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Evacuation of Children: Movement on Stairs and on Horizontal Plane

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Abstract. Little is known on the evacuation characteristics of children. Current literature on evacuation is mostly based on studies on adults. The aim of this study is to investigate the movement of children during evacuation, focusing on flow, densities and walking speeds. Ten Danish daycare centers participated in full scale evacuation experiments where two age groups 0 to 2 years and 3 to 6 years were analyzed separately. It was found that flow through doors, walking speeds and densities were age-dependent and differed strongly from the data in existing literature. The results showed higher walking speeds in spiral stairs when the children were familiar with the evacuation path. Higher person densities and faster flow through doors were obtained among the children than found in the current literature on adults. Children in the younger age group were generally slower than the older children. The children walked slower in horizontal plane than adults, however they were keen to run during the evacuations, in the latter case their travel speed increased and exceeded the adults'. Since the evacuation characteristics of children differ in many ways from those of adults, nowadays models badly comprehend the evacuation behavior of children.

Keywords: Evacuation, Children, Flow, Movement speed, Person density, Daycare center

1. Introduction

17.6% of the population in Scandinavia, 20.3% of the Americans and 13.5% of the Japanese population are children, aged 0 to 14 years [1]. However, information on this vulnerable part of the population is frequently neglected when it comes to collecting data and developing models for society. This is not only a problem when it comes to fire safety [2], but also in other areas such as medical studies [3–5], where it has consequences for estimating dosage and type of medication for children. When designing new buildings and applying performance-based codes it is important to have an understanding of human evacuation dynamics as well as having access to performance models which are valid for a broad population in order to reduce the risk of exposing occupants to critical conditions in case of fire. The existing literature provides a number of case studies of real fire incidents as well as experiments concerning fire and evacuations [6–8]. These studies

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provide information on walking speed in horizontal plan and in stairs and flow through doors as well as other aspects relevant for evacuation [9]. The results are applied in models and introduced in simulation programs [10] for prediction of the evacuation process. The majority of previous studies deal with the evacuation behavior of adults where users are expected to be able to bring themselves to safety in case of an evacuation. These include studies on evacuation dynamics in private, public, and commercial buildings with different occupational hours, where the evacuees are either familiar or unfamiliar with the building [6–14]. However in recent years studies have focused on a broader population for experiments and models. For instance by considering people with disabilities and other groups that might require assistance during an evacuation [14–18].

However, very few studies can be found which provide information on evacuation dynamics and behavior of children [6, 14, 19] and embrace buildings with mass stay of children, such as daycare centers. One of these is a study on daycare centers performed in Kobe, Japan in 1985 [20]. The focus of the research was on evacuation using stairs and slides. A new Russian study from 2009 also investigates evacuation of daycare centers for children [21]. The focus of that study is on human behavior and travel parameters. Hence, there is very little existing data on walking speeds in a horizontal plane and on stairs as well as the flow through doors and densities of children, especially for children at this young age.

At last Predtechnskii's and Milinskii's book, Planning for Foot Traffic Flow in Buildings, should be mentioned [22]. It is from 1969 and bases on 30 years of experimental and theoretical studies on movement of people in public buildings in the Soviet Union. They introduce a method of calculating person density and flow for different mixture of people, including children. Their results are used in the current study for validation.

2. Method

The present work is an experimental study on evacuation dynamics of children. Data is provided on flow through doors as well as travel speeds for children. Ten Danish daycare centers all located in Lyngby, a suburb from Copenhagen, participated in full scale evacuation experiments. Four daycare centers performed the experiment twice and one performed the experiment three times involving a total of 1,017 persons, where of 268 evacuated twice and 67 three times. The experimental period was from March to May and November 2009. Danish daycare centers host two age groups, ''younger children'' aged between 6 months and 2 years and ''older children'' aged 3–6 years.

The motion of 71 children was considered when collecting the data for movement speed; 1,078 counts (mainly children) contributed to the data collection on the flow and 66 persons (mainly children) to the data on spiral stairs. More data would be necessary to prove statistical validity. Hence, the results presented in this work are not general, but indicate trends.

A total of sixteen full scale evacuation experiments, in the form of fire drills, were performed and data was collected using video cameras. In all of the daycare

centers the subject of a fire drill had been discussed in a staff meeting. The children were less prepared than the adults but in most of the daycare centers the upcoming fire drill had been mentioned and explained to the older children, but without indicating the specific day.

Each of the experiments had a similar course of action. After arriving at the daycare center and talking to the contact person (typically the leader or a safety person[1]) the cameras were set up, focusing on the exits. Shortly before the fire drill the cameras were turned on, one by one. Then a signal was given to start the fire drill, fire alarms were used where possible otherwise an adult started a verbal warning process. The evacuation started and all children and adults evacuated to the outside and gathered at the previously determined assembly point. When all of the children had been accounted for, an "all clear" signal was given. After the drill, most daycare centers chose to discuss the fire drill with the children, which worked well and helped the children to process this experience.

The recorders were partially exposed and out of reach for the children. The dimensions of fixed points in the rooms were taken. The films were analyzed for walking speed in horizontal plane and spiral stairs and flow through doors as well as behavioral pattern.

3. Results

In the following three subsections the results of the previously described experiments are introduced. The children are on a daily basis divided into the two previously mentioned age groups, which made it possible to compare results between the two ages.

3.1. Travel Speed—Horizontal

Figure 1 shows the percentage of children moving at a certain speed interval. The speed is shown in intervals of 0.20 m/s (horizontal axis) and is measured at low person densities (<0.5 person/m^2) where the children move independently. The travel speeds are differentiated into four series: walking of younger and older children and running of younger and older children. As can be seen in Figure 1, more than 78% of the younger children have a walking speed of 0.41 m/s to 0.80 m/s and more than 66% of the older children have a walking speed in the range of 0.6 m/s to 1.00 m/s. It is also clear that younger children move slower than the older ones, regardless of whether they are walking or running. The average walking speeds were 0.60 m/s and 0.84 m/s for the younger and older age group respectively and 1.14 m/s for younger and 2.23 m/s for older, when the children ran.

Common overall values used for adults' average walking speed in a horizontal plane with low person densities is 1.2 m/s to 1.3 m/s [23, 24]. The range for this speed is marked in Figure 1 as a hatched background. Comparison of the children's movement speeds to these values from literature concerning adults

[1]A member of the staff which together with the leader of the daycare center takes care of relevant safety issues; also known as health and safety officer.

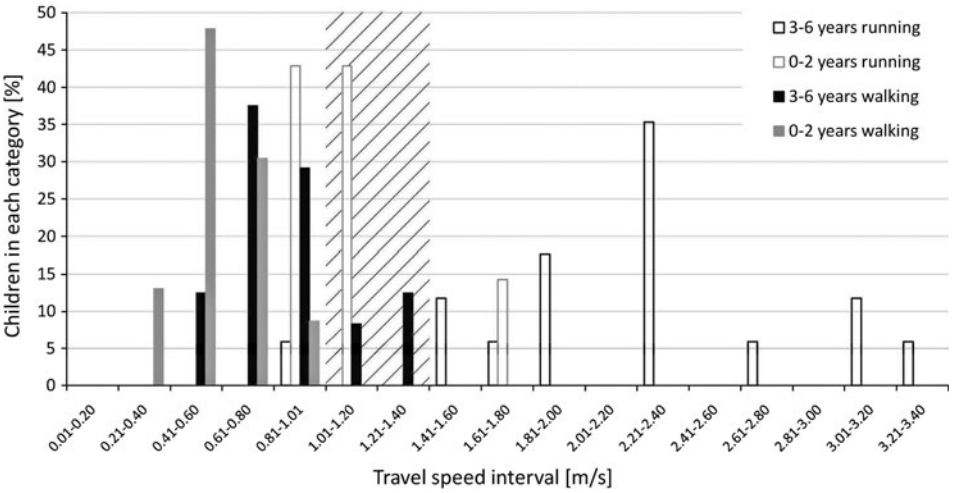

Figure 1. Travel speed (intervals of 0.20 m/s) for differentiated age groups 0 to 2 years (*grey*) and 3 to 6 years (*black*) running (*empty box*) and walking (*filled box*). A range of commonly used average walking speeds for adults is hatched.

shows that the children generally move slower, except when the older children run.

Not all children in the younger age group were able to walk by themselves; hence fewer measurements were available for that age. The travel speed of children carried by adults or holding an adult's hand was excluded in this work, since it is likely that in that situation the adult controls the travel speed more than the child. The measurements of travel speeds are all made at low person densities (<0.5 person/m^2), where the children could move freely.

3.2. Travel Speed—Stairs

The data on stairs only includes the older age group since the younger children were in all cases located at ground level. The study involves three spiral stairs. Width of the steps, the slope of the walking path (defined 0.25 m from the wider end of stair), the average travel speed and the standard deviation of the speed of each stair is shown in Table 1. The travel speed is defined as the movement along the slope of the stair.

Table 1
Results on Spiral Stairs

Stair	Width (m)	Slope (°)	Average speed (m/s)	SD (m/s)
Stair 1	0.80	33	0.58	0.31
Stair 2	0.87	33	0.38	0.07
Stair 3	0.91	30	0.13	0.06

Stair 1 is an internal stair used by the children every day. It also has an extra handrail at an appropriate height for the children. The depth of the steps (tread) in the walking path is 0.29 m and the height (rise) of each step is 0.19 m. Stair 2 is a spiral stair in a square stair case in an old house. The children do not use the stair regularly and the stair only has an inconvenient handrail in the center. The dimensions of the steps in the walking path are the same as for stair 1. Stair 3 is a typical metallic external fire escape, where the steps are see-through. The children had never used the stair before the experiment and the handrail is high and hard to reach for the children. The depth of the steps (tread) in the walking path is 0.29 m as for stairs 1 and 2 but the height (rise) of each step is 0.17 m, making the slope slightly less steep.

Although the three stairs have similar dimensions, there was remarkable difference in the average travel speed on the stairs. This can be linked to the difference in the children's familiarity of the stairs and the stairs' design, which is roughly described above.

Based on experiments on spiral stairs, involving adults [10] a general value for the average travel speed of 0.5 m/s is suggested, nondependent on the width of the stair [24]. The reason why the width is not important is that persons usually walk in a single row in spiral stairs, due to the narrow steps near the center. This was confirmed in this study; however a few passes were made when a child stopped in the middle of a stair.

As seen in Table 1 the children's average travel speed on stair 1 exceeds the suggested average travel speed for adults on spiral stairs. It can however also be seen that the standard deviation is high for stair 1 indicating a large variation in travel speed on that stair.

Figure 2 shows the travel speed of the individuals with respect to the time of them exiting the stair. The time count starts when the first person enters the particular staircase, meaning that the first mark (for each of the three staircases) shows the total travel time of the first person on the stair (horizontal axis) and the last mark (for each stair) shows the total time the stair was in use (the time from first person entering the staircase until last person exiting the same staircase).

In Figure 2 the large variation of the travel speed on stair 1 can clearly be seen and thereby large standard deviation as seen in Table 1. The first few children moved the fastest and as more children entered the stair the travel speed decreased. The fastest measured speed on stair 1 was 1.4 m/s and the slowest speed measured on the same stair was 0.25 m/s.

A likely explanation of this is that the increased person density on the stair affected the travel speed. Another possible factor is that the more hesitant children waited as long as they could to enter the stair, and they did not move as fast as the ones who were eager to evacuate.

Table 1 also presents a low standard deviation for stair 2 and stair 3 demonstrating that the travel speeds in stairs 2 and 3 are more or less steady.

The high movement speeds achieved on stair 1 and the slow speeds on the other two stairs strongly indicates that familiarity with the evacuation route leads to a faster evacuation, which was in fact one of the main conclusions of Murozaki's and Ohnishi's study mentioned earlier [20].

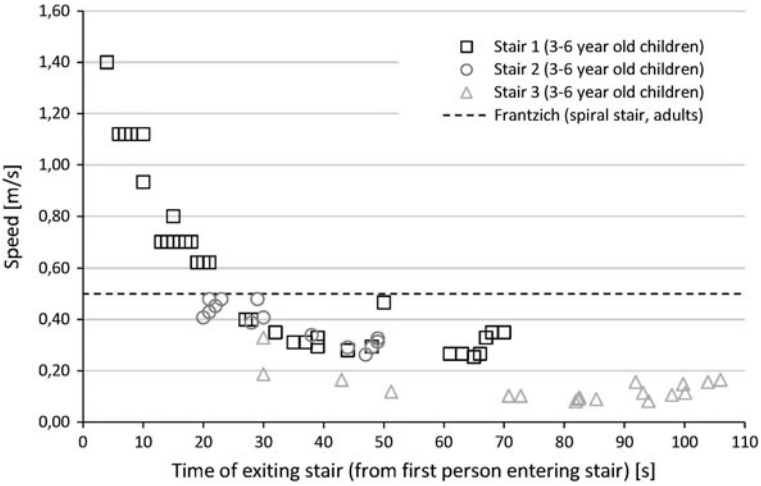

Figure 2. The individual travel speeds with respect to time of individuals exiting the stair. A *dashed line* marks the 0.5 m/s which literature suggests as an average travel speed for adults.

It was obvious from the recordings that stair 3 caused the most problems for the children, leading to an extremely low travel speed. This was the case even though the slope in the walking path was slightly less than in the other two. Apart from being insecure about walking on the stair and using the vertical bars in the handrail for support, the children were also curious and stopped to look around since this was a totally new environment for them. This shows that not only the dimensions and design of the stairs influence the travel speed.

3.3. Flow

Figure 3 shows the flow through doors for older children (age group 3 to 6 years, □) compared to younger children (age group 0 to 2 years, ○) and the corresponding trend lines (a thick black line for older children and a thick grey line for younger children), 2nd degree polynomials. The data in Figure 3 includes a few adults, accompanying the children, but the majority of the people are children. Common ratios between children and adults was three to four children per adult in the younger age group and six to ten children per adult for the older age group at the time of the evacuations. However in the flow measurements for the older children only a few adults are included as the adults typically waited until last to evacuate, and were not a part of a continuous flow.

A commonly used flow curve for adults, from Nelson and Mowrer [23], is shown as a reference in Figure 3 (thin black line). This curve can be found in numerous handbooks.

The obtained data is validated against transformed data from Predtechenskii and Milinskii [22]. The units were converted from m^2/min to pers/s for the flow and from m^2/m^2 to pers/m^2 for the density, by using Predtechenskii's and Milinskii's definition of occupying area of individuals. Their data is not obtained

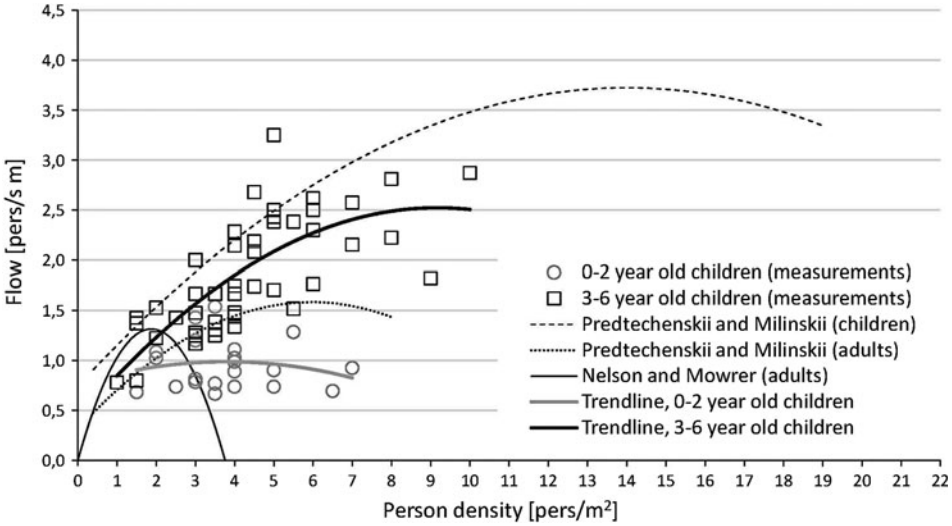

Figure 3. Flow through doors, measured during evacuation experiments, with respect to person density in pers/m^2. Trend lines (2nd degree polynomial) for the two age groups, 0 to 2 years (*thick grey line*) and 3 to 6 years (*thick black line*) are shown. For reference two transformed curves from Predtechneskii and Milinskii are shown. One presenting children (*dashed line*) where an area value for children was used for transformation, and the other curve presents adults (*dotted line*). Nelson's and Mowrer's commonly used curve for flow (adults) is also shown here for comparison (*thin line*).

from specific studies on children, however, by using different area values for children and adults when converting the units, two separate curves are developed and shown in Figure 3.

For Predtechenskii's and Milinskii's curve for children in Figure 3 (dashed line) each child is assumed to occupy 0.048 m^2, according to their book children vary from 0.04 m^2 to 0.056 m^2. For adults (dotted line) a value of 0.113 m^2 is used, which presents an adult in mid-season street dress.

It can be seen in Figure 3 that the flow increases with increasing person density. Again a clear difference can be seen between the two age groups analyzed, as the older children generally move faster than the younger ones, especially at high person densities. This difference was expected as the younger children have a lower walking speed. Other factors that might contribute to this difference are that the younger children were more hesitating, as they did not fully understand what was going on and there were more adults among the young children than in the measurements of the older children.

The data obtained does not show a clear peak. This could be explained by a lack of data at person densities higher than 6 pers/m^2. The highest person density obtained naturally, during the evacuation experiments, was 8 pers/m^2. In the measurement where the density was 10 pers/m^2 the children were instructed to stand

in a crowd by the door and then walk through when given a signal. As Figure 3 shows, this resulted in a flow of 2.9 pers/s m, but a descent in the flow at such high person density was expected.

The trend line for children 3 to 6 years in Figure 3, indicates a maximal flow of 2.5 pers/s m at 9.2 pers/m^2 and the trend line for children aged 0 to 2 years indicates a maximal flow of 1.1 pers/s m at 3.8 pers/m^2.

In contradiction to Nelson's and Mowrer's commonly used flow curve, the flow does not stop at a density of 3.8 pers/m^2 for either age group, as suggested for adults but it keeps growing with higher person densities. This may partly be explained by the size of children. Another reason could be that the children know each other and are comfortable being close to each other, whereas adults generally need more personal space.

When comparing the results from this study to Predtechenskii's and Milinskii's curve on children, more similarity can be seen in the shape of the curve (when only looking at age group 3 to 6 years). However Predtechenskii and Milinskii allow much higher person densities.

At last Predtechenskii's and Milinskii's curve for adults should be noted. It shows a lower flow than found in this study but it has the same shape as their curve for children. The reason for the same shape is, as mentioned earlier, that the data is taken from a figure in [22] showing the flow in m^2 per time unit with respect to density in m^2/m^2. This means that when converting the units to match Figure 3 the only difference between the curve for children and adults is the size of people.

3.4. Other Findings

It could be observed that the children had no problem passing the doors two side by side, even where the doors were only 0.6 m to 0.7 m wide. However when adults walked through these same doors, they usually needed to go sideways. Here the small size of the children comes to their advantage.

Concerning the effective width of the doors, it could be seen from the recorded material that the whole free width of the door was used when needed, so the door width was not reduced in the flow calculations, as if there was a boundary layer.

It was found that the two age groups (younger children aged 6 months to 2 years and older children aged 3 to 6 years) vary from each other when it comes to behavior, travel speed and flow through doors. An example of the behavioral difference is that very few of the younger children ran during the evacuations (about 5%) (not shown here), however it was common among the older children to run to the exit (about 40%). In some cases the children did not have the opportunity to run due to crowd or orders from the teachers on staying in line. It should also be noted that not all of the younger children were yet physically able to run, which also affects these numbers.

4. Conclusion

The current study presents new data concerning the evacuation dynamics of children. Sixteen evacuation experiments in daycare centers in Denmark were

performed, evacuation times were measured and video films were analyzed. The experiment gives new information on flow through doors, walking speeds in a horizontal plane and in stairs.

The experimental study indicates that evacuation characteristics of children, concerning travel speeds on horizontal planes and down spiral stairs as well as flow through doors, differ from the data in literature which is focused on adults. The travel characteristics of children are age-dependent since the results show a clear difference between the two age groups analyzed, younger children: aged 6 months to 2 years and older children: 3 to 6 years old. They also depend on how familiar the children are with the path of escape.

When looking at travel speed in horizontal planes it was found that children move slower than adults and that younger children move slower than older ones. Walking children were slower than the predicted average walking speed usually applied for adults. However, the adult walking speed is exceeded by the running speeds of younger and older children. Hereby it has to be accounted for that the older children were running in a higher frequency than the younger children. It can be concluded that the walking speed for children deviates from the data obtained and applied from literature.

The results on the travel speed on spiral stairs indicate that familiarity with the stair and the design of the stair greatly affects the speed. In the only stair which the children used on a daily basis and which had a special handrail for the children, the average travel speed exceeded the data from the literature on adults. The two other stairs had average travel speeds which were much lower than the speeds obtained from experiments with adults. The external metallic fire escape stair caused the children most problems, even though the slope in the walking path was slightly lower than in the other stairs.

Results regarding flow indicate that flow of children through doors is generally higher than the reference data on adults found in existing literature. When comparing to literature, where the size of children is taken into account a similarity can be seen in the shape of the curve, where flow increases with increasing density. A clear peak was not found, perhaps due to limited measuring points at densities higher than 6 pers/m^2, although the trend line indicates a maximum flow at 9.8 pers/m^2. The older children reached both higher person densities and higher flows than the younger children did.

Nowadays evacuation models badly comprehend the behavior of children. This suggests that children are less safe in buildings than adults. It is common that models, which are designed from data on adults, are scaled to fit children without further investigation. More data is needed for further understanding on the subject and for future models to describe not only adult's evacuation pattern, but also children's.

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