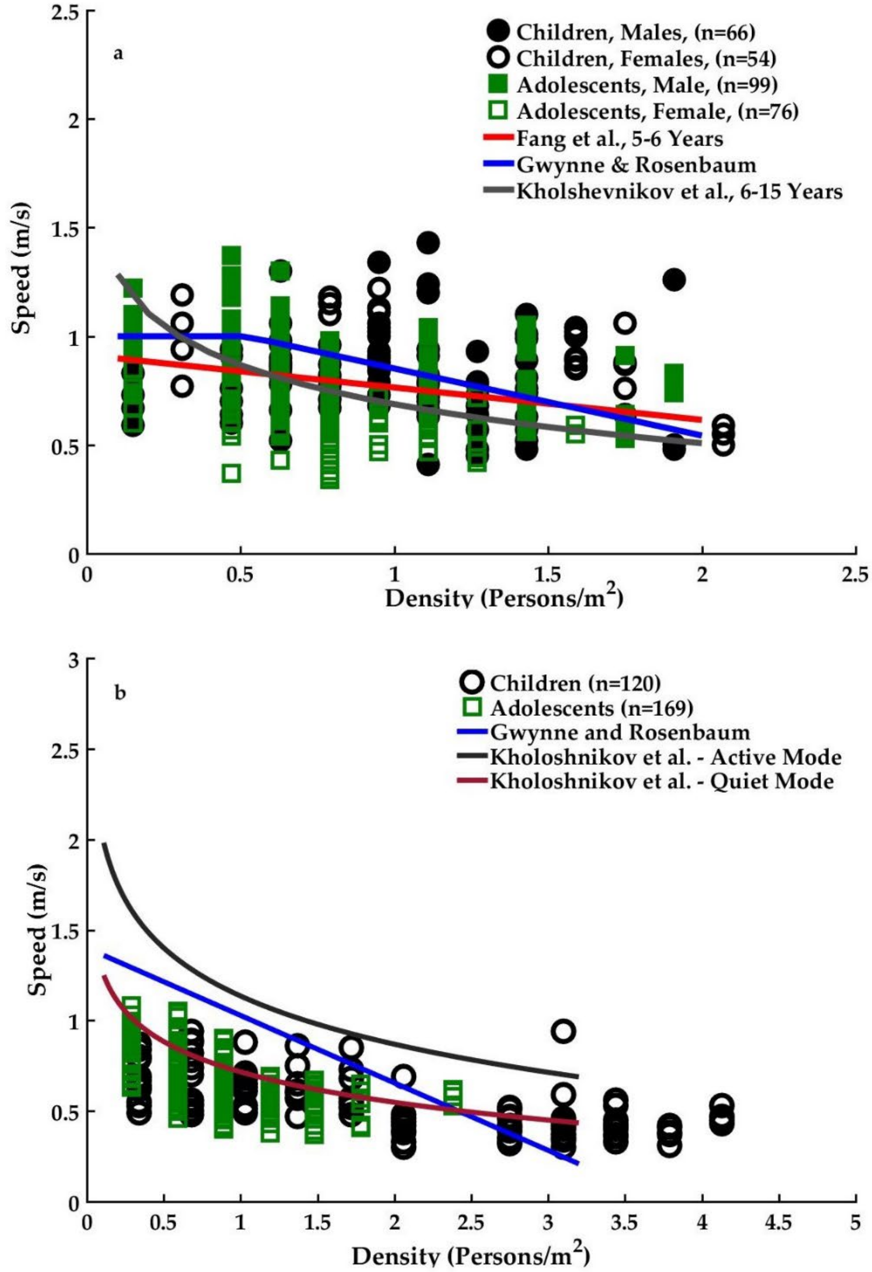

Figure 5 Plots of speeds vs. crowd density. a) Over the stairs; b) In front of the doorway

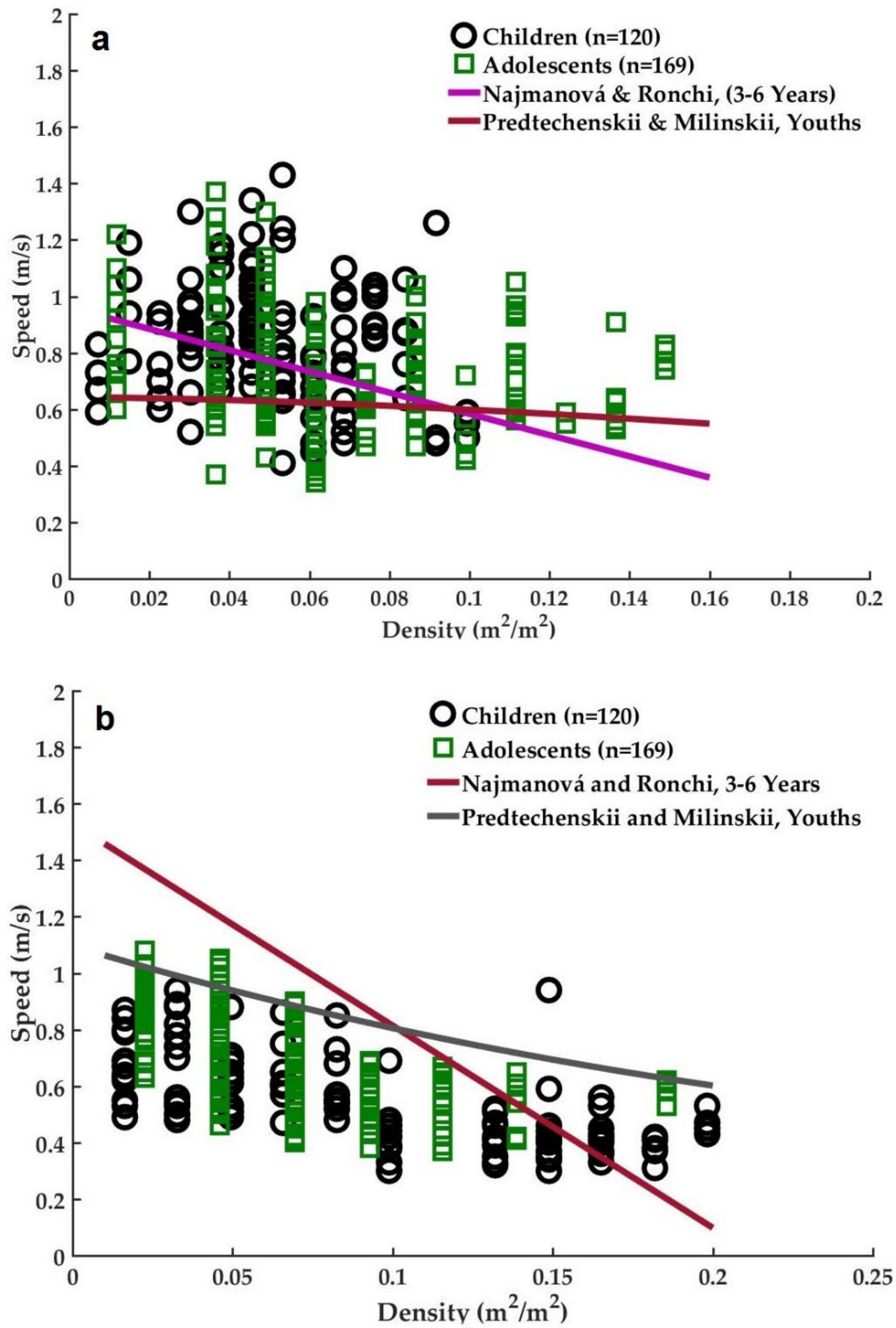

Figure 6 Plots of speed vs. occupied density. a) Over the stairs; b) In front of the doorway

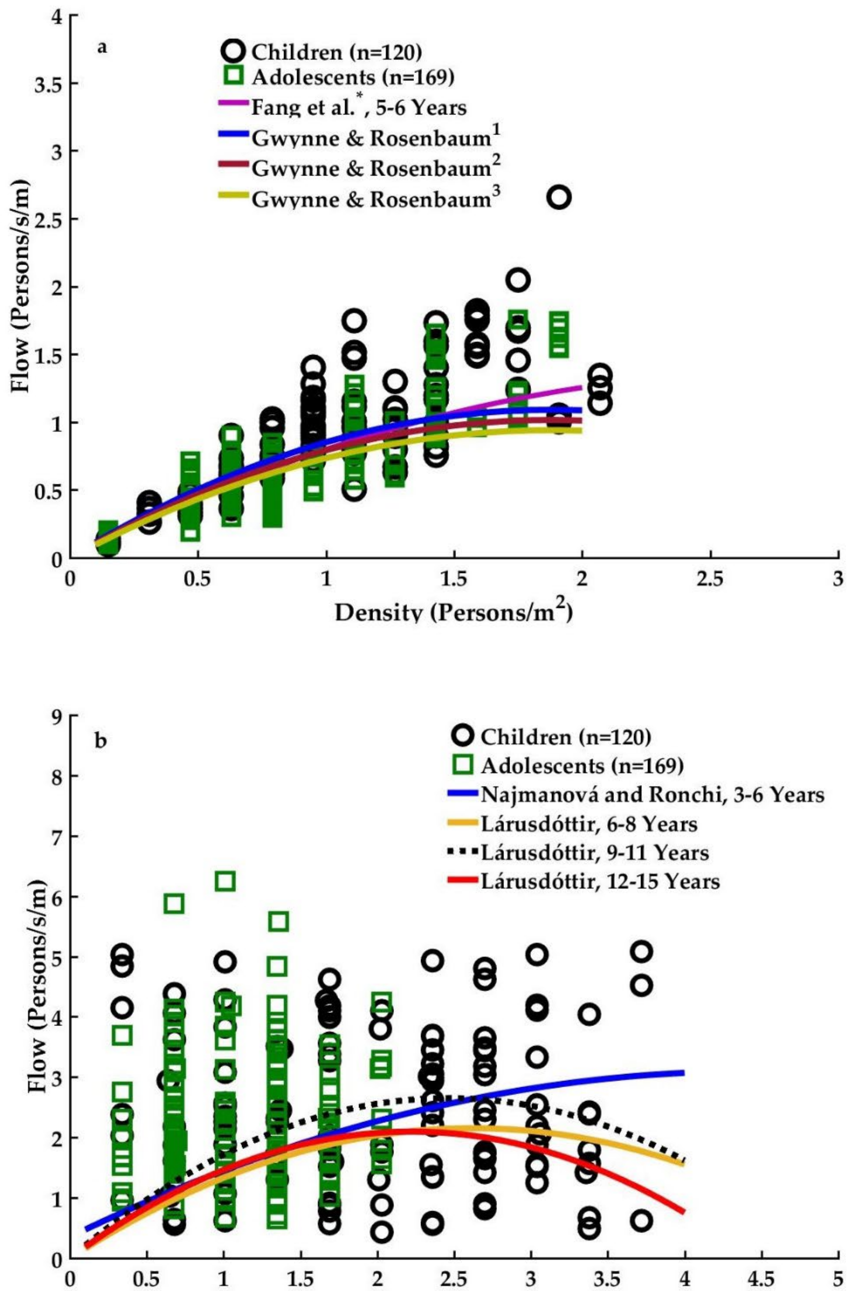

Figure 7 Plots of flow vs. crowd density. a) Over the stairs (Superscripts in figure 7a:*Stairs riser: 18 cm, thread: 28 cm, [1]riser:16.51 cm- thread:30.48 cm,[2]riser:17.78 cm- thread:27.94 cm,[3]riser:19.05 cm- thread:25.40 cm) ; b) Through doorways.

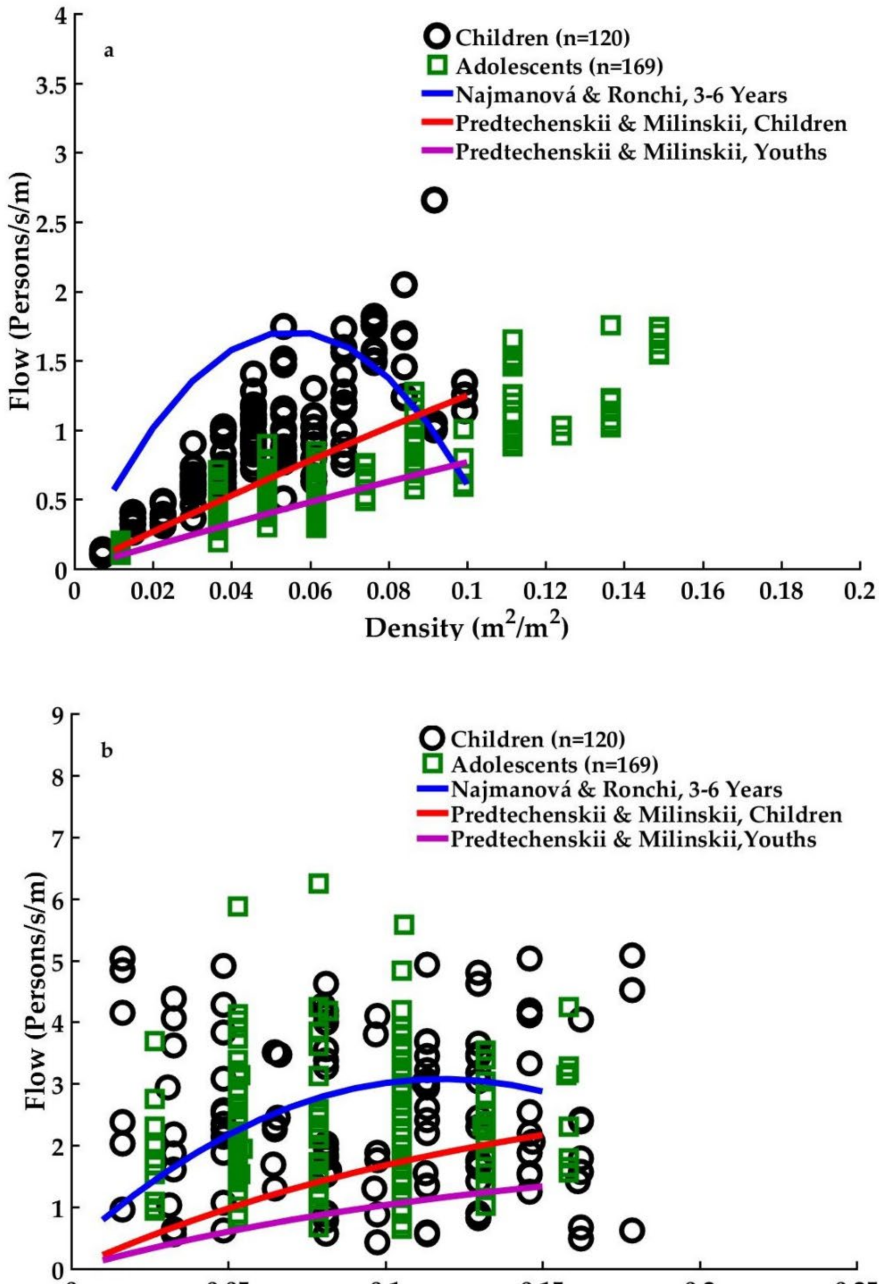

Figure 8 Plots of flows vs. occupied density. a) Over the stairs; b) Through the doorway