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Evacuation of Children
Focusing on daycare centers and elementary schools

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Focusing on daycare centers and elementary schools

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Department of Civil Engineering
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Preface

This thesis is submitted as a partial fulfillment of the requirements for the Danish Ph.d. degree. The focus of the project has been to collect data and increase knowledge on evacuation of children. The main supervisor of the project is Anne S. Dederichs, associate professor at the Department of Civil Engineering, Technical University of Denmark and the co-supervisor is Daniel Nilsson, associate professor at the Department of Fire Safety Engineering and Systems Safety, Lund University.

Starting in October 2009 and ending in September 2013, the project has most certainly been a journey, both professionally and personally, that is now about to come to an end. Little did I know when I started that I would become so fond of the academic world and of being a part of the fire safety science community. Right from the beginning I felt welcome both by colleagues at DTU and researchers in the field even though I probably made an untraditional appearance at my first conference, Pedestrian and Evacuation Dynamics, in 2010. I showed up with a three month old baby and my husband as a babysitter. After living in Denmark during my studies I returned to my home country, Iceland, for the external research stay and to complete the thesis.

This thesis consists of two parts. Part I is a synopsis of the work of the project and Part II includes the scientific papers which this thesis is based on.

Reykjavik, September 30$^{\text{th}}$ 2013

Aldís Rún Lárusdóttir

Acknowledgements

This project could not have been completed without the help, support and participation of several people and institutes.

First of all I thank the European Union for financing the KESØ project.

I thank Copenhagen Fire Department for their contribution in arranging fire drills in daycare centers in the Vesterbro area, Copenhagen as well as all the participating daycare centers for their positive attitude towards the project. I also thank Anders Lyhne Sønderriis and Søren Mortensen for their work on data collecting in the daycare centers.

I thank the fire chief of Lyngby Taarbæk Municipally, Rasmus Storgaard Petersen for his contribution in arranging fire drills in elementary schools in Lyngby as well as the schools' positive attitude towards the drills. I also thank Birgit Pedersen for her work on data collecting and initial analyzing of the elementary school fire drills.

I thank the Capital District Fire and Rescue Services in Iceland for hosting and welcoming me during my external research stay in Iceland. I thank them for treating me as one of their own and for patiently answering my questions and giving me an inside view into their work and everyday challenges.

I thank the statistical team at the Science Institute of the University of Iceland, in particular Óli Páll Geirsson, for helping with the statistical analysis.

Furthermore I thank my colleagues in the fire safety group at the Section for Building Design, Department of Civil Engineering for their support and discussions throughout the project. In particular my fellow PhD. student and now my good friend, Janne Gress Sørensen who I shared an office with, for her professional and personal support at all times.

Thanks to co-supervisor Daniel Nilsson, especially for his input on and discussions on research ethics. I also thank other members of the KESØ project at Lund University for inspiring project meetings and cooperation.

I am greatly thankful to my supervisor, Anne S. Dederichs for introducing me to the academic world and giving me the chance to do a PhD. For believing in me at all times, offering support when needed and giving space when needed. For not only being a supervisor, but also a colleague and a friend.

At last but not least I thank my family. My parents for babysitting and assisting at busy times, my sister Sólrún and Lee for proofreading assistance and especially my husband, Sigurjón Björnsson, for encouraging me to grab the opportunity when offered a PhD. position. For listening to endless project talk and being a sparring partner when needed the most. For helping me with technical problems and for doing some macro programming for me to make my life just a little easier. For standing by my side when things were hard and for taking care of our home and children when I was too busy. And of course I thank my wonderful children for bearing with me when I was away at conferences or working late.

Abstract

Saving human lives is the highest priority in case of fire, according to fire codes around the world. Codes state that everyone should be able to escape to safety in case of fire. In order to design buildings that enable this the available safe egress time (ASET) must be held up against the required safe egress time (RSET). In theory if the ASET is larger than RSET everyone gets out safely. Different calculation methods are used for the determination of both times. Results of the calculations can however never be more accurate than the data they are based on. The aim of this project is to provide new data and information on children's evacuation, which is a step towards including children in evacuation models and calculations.

Little is known about children's evacuation characteristics in fire compared to other parts of the population. In recent years there has been more focus on children's evacuation which is reflected in a rising number of publications on the topic.

This thesis comprises evacuation experiments in daycares for children 0-6 years old and elementary schools for children aged 6-15 years. Full scale evacuations were filmed allowing detailed data analysis.

Findings and results include elements of three different areas, namely measurable parameters such as travel speed and flow though doors, human behavior such as choice of route and actions and processes such as evacuation procedures and warning methods. These areas are all related and influence each other, making it hard to isolate single factors and findings. Although an engineering approach fits best to the measurable parameters, the other areas are at least equally important when investigating or predicting children's evacuation.

The key findings of the thesis are:

- Children are very dependent on adults for initiating and carrying through an evacuation where the youngest children need the most assistance in both phases. Self preservation i.e. where children descended stairs unassisted, was less than 25 % for children aged 0-2 years but over 85 % for children aged 3-6 years.

- Warning method influenced pre-evacuation time, indicating that an alarm with audio signal is preferable to a light signal only or no alarm at all.
- Children's evacuation cannot be described using adults' evacuation models throughout. Young children are slower than adults and travel speed increases with age. At the age of 12 years children can be described using adults' travel parameters on stairs.
- Children generally achieved higher person densities and flow rates than adults. The flow rate increased with age until the age of 12 years where it started lowering, approaching theoretical values for adults. Children used the whole width of doors and stairs where needed, not leaving a boundary layer as the theory for adults suggests.
- Handrails were frequently used by both age groups in the daycare centers, more when walking on their own than when assisted. It was found that children using a low handrail achieved on average a 23.5% higher travel speed than those using a handrail designed for adults.
- Training has a positive effect on evacuation time and process. Fire drills showed weaknesses in evacuation procedures which could be revised accordingly.

Although a number of findings have been made and new data has been provided there is need for further research on the topic. Suggestions include data collection as well as further use of the existing video material, for answering unanswered questions and validating the current results.

Resumé

(Abstract in Danish)
Menneskeliv har den højeste prioritet i tilfælde af en brand. Regler og love over det meste af verden kræver at alle, der opholder sig i en bygning, skal kunne bringe sig i sikkerhed, hvis en brand opstår. For at kunne designe bygninger, der opfylder dette krav, skal tiden indtil kritiske forhold opstår (tkrit) sammenlignes med den nødvendige evakueringstid (tevak). Teorien foreskriver at alle er sikre hvis tkrit er større end tevak. Der findes imidlertid forskellige måder at beregene de nævnte tider på, og beregningerne kan aldrig blive mere præcise end de data, som de bygger på. Formålet med dette projekt er at tilvejebringe ny data og information om evakuering af børn, hvilket vil bringe os et skridt nærmere i bestræbelserne på at inkludere børn i evakueringsmodeller og -beregninger.

Der er findes på nuværende tidspunkt kun begrænset viden om hvordan børn reagere og handler i en evakueringssituation sammenlignet med andre dele af befolkningen. De seneste år er der dog kommet et større fokus på hvordan børn evakuerer, hvilket også kan måles på et øget antal publikationer om emnet.

Dette projekt omhandler evakueringsforsøg i daginstitutioner med børn i alderen 0-6 år og i folkeskoler med børn og unge i alderen 6-15 år. Alle fuld skala evakueringsforsøg blev filmet, hvilket gav mulighed for en detaljeret analyse efterfølgende.

Resultaterne kan inddeles i tre områder, målbare fysiske parametre såsom hastighed og personstrøm gennem døre, menneskeligadfærd, herunder valg af evakueringsrute samt handlinger og til sidst processer, hvilket inkluderer evakueringsprocedurer og varslingsmetoder. Disse tre områder er alle forbundne og det kan være svært at adskille de enkelte resultater og opdagelser fra hinanden. Selvom den ingeniørmæssige tilgang passer bedst til de målbare fysiske parametre er de andre områder mindst lige så vigtige når børns evakuering skal undersøges eller estimeres.

Projektets hovedresultater er følgende:

- Børn er meget afhængige af voksne for at initiere og gennemføre en evakuering. De yngste børn har brug for mest hjælp i begge faser. Ved gang ned af trapper var mindre end 25

- Varslingsmetoden havde inflydelse på tiden det tog at initiere evakueringen. En lydgivende alarm var at foretrække fremover en alarm kun med lyssignal eller ingen alarm.
- Evakueringsmodeller for voksne kan ikke bruges enkeltstående til at beskrive børn. Små børn er langsommere end voksne men hastigheden stiger med alderen. Børn fra og med 12 år kan beskrives med de samme parametre som for voksne når det gælder gang nedad trapper.
- Børn opnåede generelt en højere personstrøm gennem døre end teorien angiver for voksne. Personstrømmen var stigende med alderen indtil 12 års alderen, hvor den igen aftog og begyndte at nærme sig værdien for voksne. Børn anvendte hele bredden af døre og trapper hvor det var nødvendigt. Der opstod derfor ikke et grænselag på begge sider af evakueringsruten, som evakueringsteorien angiver.
- Gelænder blev hyppigt brugt af begge aldersgrupper i daginstitutioner, dog i højere grad for de selvhjulpne børn. Når de mindste børn brugte et gelænder placeret i børnehøjde opnåede de en 23.5
- Træning har vist en positiv indflydelse på evakueringstiden og processerne under en evakuering. Brandøvelser afslørede svagheder i evakueringsprocedurer, som deraf kunne justeres.

Projektet har resulteret i en øget viden og nye data indenfor området evakuering af børn. Der er dog fortsat brug for mere forskning på området. Der skal indsamles en endnu større mængde data og de eksisterende videooptagelser skal danne grundlag for flere analyser. Dette er behøvet for at kunne besvare nogle af de ubesvarede spørgsmål som er opstået samt til validering af de eksisterende data.

Samantekt

(Abstract in Icelandic)
Þegar eldsvoði á sér stað hefur björgun mannslifa algjöran forgang samkvæmt brunavarnareglugerðum um allan heim sem tilgreina á einn eða annan hátt að allir notendur bygginga eigi að geta forðað sér örugglega. Við hönnun bygginga samkvæmt þessu þarf að bera saman áætlaðan tíma uns hættuástand myndast, (t_{h_tta}) við áætlaðan flóttatíma, ($t_{flótti}$). Samkvæmt bókinni eru allir öruggir ef t_{h_tta} er lengri en $t_{flótti}$. Ýmsum aðferðum er beitt við tímaútreikninginn en niðurstöðurnar verða þó aldrei nákvæmari en gögnin sem þær byggja á. Markmið þessa verkefnis er að afla nýrra gagna og upplýsinga um rýmingu barna, sem er skref í áttina að því að geta tekið tillit til barna í líkönum og útreikningum.

Samanborið við aðra hópa þjóðfélagsins er lítið vitað um hvað einkennir rýmingu barna. Undanfarin ár hefur þessu þó verið meiri gaumur gefinn sem endurspeglast í fleiri fræðigreinumsem fjalla um rýmingu barna.

Þetta verkefni byggir á rýmingaræfingum í leikskólum fyrir börn 0-6 ára og í grunnskólum fyrir börn 6-15 ára. Þar voru rýmingaræfingar myndaðar og gögnin rannsökuð nákvæmlega.

Niðurstöðurnar eru þríþættar og varða mælanlegar breytur svo sem gönguhraða og flæði í gegnum dyr, mannlega hegðun svo sem viðbrögð og leiðarval og kerfislega þætti á borð við rýmingaráætlun og tegund viðvörunar. Öll þessi atriði tengjast og hafa áhrif hvert á annað sem veldur erfiðleikum þegar einangra á stakar niðurstöður. Þó svo að verkfræðileg nálgur eigi best við mælanlegu breyturnar eru hinar ekki síður mikilvægar þegar rannsaka á eða spá fyrir um rýmingu barna.

Lykilniðurstöður rannsóknarinnar eru:

- Börn eru mjög háð fullorðnum þegar kemur að rýmingu og yngstu börnin þurfa mesta aðstoð í öllu rýmingarferlinu. Hlutfall sjálfsbjarga barna, sem börn gengu óstudd niður stiga, var undir 25 % hjá aldurshópnum 0-2 ára en yfir 85 % hjá aldurshópnum 3-6 ára.

- Aðferð viðvörunar hafði áhrif á tímann sem leið uns fólk hóf eiginlega rýmingu og gefa niðurstöðurnar til kynna að aðvörun með hljóðmerki sé betri en aðvörun aðeins með ljósi eða ekkert aðvörunarkerfi.
- Rýmingu barna er ekki hægt að lýsa eingöngu með rýmingarlíkönum fullorðinna. Ung börn fara hægar en fullorðnir og hraði eykst með aldrinum. Við tólf ára aldur er hægt að nota líkön fullorðinna til að lýsa göngu niður stiga.
- Börn þjöppuðu sér að jafnaði meira samanen fullorðnir og náðu örara flæði Flæðið jókst með aldrinum en þó fór að draga úr þvi aftur við tólf ára aldur þar sem flæðið nálgaðist gildi fullorðinna. Börn nýttu til fulls vídddyraopa og stigahúsa þar sem þörf var á svo að ónýtt jaðarlag var ekki sjáanlegt eins og fræðin segja að eigi við um fullorðna.
- Handrið voru mikið notuð af báðum aldurshópum í leikskólum, þó meira þegar börnin fengu ekki aðstoð frá fullorðnum. Niðurstöður sýndu að börn sem notuðu lág handrið gengu að meðaltali 23.5 % hraðar en þau sem notuðu handrið í fullorðinshæð.
- Þjálfun hefur jákvæð áhrif á rýmingartíma og rýmingarferli. Rýmingaræfingar sýndu fram á veikleika í rýmingaráætlunum sem hægt var að lagfæra samkvæmt þeim.

Þrátt fyrir margvíslegar niðurstöður og ný gögn er þörf á frekari rannsóknum á sviðinu. Lögð er til bæði ný gagnasöfnun og frekari úrvinnsla myndefnis , til þess að svara ósvöruðum spurningum og að treysta þegar fengnar niðurstöður.

List of papers

Papers I-IV

Paper I:

A.R. Larusdottir and A.S. Dederichs, *Evacuation of children - movement on stairs and on horizontal plane.* Fire Technology, Vol.48, pages 43-53, 2012.

Paper II:

A.R. Larusdottir and A.S. Dederichs, *A step towards including children's evacuation parameters and behavior in fire safe building design.* Fire Safety Science 10, pages 187–195, 2011.

Paper III:

A.R. Larusdottir and A.S. Dederichs, *Movement down stairs during elementary school fire drills.* Fire and Materials, 2013. Submitted.

Paper IV:

A.R. Larusdottir and A.S. Dederichs, *Evacuation of young children from multistory daycare centers: Travel parameters down stairs.* Fire Technology, 2013. Submitted.

Other papers

Presented at international conferences and published in conference proceedings (not appended):

A.R. Larusdottir and A.S. Dederichs. *Evacuation dynamics of children - walking speeds, flow through doors in daycare centers.* Proceedings of Pedestrian and Evacuation Dynamics Symposium, pages 139–147, 2010. (Paper I is an extended version of this paper.)

M.C. Campanella, A.R. Larusdottir, W. Daamen, and A.S. Dederichs. *Empirical data analysis and modelling of the evacuation of children from three multi-storey day-care centres.* Proceedings of Evacuation and Human Behavior in Emergency Situations, Santander, 2011.

A.R. Larusdottir and A.S. Dederichs. *Behavioural aspects of movement down stairs during elementary school fire drills.* Proceedings of Human Behaviour in Fire Symposium, 2012.

In the making:

M.C. Campanella, A.R. Larusdottir, W. Daamen, and A.S. Dederichs. *Identifying challenges when modeling children's evacuation, by comparing empirical data to simulations.* Manuscript.

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PART I

Chapter 1

Introduction

When entering the phrase "evacuation of children" into an online search engine the results primarily deal with evacuation of British children from London to the countryside which was considered safer, during Wold War II. As for this project the title *Evacuation of children* relates to moving children towards a safer location due to a potential threat, however it is limited to building evacuation.

A building evacuation may be triggered for different reasons, such as fire, earthquake, gas leak, bad weather and terror threats and they can have a different level of urgency. This project focuses on emergency evacuation due to fire, but the findings should applicable to other situations where immediate evacuation is needed.

Fire and building codes around the world focus on life safety, stating that everyone should have the chance to escape safely in case of fire [1–3]. In order to design buildings that enable this the estimated available safe egress time (ASET) is held up against the required safe egress time (RSET). There are different methods to calculate both and in theory everyone gets out safely if the ASET is larger than RSET. The calculations can however never be more accurate than the data they base on.

The research field, of human behavior during evacuations and pedestrian dynamics, is young compared to many other research fields. Some of the earliest literature, which is in fact still valid and referred to in today's research, is Predtechenskii's and Milinskii's book *Planning for Foot Traffic Flow in Buildings* from 1969 [4] and Fruin's book *Pedestrian Planning and Design* from 1971 [5]. Ever since, the research field has grown and more literature has become available.

Children are a large subgroup of the population or 15-20 % of the Western countries' population [6]. This is a large group to neglect and a vulnerable one to, making it even more important to ensure its safety. As Fruin [5] put it:

> "The child pedestrian is an especially vulnerable accident victim because of gaps in language, perception, and visual and auditory comprehension. Many aspects of human perception, such as peripheral vision, depth perception, judgement of speed and direction, and sound recognition, are attained through experience, which the child pedestrian has not yet acquired. This lack of experience causes not only perceptual difficulties, but uncertain reactions under the stress of frightening or unusual confrontations with moving traffic. In addition, children do not comprehend road signs, or if they do, they do not fully understand their responsibilities to obey these signs."

Even though this is meant in context of traffic safety it can easily be applied to fire safety. In case of fire, unexpected events can occur where advanced decision making, way finding, communication skills and physical strength might be needed, all of which a child might not have developed.

It is generally accepted that children are different from adults, although the difference is not always well documented and tested. Scaling values for adults down to fit children, without proper testing and validation, is questionable. An example of this is when it comes to estimating dosage and type of medication for children and adolescents [7].

Identifying locations and buildings where children are present is necessary in order to investigate the population and its evacuation characteristics. Apart from being at home, children are under many circumstances grouped together, namely in daycare centers or at school while their parents are at work. Furthermore children are gathered at other places for shorter periods of time such as in shopping centers' play areas, where parents can leave their children while shopping. Both types of situations mean that parents are not available during a potential evacuation resulting in a limited number of adults to initiate, guide and assist throughout the emergency.

Fire statistics show that fires are common in educational institutes and occur both during and outside of occupancy hours where civilian injury is rare and death even rarer [8]. Examples of tragic incidents however prove the consequences to life safety can be massive. In December 1958 a fire at Our Lady of the Angels School, Chicago, USA claimed the lives of 92 children and 3 teachers and injured many when the fire, ignited in the stairwell at basement level, blocked the evacuation route for those on the second floor. Key elements to the high loss of life were late discovery, warning and alarming to emergency services in combination with the layout of the building lacking a fire door and independent exits [9]. In July 2004 a fire at the Saraswathi English Medium School, Kumbakonam, India killed 87 children and one adult and injured at least 12 when the roof on third floor caught fire and collapsed down on the classrooms. Key elements here were the flammable roof material, a single exit and a single stairwell [10]. In June 2009 a fire at ABC Day Care center, Hermosillo, Mexico ultimately killed 47 young children and injured over 40 as the fire started in the neighboring compartment spreading through the roof to the daycare. This was during the "siesta" when most of the children were asleep. Here the key elements of the tragic ending were late recognition, a single narrow exit, high child to adult ratio and bad timing [11]. In May 2012 a fire at Gympanzee Nursery and Day Care in the Villagio Mall, Doha, Qatar took the life of 13 children, 4 staff members and 2 fire fighters. In this case the key elements of the outcome were a recent false alarm, malfunctioning sprinklers, inconvenient escape routes including a stair collapsing, and confusion regarding floor plans [12]. These are not the only fires in daycares and school with a fatal outcome, but only four tragic examples. Fortunately the fire at Our Lady of the Angels School fire greatly impacted and improved fire codes [13]. A common factor in these four incidents is that multiple failures lead to the fatal outcome, them being technical, human, procedural or organizational or a combination of these. As tempting as it is to claim that the mentioned incidents could never happen today or could only happen in distant or undeveloped countries, the risk must be taken seriously because failures can happen anytime and anywhere.

An overview of available literature on fire safety focusing on children is provided in the next chapter, where the most relevant literature is briefly discussed.

1.1 Objectives

The aim of the project is to bring the attention of the fire safety community and authorities to the topic emergency evacuation of children and to increase knowledge on the subject. The project is expected to provide new data on children's evacuation parameters which can influence future guidelines and designs. Hopefully it will lead to expansion of current models, praxis and regulations to comprehend children.

This project comprises evacuation experiments in daycares for children 0-6 years old and elementary schools for children aged 6-15 years where full scale evacuations are filmed allowing detailed data analysis and extraction.

1.2 Structure of the report

This thesis consists of two parts. Part I is a synopsis where the subject is introduced and the background and previous findings on the matter mentioned. The methodology of the project as well as the results are discussed comprehensively, ending with a conclusion chapter including a section on future work. Part II includes three scientific journal papers and one peer-reviewed paper published in conference proceedings which this thesis is based on. Other papers presented at conferences are listed in the List of Papers but not included. The four appended papers are throughout the thesis referred to as Paper I-Paper IV.

Chapter 2

Literature background

Predicting people's actions and evacuation patterns has an increased importance since performance based fire codes have been implemented in Denmark and around the world in recent years. Today's models, regulations and manuals rely on numerous studies, reports and experience [14–16]. There is literature available on numerous building types such as highrise buildings [17–19] assembly buildings [20], apartment buildings [21, 22] and public buildings [23]. Furthermore publications are available on specific topics such as effective width [24], panic [25, 26] and computer models [27, 28]. Much of the research mentioned is only valid for able bodied adults, however some population groups that are considered vulnerable have also been specifically addressed, such as the elderly and people with disabilities [29–34]. Children are also considered a vulnerable population group and are over represented in fire death statistics in many countries [35].

The human factor in fire safety is still weakly considered in nowadays fire regulations, praxis and models, while there are extensive regulations concerning the technical side of the fire safety, such as installations and structural parts of the building. The importance of including the human factor is however being realized and an example of that is the ongoing research and discussions concerning elevator use for evacuation, where the main concern is not the technical challenges of making elevators safe to use in fire, but how to get people to use them in an emergency after decades of convincing people not to do so [36–40].

2.1 Overview - focus on children

Tables 2.1 and 2.2 list many of the publications available on the fire safety of children. The literature is sorted by publishing year and it spans from the year 1975 to 2012. Publications published before this project came to life are included in table 2.1 while publications published in the years 2009-2012 are listed in table 2.2.

Table 2.1: Brief overview of available literature on fire safety of children prior to 2009

Year	Title of paper/report	Author(s)	Country	Age	Method	Key words
1975	A fire signal system for deaf school children [41]	Kravontka, S.J.	USA	-	study	visual evacuation signal, guide lines
1985	A study of fire safety and evacuation planning for pre-school and day care centers [42]	Murozaki, Y. & Ohnishi, K.	Japan	0-5	fire drills, questionnaires	training, flow, travel speed, design
1986	Evacuating schools on fire [43]	Van Bogaert, A.F.	Belgium	-	study	evacuation episodes, design,special schools
1986	Fire safety research and measures in schools in Belgium [44]	Van Bogaert, A.F.	Belgium	-	study, material testing	national norm, prevention, restriction, protection, disabled pupils
1994	Investigation of a behavioural response model for fire emergency situations in secondary schools [45]	Horasan, M. & Bruck D.	Australia	12-20	questionnaire	behavioural response modeling, fire safety training
1999	Non-awakening in children in response to a smoke detector alarm [46]	Bruck, D.	Australia	6-17	experiments, interviews	sleep, youth, smoke detector
2001	The development of an education program effective in reducing fire deaths of preschool children [47]	Gamache, S. & Porth, D.	USA	3-5	pre and post field test evaluation	preschool program, fire safety education, fire statistics
2003	Comparison of an evacuation exercise in a primary school to simulation results [48]	Klüpfel, H. et al	Germany	6-10	fire drill, simulations	drill vs simulation, repeated drill
2003	Balancing safety and security in the school environment [13]	Szachnowicz	USA	-	study	fire challenges, balancing ingress and egress
2004	A study on school children's attitude towards firesafety and evacuation behaviour in Brazil and the comparison with data from Japanese children [49]	Ono, R. & Tatebe, K.	Brazil & Japan	11-14	comparing survey	fire safety awareness, fire safety education, cultural aspects
2006	Towards the design and operation of fire safe school facilities [50]	Hassanain, M.A.	Saudi Arabia	-	study	fire risk assessment, fire hazards, design

It can be seen that the number of papers on children has increased a lot in recent years. In fact 12 out of the 23 publications listed have been published since this project came about in 2009, five of them originating from it.

It is also interesting to see that the publications span a wide range geographically and culturally, originating from ten different countries.

The range of the content of the papers listed in table 2.1 and 2.2 is also wide and even though not all of the papers are directly relevant to this study the purpose of including them is to show publications where children were in focus.

In addition to the papers mentioned here, where children or facilities for children are the main subject, there also exist publications where children are mentioned or results on children are included even though children are not the main topic. Those data and findings are equally important and contribute to the knowledge we have on children.

Table 2.2: Brief overview of available literature on fire safety of children 2009-2012

Year	Title of paper/report	Author(s)	Country	Age	Method	Key words
2009	A study on evacuation of school buildings for elementary education [51]	Ono, R. & Valentin, M.V.	Brazil	11-14	simulations	alternative designs, fire exits, regulation requirements, multi story schools
2009	Pre-School and school children building evacuation [52]	Kholshevnikov V.V. et al	Russia	3-17	fire drills, questionnaire	pre-evacuation, staff training, travel speed, stairs, design
2010	Evacuation dynamics of children - walking speeds, flow through doors in daycare centers [53]	Larusdottir, A.R. & Dederichs, A.S.	Denmark	0-6	fire drills	travel speed, flow, age dependance, spiral stairs
2010	The evacuate training problems of earthquake in China [54]	Lu, C.	China	3-18	study, fire drills	escape rules, speed vs. age, stairs
2011	A step towards including children's evacuation parameters and behavior in fire safe building design [55]	Larusdottir, A.R. & Dederichs, A.S.	Denmark	0-6	fire drills	pre-evacuation time, flow model, travel speed, behavior, assistance
2011	Empirical data analysis and modeling of the evacuation of children from three multi-storey day-care centres [56]	Campanella, M.C. et al	Denmark	0-6	fire drills, simulations	drill vs simulation, evacuation procedure
2012	Evacuation of children - movement on stairs and on horizontal plane [57]	Larusdottir, A.R. & Dederichs, A.S.	Denmark	0-6	fire drills	travel speed, flow, effective width, age, spiral stairs
2012	Study of Children Evacuation from Pre-school education institutions [58]	Kholshevnikov V.V. et al	Russia	0-7	study, fire drills	pre-evacuation, travel speed, stairs, density
2012	Behavioural aspects of movement down stairs during elementary school fire drills [59]	Larusdottir, A.R. & Dederichs, A.S.	Denmark	6-15	fire drills	travel speed, stairs, behaviour
2012	Children evacuation: empirical data and egress modeling [60]	Capote, J.A. et al	Spain	3-16	fire drills, simulations	egress time, flow, travel speed, stairs, drill vs simulation
2012	Walking speed data of fire drills at an elementary school [61]	Ono, R. et al	Brazil	6-14	fire drills	egress time, travel speed, stairs, controlling factors
2012	Children behaviour during evacuation process in school buildings [62]	Capote, J.A. et al	Spain	3-16	fire drills, simulations	pre-evacuation time, flow, travel speed, stairs, drill vs simulation

An example of that is a study on evacuation from apartment buildings where families with children were among participants. This resulted in some specific results on travel speeds for children, even though the sample size was small [22, 63]. Another example of a study where children were included, is a study focusing on people with disabilities, where disabled children were a subgroup [31].

2.1.1 Travel parameters - daycares and schools

The 1985 paper from Japan by Murozaki and Ohnishi [42] was the only paper available which was directly related to evacuation of young children when the first evacuation experiments in Danish daycare centers were conducted in 2009. It was inspiring for the project and it being almost 25 years old at the time and from Japan made it even more interesting to collect new data from Denmark.

The same year as the first experiments of the current research were conducted in 2009, a paper was presented at the 4th International Symposium on Human Behaviour in Fire on the topic evacuation of pre-schools in Russia, by Kholshevnikov et al. [52]. Although very relevant and with many common factors of the present research, it provided limited data on travel parameters. An extended version of the paper was however published in a journal in 2012 [58]. It included large amounts of data on pre-school evacuations and children's travel parameters, including results on pre-evacuation time, flow through doors and travel speed which are amongst the focus points of the present research. However, much of the data is gathered through everyday use of the building and experimental setup.

The reason for also investigating school evacuations was to attempt to extend the data collection to comprehend a continuous age range of children 0-15 years. On the 5th International Symposium on Human Behaviour in Fire 2012 there was a session dedicated to school evacuations. In fact there were three papers presented, including one from the current research, introducing somewhat similar results, all from different countries and teams of researchers. All studies included data on travel speed down stairs for elementary school children. The study from Spain by Cuesta et al. [60] also included computer simulations and an investigation of whether the youngest children placed one or two feet per step. The study conducted in Brazil by Ono et al. [61] included discussions on how the travel speed of a group was influenced by the child walking in front, referred to as the leader, and how the children that lagged behind sprinted to catch up.

At last a report from the NFPA, is very relevant to this research [64] (not listed in table 2.2 because it is not published yet). The main topic is children's self-preservation and it is based on questionnaires, where professionals working at daycare centers and experts in children's development participated. Questions concerning child to adult ratio and self-preservation, when children can be expected to walk unsupported on a horizontal surface and in stairs as well as when children can be expected to follow simple instructions are particularly relevant.

Results from the mentioned studies will be referred to and displayed where relevant for comparison.

Judging from recently published and presented papers, there are ongoing studies in several countries. Hopefully the literature on children will be further enriched in the near future.

2.1.2 Fire safety education for children

There exist fire safety educational programs for children in several countries, starting already at the pre-school age 3-5 years. When designing such programs the age of the audience plays a leading role, since learning skills develop throughout the childhood. While testing these programs is important to measure their understanding and effectiveness, it is both difficult and time consuming when looking at programs for pre-school children. This is due to the fact that children at that age need to be interviewed to measure their individual knowledge and that finding a measurable variable of the effect is complicated [65].

However one of the listed papers in table 2.1 concerns the fire safety program "Learn not to burn" where children's fire safety knowledge is measured before and after completing the program and related to statistics on fires and fire deaths. The program should reduce the risk of fire and burn, teach the children how to react to fire and to escape safely in case of fire. The program showed a considerable knowledge increase on the topics taught and a reduction in child-set fires [47].

In Iceland there is a program running for 5 year old children, the oldest children in daycare. It has some of the same elements as the program described above, it however also focuses on fire safety in the daycare. The children are taught how to do monthly inspections of certain fire safety matters which they take turns on doing along with their teachers. This way they are involved in embracing safety and are made aware of the procedures. How the children and staff are kept involved, active and interested has some of the elements introduced in [66], where it is described how people should be helped on their own terms. This is done by including the resident population of the building and using their strength and knowledge to embrace safety.

The Icelandic fire safety educational program has not been scientifically tested yet, however there are indications of the program showing improvement in fire safety knowledge and one reported incident of where a child reacted according to the education in a real fire. A summary of the program can be seen in Appendix A.

CHAPTER 3

Method

As described in the Introduction the main objective of the project has been to collect data on the evacuation of children and to disseminate the results to the fire safety community. In the long run the work should contribute to improved fire safety for children and awareness of the similarities and differences between children's and adults' evacuation.

The choice was made to perform fire drills in buildings which naturally occupy groups of children. Other possibilities were considered less feasible. Doing experiments at a fixed location or in a lab would require access to such facilities and using questionnaires or interviewing fire survivors was considered less appropriate for children and more difficult to get access to and recruit potential subjects. The fire drills were full scale and semi unannounced. Semi unannounced in this context means that most of the children (or their parents) knew which week there would be a fire drill, the teachers knew the day and the leader/headmaster knew the day and the time. Although it would be optimal to have the drills totally unannounced for the most natural response and behavior it was not possible to due the filming.

The findings of the experiments are considered representative for the type of buildings involved. Furthermore it should be possible to generalize some of the results to children in other type of buildings. The main limitations of using a natural environment concerned not having control over the physical dimensions of the evacuation routes, the precise size and composition of the populations and camera locations were somewhat restricted. However the recruiting was easier since individual recruiting was not needed and the social bonds between participants were natural.

The method used throughout the project will be described in the following subsections. Beginning with some background information before mentioning the ethical considerations. Then introducing the experiments conducted including the equipment and setup. At last the method used to analyze the data is covered as well as the statistical analysis.

3.1 Background information

Danish daycare centers accept children from the age of 6 months. From that age and until the children turn 3 years their institution is called "vuggestue" in Danish which could be translated to nursery. This age interval is referred to as the younger children or children 0-2 years in papers on the research (Paper I, Paper II and Paper IV). From the age of 3 and until the children start school their institution is called "børnehave" in Danish which could be translated to kindergarten. This age interval is referred to as the older children or children 3-6 years in the same publications. Daycare centers can either include both age groups or be specified for one or the other.

Most children in Denmark start school in the year they turn 6 years old (some start one year later) which is why the youngest class in the schools, class 0, is defined as 6 year old children This gives a small overlap between the oldest children in daycare and the youngest children in school, since school has a common start in the autumn and is not dependant on each child's birthday. Elementary school has classes 0-9, defined as being for children and youth aged 6-15 years as referred to in Paper III.

When comparing Danish requirements to fire safety measures in schools and daycare centers for children, the fundamental difference lies in the employment category. Schools and other educational buildings are defined as being category two and/or three depending on the number of people. The assumption is that people are awake and able to evacuate by themselves but might not know the building's emergency exits. Daycare centers are on the other hand defined as being in employment category six, which is a wide category of every building with people not being able to bring themselves to safety for one reason or another. Other examples of buildings in this category are prisons, homes for the elderly, homes for disabled people and hospitals. Requirements regarding fire safety vary depending on the employment category.

At last it should be mentioned that an update to the Danish building regulations in 2004, required automatic fire alarms (with at least staff notification) for employment category six [1]. This however did not apply for buildings, including daycare centers, built before then which is the reason why not all participating daycare centers had a fire alarm.

Annual fire safety inspections should be performed in both schools and daycare centers, however facilities with less than 50 occupants are excluded.

3.2 Ethics

The experiments involved in this project are classified as observational studies by the Danish Council of Ethics, because the participants are not exposed to any extreme or unusual circumstances (such as hinders, smoke etc.). This meant that permission from the Danish Council of Ethics was not needed. Furthermore no sensitive information was gathered about the participants (such as on health, religion etc.), thus the project did not need permission from the Danish Data Protection Agency.

Some thought was given to ethics, even though the project did not need formal ethical approval. The Swedish application form for ethical approval was inspiring with respect to benefits of the research. In that context it can be said about the experiments performed that the participants (children and staff/teachers in the institutions involved) benefitted directly from participating since they got training in evacuation and increased awareness and knowledge on fire safety and evacuation. The participating population in general (children and staff/teachers at each time) also benefits from the experiments since the results should increase scientific knowledge on the subject and thereby increase the level of safety in these types of buildings in the future.

Due to policies on photographing and filming in many of the daycare centers involved all parents were informed about the fire drill and filming in the daycare centers beforehand. Only a few expressed their concern, it was however rarely about the filming itself but more about the fire drill. The leaders answered their questions and reassured the parents that their children's welfare was of highest priority. Apart from the hesitation at the beginning, the project was in whole generally met with a positive attitude and was welcomed both by staff and parents.

3.3 Experiments

Table 3.1 shows an overview of the experiments stating the type of institute (daycare or school), age interval, location, year of experiments, number of experiments, number of available cameras and at last the main focus of the research. All experimental periods provided results on more subjects than the one main focus mentioned in table 3.1.

Table 3.1: Overview of experimental periods

type	age	municipally	year	# exp	# cam	main focus
daycare	0-6 years	Lyngby Taarbæk	2009	16	10	flow through doors [1]
schools	6-15 years	Lyngby Taarbæk	2010	7	59	travel speed down stairs[2]
daycare	0-6 years	Copenhagen	2011	9	59	travel speed down stairs

[1]Results in [67] are based on part of the data
[2]Results in [68] are based on the data

The goal of the first experimental period was to get an overview of evacuations in daycare centers and to gather data on flow through doors, also at high person densities.

The second experimental period where elementary schools were evacuated, the goal was to identify at what age children can be described by evacuation theory which is based on adults, focusing on movement on stairs.

The goal of the third and last experimental period was to continue to investigate young children's evacuation focusing on movement on stairs.

3.3.1 Equipment and setup

Since the experiments were run over two years covering three experimental periods, the method developed with time as increased equipment and resources became available as well as gained experience and knowledge in the field. All changes were however considered carefully to ensure comparability between the results. The goal of all changes was to minimize errors and to make the analysis more consistent.

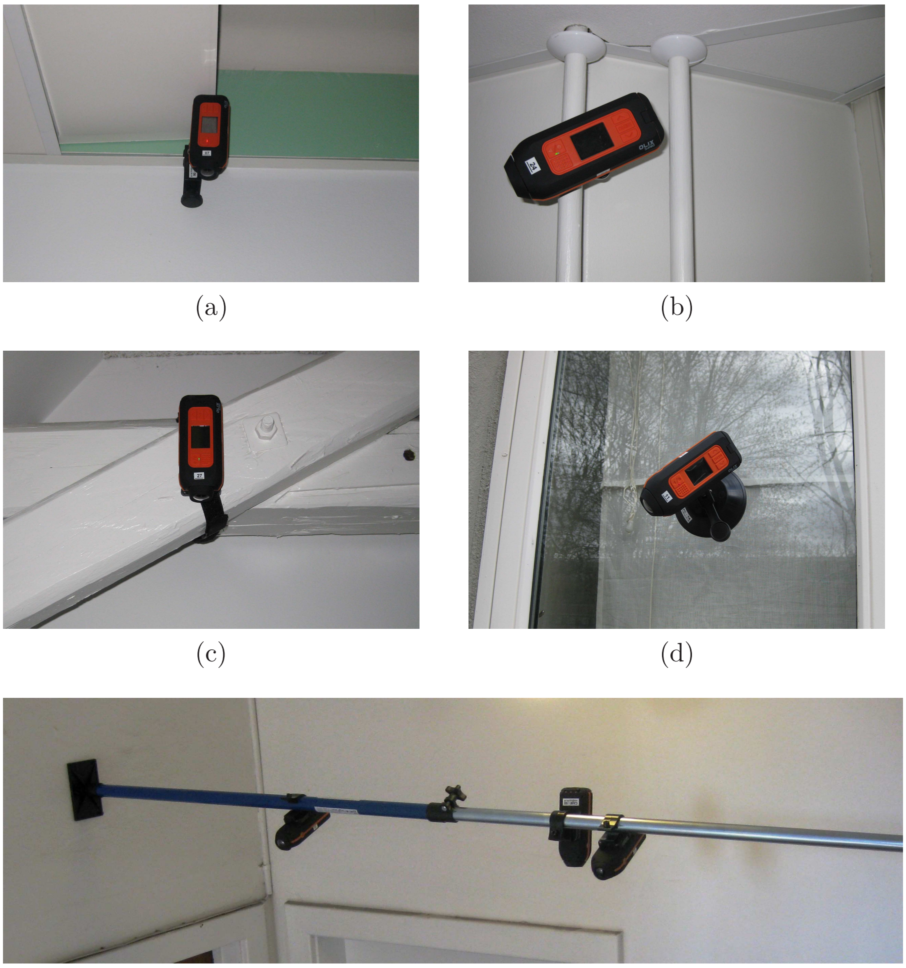
The filming equipment available at the beginning consisted of seven different recording devices, ranging from camcorders to a webcam connected to a laptop. Mounting solutions were limited to furniture where the cameras could stand using duct-tape for support. At the end of the project DTU had established a mobile evacuation lab of 59 compact action cameras as well as different mounting equipment. Figure 3.1 shows examples of cameras mounted using different solutions. The mounting equipment included multipurpose clamps (a), pipe fasteners (b), velcro strips (c), vacuum cups for use on glass (d) and vertical pressure bars (e) which were used with the pipe fasteners and were practical for hallways and stairs where there was limited furniture.

The cameras are of the make X170 from Drift Innovations. They have a 170° wide angle lens which makes it possible to capture a large area with a single camera. They furthermore have a remote control and are very light weight which makes mounting easier with the help of various mounting equipment. The cameras were synchronized by going by each camera with a stop watch running and filming the time. Then it was enough to identify the start of the drill using one camera and the local time code on the other cameras could be calculated. This was most important where there was not an acoustic alarm system where the start of the fire drill could be identified by the sound.

In addition to more and better equipment, human resources became available with the support of the European Union, through the KESØ project standing for Kompetence center for Evakuering Sikkerhed i Øresundregionen (Competence center on Evacuation Safety in the Oresund region), which is a cooperation project between DTU and LU. This meant helpers could be recruited to assist with camera setup at the largest locations.

3.3.2 Fire drills

Common factors for all conducted experiments were that the date and time for the fire drills were chosen in cooperation with the participating institutes, daycares and schools,



(a) (b) (c) (d) (e)

Figure 3.1: Different mounting solutions for cameras during fire drills.

avoiding special activities as well as lunchtime and naptime. Even though in reality an evacuation might be initialized at any time, an optimal time with respect to the daily routines was chosen. The fire drills were typically held around 10 am, at that time the daycare children were most often in their group rooms with the assigned staff and the school children were in class with their teacher. Only one of the participating daycare centers had performed an evacuation exercise in recent years. To encourage all daycare centers to continue to train emergency evacuation it was important to contribute to a good experience. Five out of seven participating schools claimed to execute at least one fire drill per year and one of them 4-6 drills per year. The schools are required to have an annual fire drill, whereas it is recommended for daycares and not mandatory.

The course of action for each experiment was approximately as follows:

Prior to the day of the drill

- Met with leader or other person at location where the existing evacuation plan (if avaliable) was discussed as well as the upcoming fire drill. Possible camera locations were marked in a plan drawing of the buildings as well as the expected number and age of the children in each part of the facility.

Day of the drill

- Setup of cameras (at a few locations, this was done the day before).
- In front of doors and on landings on the stairs, mats with a chess pattern were placed on the floor and filmed (black and white squares) and were used for measuring density when analyzing the films.
- Synchronization of cameras.
- Fire drill initiated by activating the fire alarm or alarming a member of staff.
- The evacuation itself (and in the last experimental period also calling the fire department).
- Gathering at safe area outside ensuring everyone is out (and in the last experimental period also informing fire department of the situation).
- Occupants returned to building and prior activities.
- Taking down the cameras.
- Staff discussed the fire drill with the children.
- Recovering data files from cameras.

In the following days

- Internal evaluation of fire drill amongst staff

3.4 Data analyzing

The films were processed manually by using Adobe Premiere Pro which among other things allows for playback frame by frame, having multiple files open at the same time and having a background layer during playback. Data retrieving, organizing and simple calculations were made in Microsoft Excel. Figures, except for pictures, are generated in Matlab and RStudio.

When analyzing the films a number of relevant things were noted in a spreadsheet. Each participant got a number, a physical description of the clothing and/or other identifying factors, age/age interval and gender. In addition to this the time step when passing relevant points during the evacuation was noted, as were actions and behavior where relevant. The identifying was necessary to be able to track each individual between cameras allowing extensive mapping of the evacuation.For the last batch of experiments made in multistory daycare centers in Copenhagen notations were also made concerning carrying, other assistance by adults and use of handrail when traveling down stairs. Handolding between students was investigated in the schools.

3.4.1 Flow

Flow through doors was measured by counting the number of people [pers] passing through a door and dividing by the time [s] it took the group to pass. Only continuous flow was used. To correct for different door widths the actual flow [pers/s] is divided by the door width [m] resulting in a specific flow [pers/sm]. For reference, when introducing and discussing the results a flow curve from Nelson and Mowrer's chapter in the SFPE handbook is used [16]. Figure 3.2 shows the curve for doors and hallways but also stairs with three different proportions of tread/rise of the steps (T/R).

3.4.2 Effective width

Evacuation theory suggests that when calculating flow through doors, hallways or stairs the width should be reduced since people avoid touching door frames and walls. The amount of reduction depends on the structure according to [16]. It was however observed in this research that the whole width of the doors was used when needed and the same was evident for the stairs. It was commonly seen that children supported themselves by leaning against the wall or stroking the wall with their hand when there was no handrail present. Due to these observations on the films, no reductions are made to the door widths or stairs due to a boundary layer. The effective width is therefore defined equal to the free width for the results of this research.

3.4.3 Travel speed

All speed measurements were made in [m/s] and calculated by dividing the distance traveled [m] by the time [s]. For horizontal plan, speed data is available for free walking speed,

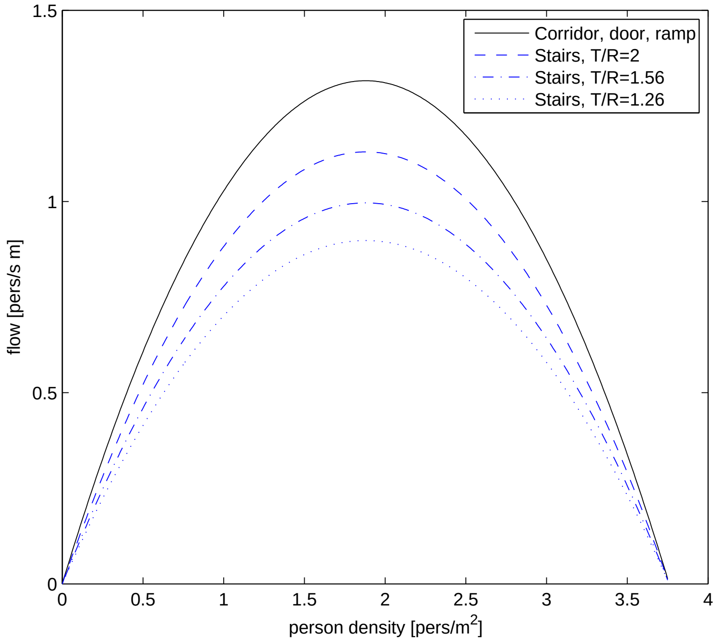


Figure 3.2: A frequently used flow curve fitted for different use [16].

where the children move independent of each other. A commonly used free travel speed in horizontal plane for adults is 1.2-1.3 m/s [16, 69].

On stairs the distance was measured in line of travel, the diagonal slope of a stair. In case of spiral stairs a walking path was defined, since the line of travel depends on where on the stair it is measured. Since the children walked in a single row (with few exceptions) the same walking path is used for all. When measuring travel speed on stairs the landings are excluded, that is, a new speed measurement was made for each flight of stairs. Due to reasons concerning density calculations, which is explained in the following, stairs between floors without landings were divided in two parts as if there were a landing in the middle. A curve in the SFPE handbook also shows a commonly used relationship between travel speed and density. Figure 3.3 shows this curve for horizontal plane but also stairs with three different proportions of tread/rise of the steps (T/R).

3.4.4 Person density

Person density $[pers/m^2]$ related to flow through doors was measured in $1m^2$ directly in front of the respective door. Door mats, or other obstacles were used as reference. In some cases tape was used to mark the area.

When finding a corresponding density to a travel speed down a flight of stairs the average density occurring on the same flight of stairs while the person in question is on the stair,

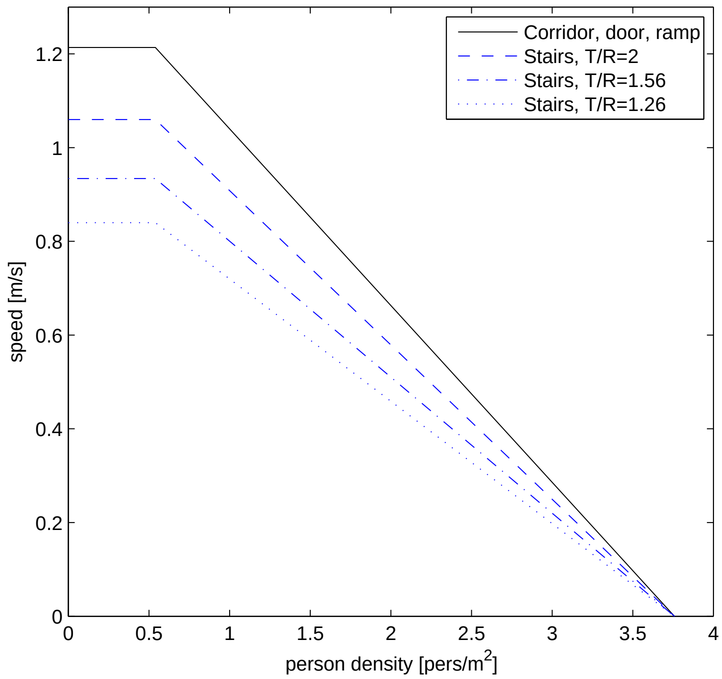


Figure 3.3: A frequently used travel speed curve fitted for different use [16].

was used. For the second experimental period the number of persons on the stair was manually counted and noted every second and used for these calculations. For the third experimental period the time stamps were used to calculate it automatically. Furthermore it was decided to place an artificial landing if there were no landings in between floors, for calculating both speed and density. The main reason for this is to avoid large differences in the area used for density calculations. Also to minimize errors when a group of people is entering or emptying the stair. If the number of people who just entered a stair together is divided by the whole area of the stair, it results in indicating by far a lower person density than the people are experiencing.

The described method of how to measure density in stairs was a common decision of the group at DTU working with evacuation to ensure compatibility, at least between results from DTU. Methods regarding density calculations were found to be poorly described in existing literature, it however suggests that the density is in some cases measured at the landings or platforms between floors using either the whole landing or a reduced area. As emphasized in [70, 71] comparisons between studies should be made with caution due to differences in measuring technique.

Another unit used to measure person density is m^2/m^2, which indicates the area projected by people out of the available area. A person's horizontal projection is estimated according to age, clothing and accessories, so a child occupies less space than an adult and an adult in winter clothing with a suitcase even more. This method is introduced and used in Predtchenskii's and Milinskii's book [4] and should be useful when dealing with mixed populations, as it is not necessary to estimate that all people are of equal size. Despite the advantages it is rarely used today, although Paper I includes a discussion of this method of measuring density in relation to daycare evacuations.

3.5 Statistics

For statistical calculations the software RStudio was used. For initial graphical investigations to spot differences between groups or factors it was used to make box plots, showing means, upper and lower quartiles, 1.5 IQR (inter quartile range) and outliers. RStudio was then used for analysis of variance if the box plots indicated a difference, using $\alpha = 0.05$ (95 % confidence level). At last a Tokey test was performed to investigate in more detail if and between what subgroups there was a statistically valid difference, again using $\alpha = 0.05$.

Chapter 4

Results and Discussion

The results of this project will be summarized here. Most of the results are included in Paper I - Paper IV, however some new perspectives will be given here as well as comparisons and results of statistical tests that have not all been previously displayed and discussed.

It is challenging to present the results of a project like this, to leave nothing out but still have a continuous flow, to display things in the right context and still avoid too much repetition. The complexity also lies in the fact that the results are spread but relate to each other and findings in one area might affect how to view findings in the next. In the first section of this chapter the staff involvement throughout the fire drills is discussed. Then sections 4.2-4.9 are arranged in a near chronological time order with respect to a fire drill. At last there are sections 4.10-4.14, which refer to findings and results in some of the other sections, but with a different approach and/or context.

4.1 Staff involvement

The staff in daycares and schools for children bear great responsibility in case of fire. As mentioned in Chapter 3 the Danish Building Code [1] defines daycares in employment category 6, where occupants are not expected to be able to evacuate unassisted due to immobility, cognitive challenges or imprisonment. Other facilities in employment category 6 are homes for the elderly or disabled, hospitals and detention facilities. Children in daycare centers sometimes have all of those vulnerabilities as they have undeveloped motor skills, limited understanding of the situation and doors are frequently locked or have doorknobs at high locations. Figure 4.1 shows two examples of doors in daycare centers with doorknobs out of reach for small children.

Schools however usually fall into both employment categories 2 (normal classrooms) and 3 (auditoriums for 50 people or more), where occupants are expected to be able to evacuate

(a) (b)

Figure 4.1: Examples of doorknobs located out of reach for children.

unassisted but might not be familiar with the building. Assistance is provided to children throughout the day with various tasks however in an emergency situation it can be critical. The typical child to adult ratio goes from being 3-4 children per adult at the age 0-2, to 5-10 per adult for children aged 3-6. At the age of 6 one teacher is responsible for a whole class of 15-30 children. The differentiation in employment categories between daycares and schools along with the child to adult ratio indicates that younger children need more assistance during evacuation than the older ones.

4.1.1 Detection and warning

The task of detecting a fire and raising the alarm is in the hands of staff if this does not happen automatically. Technical installations are not available in every daycare or school and a fire might not be detected by a smoke detector due to its location or the warning system might require manual activation. A child can not be expected to know the signs of a fire and react accordingly. However, it is likely that a child would contact a member of staff if it notices something odd, since that is what they typically do when something is wrong. As children grow older they gain more knowledge on fire safety and are capable of more rational thinking.

On at least two occasions an acoustic fire alarm was activated in the daycare centers and no reaction could be seen amongst the children, they just continued their activities until a member of staff started calling out. On another occasion a strobe light was activated (the audio alarm did not function) and only a few children noticed it. These are indicators that young children are very dependent on adults to initiate a warning to all occupants.

This research showed that where there were no fire alarms or detectors, the warning process delayed the evacuation. It took up to 225 seconds to warn everyone in a two-story daycare center (where a staff member walked from one room to another delivering the message). In one case, a staff member forgot to warn the others and just evacuated the children in his care, causing a delay of several minutes for the remaining occupants, where the warning time reached 322 seconds.

4.1.2 Reaction and decision making

Likewise the task of interpreting the fire cues or warning signals and initiating the evacuation (as well as fighting a fire if possible) is the staff's responsibility. A member of staff should also phone the fire department. The younger children are likely to need more support here than the older ones since some have never heard the alarm before and do not know the meaning of it.

It was observed that the children were easily distracted from the task of gathering or leaving the room. Seeing an exciting toy could trigger a child to go towards the toy instead of following instructions. This meant that adults needed to physically guide many of the children towards the exits by carrying, handholding or other physical touching. A difference could be seen between the two age groups in the daycare centers regarding this.

Results on the assistance received in this initial phase, when the evacuation is starting, are shown in table 4.1. The table shows a clear difference between the two age groups, that is the younger children needed more physical assistance while the majority of older children were capable of evacuating following verbal instructions only (no physical assistance).

In the schools it was observed that children aged 6-8 years waited for their teachers for instructions while children from the age of 9 could be seen reacting to the fire alarm before the teacher. It is however still the teacher's responsibility to instruct the children to evacuate and make sure everyone does so.

4.1.3 Travel to safety

Last but not least it is the adults' task to assist the children throughout the evacuation and gather them at a safe meeting place. A member of staff should also meet with the fire department and inform them of the situation.

Table 4.1 shows the frequency of carrying, physical assistance (adult handholding) and walking without physical assistance on stairs. When registering the level of assistance on the stairs it was only the stair itself that counted, that is only if there occurred handholding while descending did it count as physical assistance.

Table 4.1: The level of assistance for children in daycare centers in the initial phase of the evacuation and when descending stairs.

	initial phase		descending stairs	
level of assistance	0-2 years	3-6 years	0-2 years	3-6 years
carried	22.2 %	1.8 %	33.3 %	0.9 %
some physical assistance	57.6 %	12.3 %	42.3 %	13.9 %
no physical assistance	20.2 %	85.9 %	24.3 %	85.2 %

The frequency and level of assistance between the initial phase and when descending stairs can be compared in table 4.1. There is minimal difference in the age group 3-6 years between initial phase and descending stairs. Looking at the age group 0-2 the results are also similar, the most obvious difference is that more children needed carrying when traveling on stairs. This corresponds to the results of the NFPA study [64] on self-preservation where it was found that children are older when they can descend stairs unassisted than walking on horizontal plane.

4.2 Pre-evacuation activities

Least is known about the pre-evacuation phase even though it can be the most time consuming. It is hard to measure and predict, as it is very dependent on the precise circumstances and human behavior. Increased effort has been put into research on human behavior in fire in an attempt to better understand this phase, introducing behavioral models which describe common activities prior to evacuating [14].

The most common activities performed by staff inside the group rooms before leaving with the children for evacuation were taking the name lists, gathering children in a group, explaining the situation to the children, fetching clothes/shoes for children, turning off lights and closing windows. Furthermore some staff members performed personal tasks such as grabbing own belongings, putting on a coat or finishing coffee. Where a warning system was present 44 % went to investigate the situation, confirm the alarm or consult with peers, after hearing an alarm. Table 4.2 shows an overview of the most common tasks regardless of warning method. The name list should provide information on what children belong to the group and if they have arrived or left for the day. Gathering children was only registered as a pre-evacuation activity if all the children were gathered before allowing any children to leave the room. Explaining the situation was registered if the children were told what was going on in more detail than "this is a fire drill" or "everyone out". In addition to the tasks mentioned, adults instructed and assisted the children with the evacuation. The children did not perform dedicated pre-evacuation tasks inside the group rooms other that playing/running around until an adult instructed them to stop or physically intervened.
Table 4.2 does not include the task of putting on clothes, if this was done outside of the group room. It was not common practice but was done in a few cases.

Table 4.2: Pre evacuation tasks performed.

task performed by adult	frequency
take name list	50 %
gather children before leaving room	29 %
personal tasks	16 %
explaining situation to children	13 %
closing windows/turning off lights	11 %
fetching clothes and dressing children	5 %

The concept of putting outdoor clothes on during an evacuation is questionable. It might seem harmless during fire drills, however one of the key elements in training, especially for children, is repetition and practice [65]. It is therefore important that the evacuation process is similar during drills and in the event of fire. It is not desirable having to argue about an exception to a rule in a real emergency. In addition, the layout of daycares varies where clothes and shoes are not always located in the evacuation path. It can however not be ignored that weather conditions can be extreme, depending on the season and country. The alternative to give the children blankets instead of dressing them is suggested in [58] and some of the participating daycare centers had blankets ready, accessible from the outside, to grab if needed.

The drills were performed in autumn in schools and in spring time in daycares. The winter months were avoided to minimize problems regarding clothing during the fire drills. As mentioned a few daycare centers spent time dressing the children before evacuating but the majority proceeded with evacuation without doing so. At a few places the clothing situation was solved by having the children wear their shoes inside on the day of the drill or being extra careful with making the children wear their indoor shoes.

In the schools children were in most cases wearing shoes, so that was not an issue.

4.3 Pre-evacuation times

The pre-evacuation time is, in this thesis, defined as the time that passes from when the alarm is raised until leaving the current room. This is easier to measure than the time until a person starts moving towards an exit since a lot of movement occurred inside the room before actually leaving it. The same method was used by Kholshevnikov et al. [58], that is the moment a child leaves a group cell is used to define when the pre-evacuation activities end. As mentioned in the previous section, this method does not include pre-evacuation activities such as dressing that might take place outside the group room. Another example of a task that is not included is gathering children a second time, in cases where the children left the room but then start playing or running around again.

The pre-evacuation time in daycares (from the start of the fire drill until the last child had left out of group room) varied greatly, ranging from 42 seconds to 481 seconds for children aged 0-2 and from 10 seconds to 545 seconds for children aged 3-6 years.

On at least three occasions, the observed pre-evacuation times were longer due to unforeseen and/or unusual circumstances. The first occasion occurred when a staff member failed to warn others of the situation and evacuated with only the nearby children, resulting in a delayed warning and consequent delayed start of the evacuation. The second occasion occurred when staff did not react to a strobe light with no simultaneous audio warning (due to a malfunction) resulting from late recognition and uncertainty that it was a fire warning signal. The third occasion occurred when difficulties reading and interpreting the message on the fire alarm control panel (in order to choose the safest evacuation route given the fire location) delayed the evacuation by about five minutes. These three examples illustrate the variety of scenarios that an evacuation design must cover, even if they are rare.

The average verbal warning time was 102 seconds for groups where there was not a fire alarm system. The rooms near the "fire origin" have a warning time of only few seconds, while remote rooms have a longer warning time. If the results where a staff member forgot to warn and returned later to do so are excluded, then the average verbal warning time is 79 seconds.

The average time for gathering the children by the door or in a circle before evacuating was 71 seconds with a standard deviation of 34 seconds. It was noted that, compared to older children, the younger children moved more slowly but received more assistance and were usually in smaller groups, which resulted in no material difference between the two age groups. Furthermore, the average time between the first and last child leaving a particular room of origin was 20 seconds, with no difference between age groups, most likely due to the reasons already mentioned.

The average pre-evacuation time, including warning time and results from daycares with delays described above, is 222 seconds for the younger age group and 114 seconds for the older age group. The average time from warning until having lest the room is 168 seconds for the younger age group and 54 seconds for the older age group. If the time from verbal confirmation is used in the cases with the alarm where they waited for instruction and where the flashing light was ignored/not seen, then the averages are 56 seconds and 36 seconds for the younger and older children respectively. Since no difference was found between the age groups in gathering time (where that was done) or time it took to empty the rooms, the difference between the age groups in the time from warning/warning confirmation until having left the room, must be due to the other pre-evacuation activities including decision making. Note that, at some locations where there was a delayed evacuation due to need of further warning, the staff had already gathered the children and waited with them ready to evacuate; Time used for gathering the children being excluded from the averages for pre-evacuation activities if the task was performed before receiving the second warning.

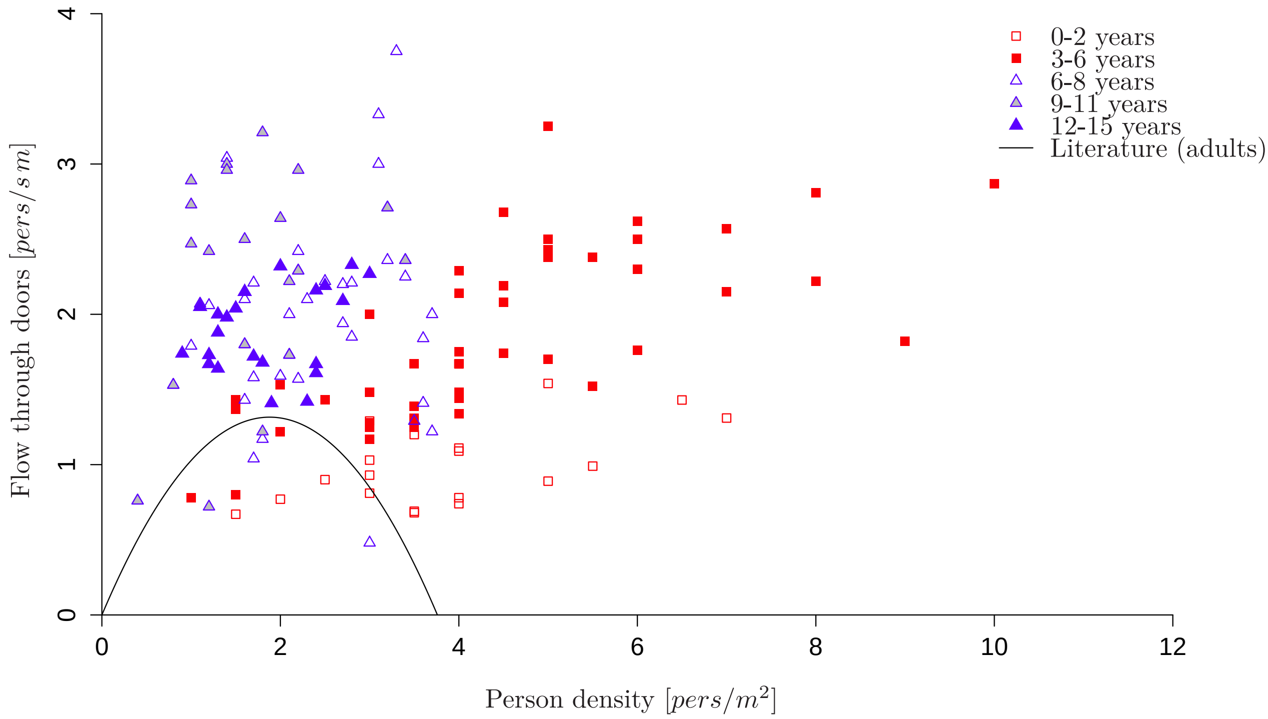


Figure 4.2: Data points showing flow through doors in daycares and schools with respect to density. Reference curve on adult's flow from Nelson and Mowrer [16]

4.4 Flow through doors

Doors and stairs are typical congestion points during evacuations. According to handbooks [16] the theoretical flow curve (flow with respect to density) is a second degree polynomial with intersection at 0.0, a maximum flow at a density just below 2 $pers/m^2$ and the flow becoming zero before the density reaches 4 $pers/m^2$ due to congestion.

Data on flow through doors was collected from both daycare centers and schools, including 1840 counts through doors in schools and 1000 counts through doors in daycares. The majority were children, although up to one in every four were adults amongst the youngest age group. The combined results can be seen in figure 4.2 where the results are categorized into the following age groups: 0-2 years, 3-6 years, 6-8 years, 9-11 years and 12-15 years. Results on flow for children in daycare aged 0-6 years have been published in Paper I and Paper II.

It can be seen that in the schools the highest measured person densities were around 4 $pers/m^2$ whereas in the daycare centers it reached 10 $pers/m^2$.

Paper II displayed the function for flow through doors with constants appropriate for children of 0-2 and 3-6 years. Equation 4.1 for specific flow, F_s, is here displayed with constants for the five age groups identified in figure 4.2.

$$F_s = (1 - aD)\,kD \tag{4.1}$$

where:
D = density in $pers/m^2$

$a_{0-2} = 0.079$	$a_{3-6} = 0.062$	$a_{6-8} = 0.191$	$a_{9-11} = 0.203$	$a_{12-15} = 0.225$
$k_{0-2} = 0.399$	$k_{3-6} = 0.622$	$k_{6-8} = 1.645$	$k_{9-11} = 2.153$	$k_{12-15} = 1.887$

The trend is that the flow increases with age but begins to decrease and tends towards the adults' flow curve from literature at the age of 12-15 years. Figure 4.2 also shows that, for the age group 12-15 years, there are no data points below the curve, while, for the other age groups, up to 20 % of the measurements landed below. It can therefore be concluded that, from the age of 12 years, adult values can be used.

Figure 4.3 shows a box plot for all 12 age categories. The mean values for flow through doors are shown with a thick line, the upper and lower lines of the box present the 25$^{\text{th}}$ and 75$^{\text{th}}$ percentile, the end of the lines present 1.5IQR (inter quartile range) and the points are outliers. These results do not take the density into account. The flow rate can be seen increasing with age and reaching a maximum at the age of 9 years and then decreasing again. It can also be seen that a certain stability is reached at the age of 12 years. It is furthermore noticeable that the flow rates for 6 year old children were lower than for the 7 and 8 year old children, although 6-8 year old children are presented in figure 4.2 as one age group. This difference can partly be explained by those students being new to the buildings and the situation compared to the older students, having attended the school for less than 2 months. Figure 4.3 also gives an idea of the spread of the flow rates within each age category, although the large spread for the age group 3-6 years can be explained by the large density range.

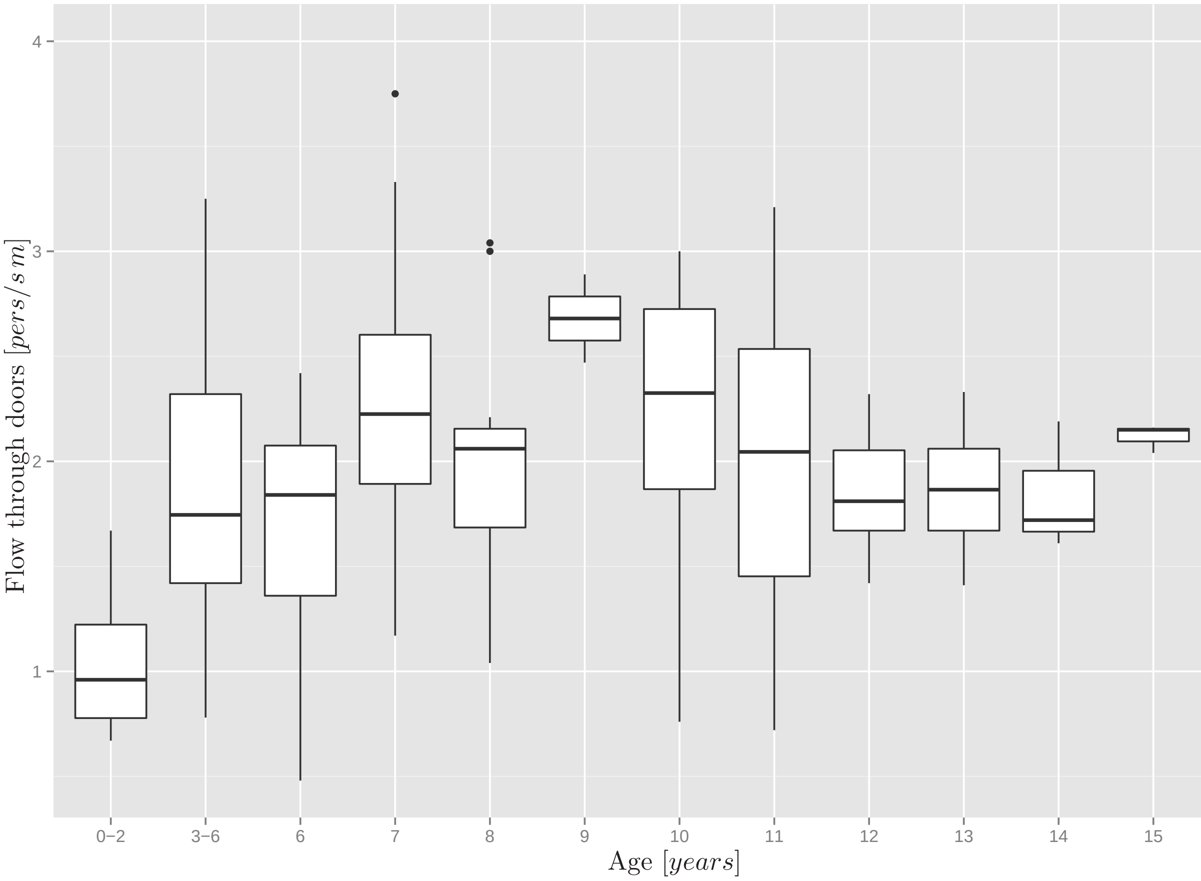


Figure 4.3: Boxplots showing flow through doors for the twelve age variables.

In addition to the datapoints shown in figure 4.2, there were a few flow measurements with mixed age groups, 5 in daycares and 16 additional measurements in schools. The data in table 4.3 includes those measurements for the school, where the combined age group 6-15 is displayed. For comparison, the results from Kholshevnikov et al. and Capote et al. are shown in table 4.3. More detailed tables for the present research can be seen in Appendix B, where in addition to the number of measurements and mean flow, the standard deviation, 95 % confidence intervals, minimum, maximum and median values are also included.

Table 4.3: Mean flow rate values through doors represented for different density intervals, for daycares and schools. Results from Kholschevnikov et al. [58] and Capote et al. [60] are included for comparison

	Current study						Kholshchevnikov		Capote	
density	0-2 years		3-6 years		6-15 years		4-7 years		3-16 years	
interval	n	flow	n	flow	n	flow	n	flow	n	flow
$[pers/m^2]$	[#]	$[pers/sm]$	[#]	$[pers/sm]$	[#]	$[pers/sm]$	[#]	$[pers/sm]$	[#]	$[pers/sm]$
$[0,1)$	-	-	-	-	5	1.27	-	-		
$[1,2)$	1	0.67	4	1.10	42	1.99	32	1.98		
$[2,3)$	2	0.84	3	1.39	27	2.23	42	2.50		
$[3,4)$	7	0.95	9	1.42	21	2.13	11	2.71		
$[4,5)$	5	1.08	11	1.89	1	1.61	51	3.03	-	0.67 - 2.59
$[5,10)$	5	1.23	16	2.31	-	-	289	3.39		
$[10,15)$	-	-	1	2.87	-	-	183	3.36		
$[15,20)$	-	-	-	-	-	-	6	1.65		

Firstly a trend difference can be seen between the measurements in the daycare centers and schools. The person density only reaches 4 $pers/m^2$ on one occasion in the schools, while in the daycare centers at least half of the measurements are made at person density 4 or higher with the highest measured density of 10 $pers/m^2$. It can be seen that the flow rate increases with increased density and a decline cannot be seen in this table for the daycare centers. However, for the school children, a maximum flow rate is reached at the density interval [2,3) $pers/m^2$ and the flow rate decreases at higher densities.

A part of the difference in flow rates between children and adults can be explained by the fact that children are physically smaller and that they need a less private atmosphere and experience crowd movement on regular basis.

Looking at the numbers from Kholshevnikov's study, the flow rate increases up to the density of 10 $pers/m^2$. The numbers for density intervals [5,10) and [10,15) represent weighted averages, as the study had smaller density intervals. Furthermore, it can be seen that a large amount of measurements are made at densities 10 $pers/m^2$ and above, opposed to the measurements of the current research, where the highest density measured was at 10 $pers/m^2$.

Capote did not specify the number of measurements or at what densities. The numbers displayed in table 4.3 are the lowest and highest average flow rates of six occasions, measured at three different exits during two fire drills.

Effective width, where a door width is reduced due to a boundary layer on the sides, was here considered equal to the free width of the door, meaning that there was no unused boundary layer on the sides. Capote reduces every door by 0.3 m (2x 0.15 m) according to theory on effective width [16]. This results in higher flow compared to if this was not done. Kholshevnikov does not mention if the effective width is a reduction of the free width of a door.

4.5 Travel speed in horizontal plane

Results for travel speed in horizontal plane for children 0-6 years have been published in Paper I and II and are briefly described here. Travel speed was measured in daycares on horizontal plane, where the children moved freely (low person densities, $< 0.5\ pers/m^2$). A distinction was between walking and running, results can be seen in table 4.4.

Table 4.4 shows that the younger children walked and ran slower than the older ones. These results are based on a limited number of measurements. Another finding was that around 40 % of the children aged 3-6 years ran during the evacuations compared to 5 % of the children aged 0-2 years.

Table 4.4: Travel speed on horizontal plane of free movement for children in daycare centers.

	children 0-2 years		children 3-6 years	
	mean [m/s]	SD [m/s]	mean [m/s]	SD [m/s]
walking	0.60	0.17	0.84	0.25
running	1.14	0.30	2.23	0.64

4.6 Travel speed down stairs

Travel speed and density were measured in seven stairwells in six daycares for children aged 0-6 years and in seven stairwells in four elementary schools for children aged 6-15 years. These results are included in Papers III and IV presented separately for children in daycares and schools. Travel speed measurements (without person density) were also obtained on three spiral stairs in daycare centers used by children aged 3-6 years; these results are published in Papers I and II where they are described in more detail.

The data set contains 3645 speed/density data points. There were a total of 12 age categories: 0-2 years and 3-6 years in daycare centers and one for each year for school children. There were approximately an equal number of boys and girls for each age category, except for age 12 and 14 (more boys) and age 13 (more girls).

Figure 4.4 compares the commonly used Nelson's and Mowrer's curve [16] and this research's twelve age categories, with the youngest children in the top left chart and the oldest in the bottom right chart. The travel speed is shown with respect to density. There are fewer data points for ages 7-9 years because of their classes' locations within the schools resulting in less use of stairs.

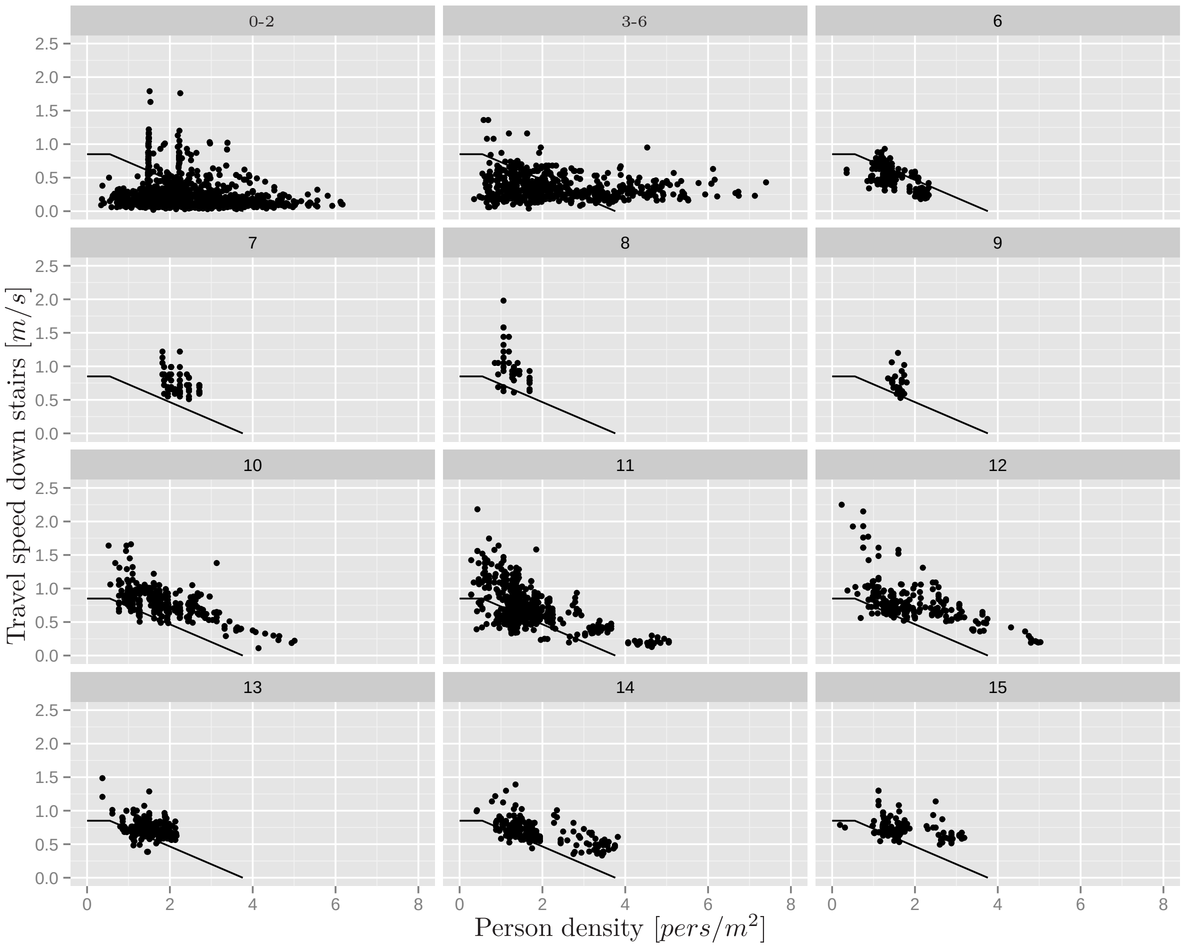


Figure 4.4: The complete data set presenting travel speed down stairs vs. density for the twelve age categories (age in years is noted above each graph).

A correlation between the travel speed and density can be seen in figure 4.4 for the school children. However, lack of data points and limited density variation for some of the age categories is restricting. Regarding the children in daycare centers, the decrease in travel speed at increased density was not as obvious as for the school children.

Figure 4.4 shows that from the age of 12 years the travel speed was rarely below the reference curve typically used for adults. It is therefore concluded that from the age of 12 years, adult values can be used to describe travel down stairs.

Due to the correlation between travel speed and density, it could be misleading to use pure averages to compare results between age groups because the measurements for all ages are not equally distributed across density. For further analysis, density intervals (in $pers/m^2$) are created as follows: [0,1), [1,2), [2,3), [3,4), [4,5) and [5,10). These are used to compare the means for each density interval between age groups.

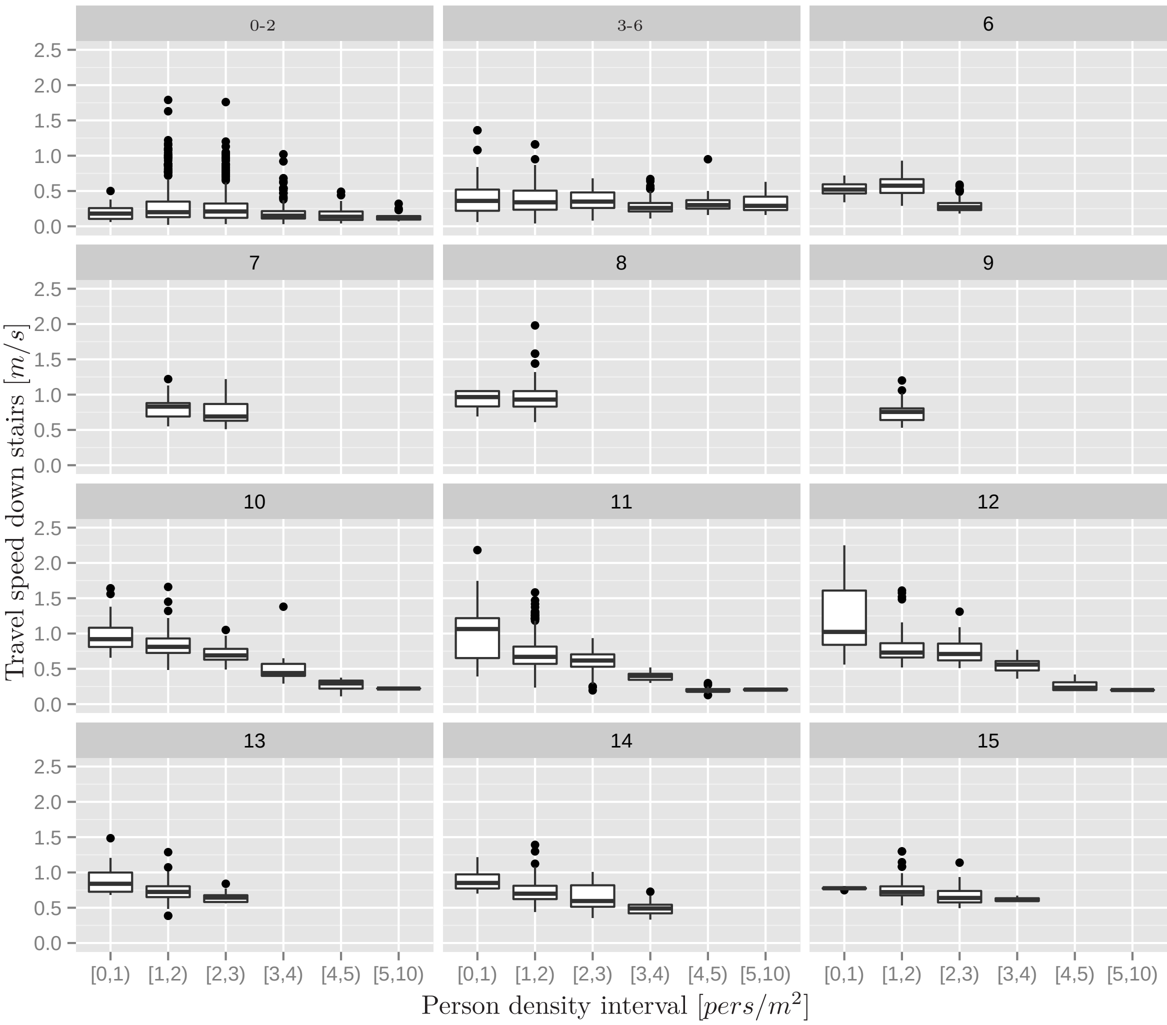


Figure 4.5: Boxplots showing travel speed down stairs with respect to density group for the twelve age variables.

Figure 4.5 shows boxplots for the twelve age categories where travel speed down stairs with respect to density interval is displayed. The boxplots show the mean of the sample with a thick line, the upper and lower edges of the box present 25th and 75th percentile, the end of the lines present 1.5IQR (inter quartile range) and the points are outliers. The boxplots show the relation between speed and density more clearly than the raw data points and at what density intervals the data points were collected. The boxplot also gives an overview of the spread of the data where the general trend is more variation in speed at low densities. A number of outliers on the upper side can be seen at the density interval [1,2) $pers/m^2$, indicating free and unrestricted movement at that density. That is confirmed by the video films, and by the fact that a density of 1 $pers/m^2$ was exceeded with 2-6 people on a flight of stairs simultaneously depending on the width and number of steps.

The results for children in daycare, shown in figures 4.4 and 4.5, include data on all children, regardless of whether a child was carried, assisted by handholding or walked by itself. Results on the effect of the assistance on travel speed are discussed in section 4.7. In the following, when comparing results between age groups and other literature, the carried children's data will be excluded or presented separately. This is because the person walking is an adult and it would be misleading to represent that as a travel speed for a child.

Table 4.5 shows speed results for the children aged 0-2 years of this research compared with Kholshnevnikov et al. for children under 3 years [58], where the number of data points and mean travel speed are shown for each density group defined. Results from Murozaki [42] are also included in the table where the minimum and maximum of five mean travel speeds are displayed, although no density data was available.

Table 4.6 shows speed results for the age group 3-6 years from daycares and for 6 year old children from schools from this research and results from Kholshnevnikov et al. [58] for children aged 3-4 years 4-5 years and 5-7 years as well as results from Capote [60] for the age group 4-6 years. Results from Capote are shown for two fire drills performed but no person densities were provided.

Table 4.7 shows speed results for age groups 6-8 years, 9-11 years and 12-15 years from this research. Note that the 6 year old children are included in two tables, first independently and then included in the age group 6-8 years. Results from Capote are displayed as before and results from Ono [61] are also included. Ono's results are the minimum and maximum mean values within the age intervals displayed during three fire drills; the results did neither include the number of measurements nor the person density.

Extended tables including the standard deviation, 95 % confidence intervals, minimum, maximum and median values in addition to the number of measurements and the mean values are displayed for the current research in Appendix C. There are tables for each of the twelve age categories.

The average travel speeds follow a similar trend to the flow through doors for the age categories 0-2 years, 3-6 years, 6-8 years, 9-11 years and 12-15 years. That is the speed increases with age but then reaches a maximum at the age 9-11 and the age group 12-15 being slower. Lower speeds were achieved in this research compared to results of other studies in literature available on children.

Table 4.5 shows that the results from Kholshevnikov and Murozaki have values that are in

Table 4.5: Mean travel speed down stairs represented for different density intervals, for daycares age groups 0-2 years. Results from Kholshchevnikov et al. [58] and Murozaki et al. [42] are included for comparison

density interval	Current study 0-2 years (not carried)		Current study 0-2 years (carried)		Kholshchevnikov up to 3 years		Murozaki 0-5 years (including adults)	
	n	speed	n	speed	n	speed	n	speed
[$pers/m^2$]	[#]	[m/s]	[#]	[m/s]	[#]	[m/s]	[#]	[m/s]
$[0,1)$	42	0.18	4	0.31	73	0.34	23-56	0.27-0.36
$[1,2)$	248	0.19	117	0.55	71	0.33		
$[2,3)$	259	0.19	141	0.40	43	0.34		
$[3,4)$	124	0.15	71	0.31	24	0.33		
$[4,5)$	41	0.11	23	0.24	-	-		
$[5,10)$	12	0.13	7	0.15	-	-		

Table 4.6: Mean travel speed down stairs represented for different density intervals, for daycares age group 3-6 years. Results from Kholschevnikov et al. [58] and Capote et al. [60] are included for comparison

density interval	Current study 3-6 years (not carried)		Current study 6 years (from school)		Kholshchevnikov 3-4 years		Kholshchevnikov 4-5 years		Kholshchevnikov 5-7 years		Capote 4-6 years (drill 1 & drill 2)	
	n	speed	n	speed	n	speed	n	speed	n	speed	n	speed
[$pers/m^2$]	[#]	[m/s]	[#]	[m/s]	[#]	[m/s]	[#]	[m/s]	[#]	[m/s]	(#)	[m/s]
$[0,1)$	65	0.41	11	0.53	26	0.50	8	0.67	45	1.16	47 & 46	0.48 & 0.61
$[1,2)$	202	0.39	150	0.58	50	0.42	26	0.56	102	0.97		
$[2,3)$	111	0.37	49	0.31	38	0.38	37	0.50	122	0.88		
$[3,4)$	85	0.28	-	-	27	0.34	36	0.45	46	0.78		
$[4,5)$	52	0.33	-	-	4	0.32	12	0.42	26	0.72		
$[5,10)$	27	0.34	-	-	-	-	-	-	4	0.68		

Table 4.7: Mean travel speed down stairs represented for different density intervals, for school children age groups 6-8, 9-11 and 12-15 years. Results from Capote et al. [60] and Ono et al. [61] are included for comparison.

density interval	Current study 6-8 years		Current study 9-11 years		Current study 12-15 years		Capote 8-12 years (drill 1 & drill 2)		Capote 12-16 years (drill 1 & drill 2)		Ono 6-8 y (lowest - highest mean)	Ono 9-11 y	Ono 12-15 y
	n	speed	n	speed	n	speed	n	speed	n	speed	speed	speed	speed
[$pers/m^2$]	[#]	[m/s]	[#]	[m/s]	[#]	[m/s]	[#]	[m/s]	[#]	[m/s]	[m/s]	[m/s]	[m/s]
$[0,1)$	15	0.63	112	1.00	70	1.01	48 & 102	0.87 & 1.06	104 & 63	1.00 & 0.95	0.68 - 1.03	0.68 - 1.49	0.96 - 1.53
$[1,2)$	208	0.68	628	0.76	531	0.75							
$[2,3)$	95	0.52	116	0.66	96	0.70							
$[3,4)$	-	-	42	0.42	58	0.53							
$[4,5)$	-	-	26	0.22	8	0.27							
$[5,10)$	-	-	3	0.21	1	0.20							

between the two groups shown for this research or higher. It is specified by Murozaki that adults are included in the measurements, which could contribute to raising the average travel speeds as well as the children's age range being 0-5 years.

Table 4.6 shows some similarities between the different studies, where speeds of the age group 3-6 years in daycares are closest to those found for children 3-4 years old by Kholshevnikov. Speeds found in this research for 6 year old children in schools are close to Kholshevnikov's results on children 4-5 year old and Capote's results for children aged 4-6 years, although Capote's results do not include specific densities making comparison difficult. As mentioned in chapter 2 Kholshevnikov's measurements are not made during fire drills but during normal use of the buildings and during special experiments with groups of children. This difference in method must be kept in mind when comparing the results, however the effect is not known.

In table 4.7 it is difficult to directly compare the results of the current research to those of Capote and Ono, since neither includes density values. However the common trend of all three studies is that the youngest age group in the schools were slower than the two other age groups and there was not much difference between the other two.

4.6.1 Spiral stairs

When using the three spiral stairs, children evacuated in a single row, with very few exceptions. As mentioned these three stairs were all used by children aged 3-6. The travel speed results spanned a wide range and were affected by both the design of the stairs and the children's knowledge of the stair and evacuation route in whole. Mean travel speed, min, max and standard deviations for the three stairs are shown in table 4.8. The table shows that the greatest difference was between stair 1 and 3. The difference in design between stair 1, where the children achieved the highest mean speed, and stair 3, where the travel speed was lowest, was the material of the stair and position of a handrail. The more troubling one for the children was an external metal grid fire escape, where the steps were see-through. The handrail was high and with vertical bars. The stair where the children traveled the fastest was an internal wooden spiral stair with two handrails, one at a normal height and one lower, suitable for the children. The design was such that one could slide a hand continuously along the handrail all the way down.

Table 4.8: Travel speed measured on three spiral stairs used by children aged 3-6 years.

	children 3-6 years			
	mean [m/s]	min [m/s]	max [m/s]	SD [m/s]
stair 1	0.58	0.25	1.40	0.31
stair 2	0.38	0.29	0.48	0.07
stair 3	0.13	0.08	0.33	0.06

There was also a difference in knowledge of the evacuation path and training. The children did not know about the metallic fire escape and had never used it before. It was observed that the children were insecure walking on the stair and needed to concentrate a lot, moving their hand from one vertical bar to the other for support. They frequently looked down through the metallic grid but also stopped and looked around, perhaps enjoying the view, as they had never been there before. The internal staircase was their primary stair between floors and was used every day when going out to the playground. The children were therefore comfortable using the stair in large groups.

The difference in standard deviation can also be seen in table 4.8, where stair 1 has the highest standard deviation. It was noted that the highest travel speeds were accomplished by the first children that used the stair. The speed decreased as more children entered the stair, most likely due to congestion, but also because the more hesitant children could be seen waiting until last.

4.7 Assistance in stairs

As mentioned in the first section of this chapter, adults are highly involved in an emergency evacuation from the beginning to the end. The frequency and level of assistance provided to the children have already been presented separately for children 0-2 years old and children 3-6 years old. Figure 4.6 shows the mean travel speed on stairs for each level of assistance for both age groups.

Figure 4.6 indicates that for children aged 0-2 years, the level of assistance greatly affects travel speed on stairs. This on the other hand does not seem to be the case for children aged 3-6 years. The null hypothesis used in an analysis of variance are that the means are the same regardless of level of assistance. With an alpha value of 0.05 the null hypothesis was rejected for the younger children, aged 0-2 years but failed to reject for the older children, 3-6 years. The statistical tests confirm what figure 4.6 shows. The Tukey test was used to determine where (between which levels of assistance) there was a difference in travel speed for the children 0-2 years. Using $\alpha = 0.05$ it was confirmed with 95 % level of confidence that there was a difference between all levels of assistance. However, the greatest difference in travel speed was between children who were carried and children that walked themselves followed by the difference between children who were carried and children who were assisted. There was only marginal difference between children who were

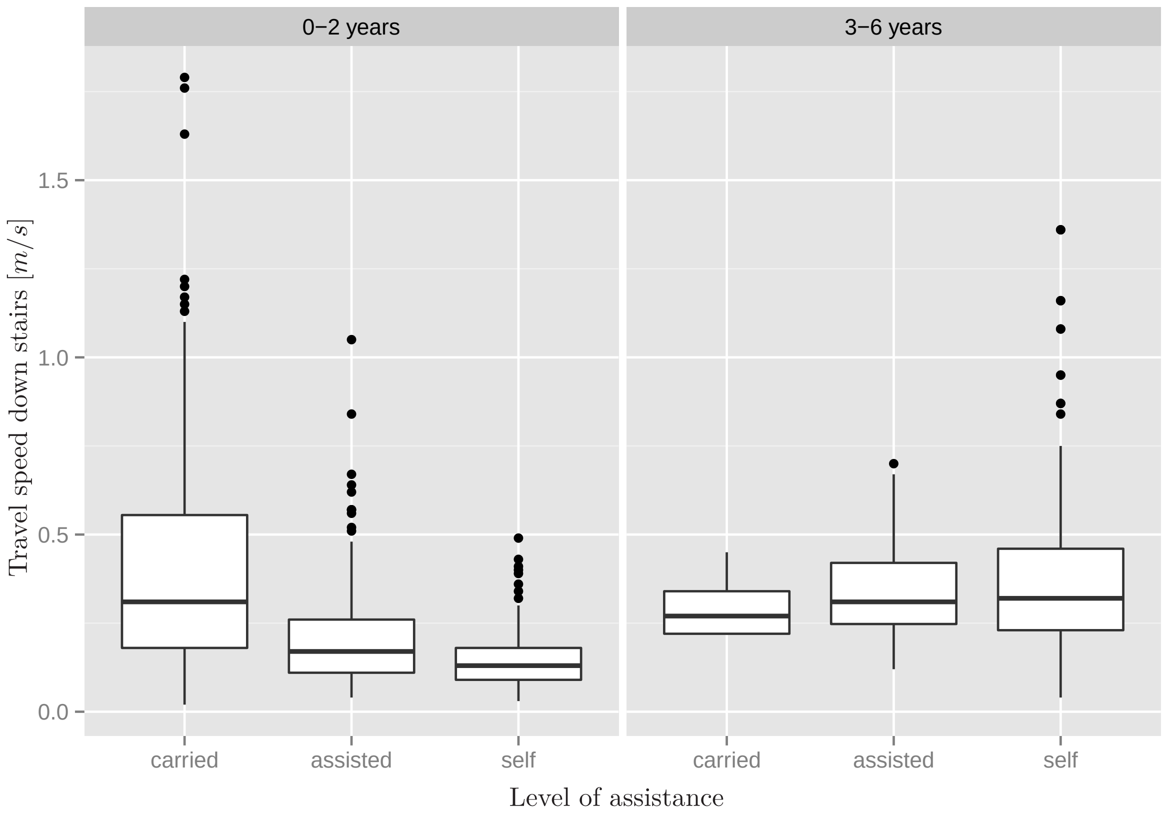


Figure 4.6: Boxplots showing travel speed down stairs with respect to age group and level of assistance.

assisted and those who walked themselves, where the children being assisted achieved a higher travel speed on average as seen in figure 4.6.

The boxplots in figure 4.7 show how person density affects the travel speed in daycares, divided into the three levels of assistance and the two age categories. It is interesting to see that the traditional relationship between speed and density is most obvious where the children are carried. This indicates that young children are not as affected by the person density as adults are.

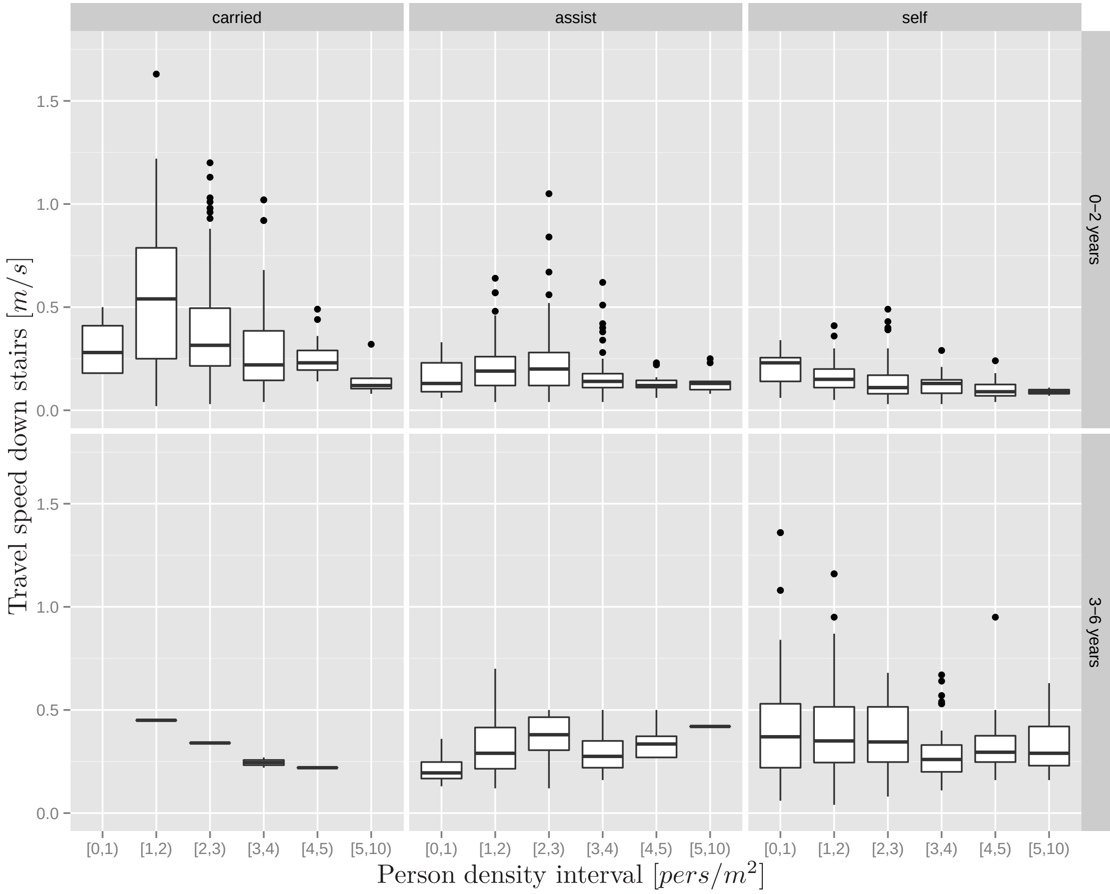


Figure 4.7: Boxplots showing travel speed down stairs with respect to age group and level of assistance for each density interval.

4.8 Handrail use in stairs

Handrail use during evacuation of daycare centers was observed. The findings are included in Paper IV where some more detailed descriptions are provided. In two stairs, used by children aged 0-2 years, there was a low handrail on one side and a high handrail on the other.In one stair, also used by children aged 0-2 years, there was a low and a high handrail on the same side of the stair and no handrail on the other.

The low handrails were 34-61 cm high. Table 4.9 shows the frequency of handrail use for children in daycares. It shows that over 90 % of children 0-2 years old, who did not receive assistance from adults, used a handrail for support whereas less than 60 % of children aged 3-6 years did the same. This complies with the children's physical development, as the older children had better physical control and stability and did not need as much support to walk on stairs. Another reason could be that there were no handrails available at optimal height for children in the older age group.

For both age groups the handrail use frequency decreased when they received assistance from adults. This is not surprising as handholding provided enough support for some of the children. Furthermore the adult often controlled the path taken on the stairs and it did not always allow for the child to hold on to the handrail.

Apart from noting for each child if a handrail was used or not when descending the stairs it was noted if the handrail was low or high or the only handrail available (high). Figure 4.8 shows a boxplot to compare the speeds of the children holding a handrail, depending on the height of it. It is interesting to see that on average the children using a low handrail for support achieved a higher travel speed than the others. An analysis of variance confirmed that there was a statistical difference. On average the children in the age group 0-2 years using a low handrail walked 23.5 % faster than the ones using other handrails.

Table 4.9: Frequency of handrail use for children during daycare fire drills.

		handrail	no handrail	other	total
0-2 years	self	92.7 %	6.5 %	0.8 %[1]	100 %
	assisted	75.0 %	21.8 %	3.2 %[2]	100 %
3-6 years	self	58.6 %	41.4 %	-	100 %
	assisted	44.7 %	53.3 %	-	100 %

[1] children that crawled backwards down
[2] children that held adults in both hands

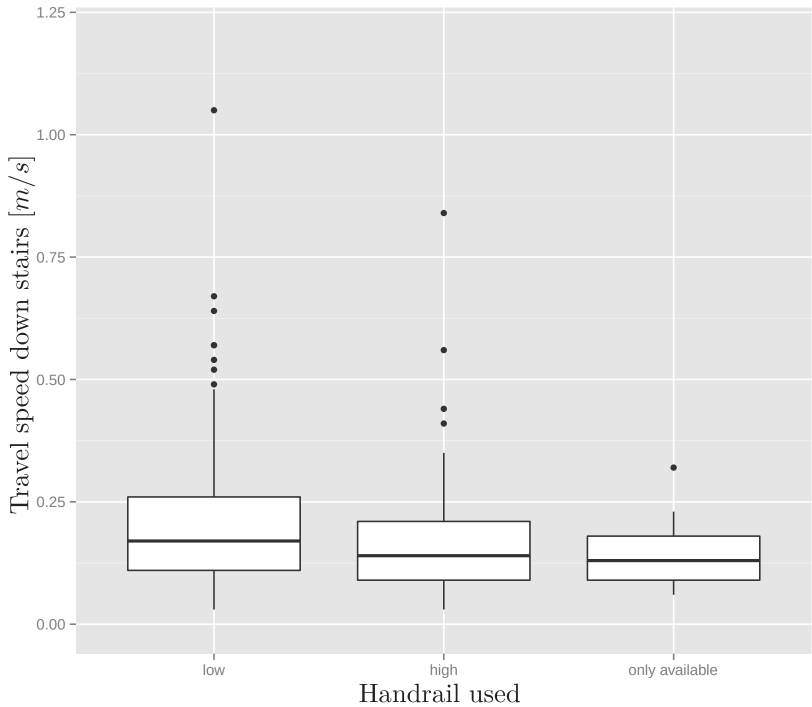


Figure 4.8: Boxplots showing travel speed down stairs with respect to the handrail used.

4.9 Handholding in stairs

During daycare evacuations handholding only existed between adults and children with the exception of four children (two pairs) that held each other's hands. However this was common practice for the lower classes in the school evacuations. Results on handholding amongst school children are included in Paper III, where they are described in more detail. Table 4.10 shows how the handholding decreases by increasing age of the school children. It also shows how the children continue walking side by side even though they do not hold hands. After the age of 9 years handholding was rarely seen.

It was observed from the films that the handholding and walking in pairs continued until outside and the whole class walked together and did not mix together with other children. For the older classes, where this pairing was not evident, there was more blending between the classes and more overtaking on the stairs.

Table 4.10: Frequency of handholding (between students) during elementary school fire drills.

	class 0 6 years	class 1 7 years	class 2 8 years	class 3 9 years	class 4-9 10-15 years
students holding hands	100 %	82 %	48 %	29 %	<5 %
students walking in pairs	0 %	18 %	44 %	29 %	
students walking alone	0 %	0 %	8 %	42 %	

The handholding originates from teacher's instructions where the youngest school children follow the instructions literally but as the children get older they seem to obey the instructions on an organized evacuation but do not necessarily physically hold hands. This growing independency was also seen in the initial phase where children started to react before the teacher.

4.10 Gender difference

Since each individual was identified by gender, the travel speed down stairs and the level assistance was analyzed for gender difference or trends. For travel speed this was done for each age /age category. For the level of assistance it was only done for age categories 0-2 years and 3-6 years. In a few cases the gender could not be identified with high accuracy and the individual's gender categorized as undefined. This only happened amongst the youngest children.

Table 4.11 shows that a similar proportion of boys and girls received each level of assistance when descending the stairs.

Figure 4.9 shows a boxplot comparing males and females separately for the level of assistance for the daycare age groups. Comparing the mean travel speeds between boys and girls a difference cannot be seen except when the children are carried. An analysis of variance is used to test the null hypothesis that the means are the same for females and males, when the children walk self or receive assistance. The hypothesis is not rejected (failed to reject) indicating no gender difference. The difference when the children are carried is not interesting as that speed depends on the adult who carries the child.

Table 4.11: Assistance received with respect to gender.

age group	level of assistance	female	male
0-2 years	carried	34.3 %	32.3 %
	assisted	43.3 %	42.5 %
	self	22.4 %	25.2 %
3-6 years	carried	1.9 %	0 %
	assisted	11.6 %	15.9 %
	self	86.4 %	84.1 %

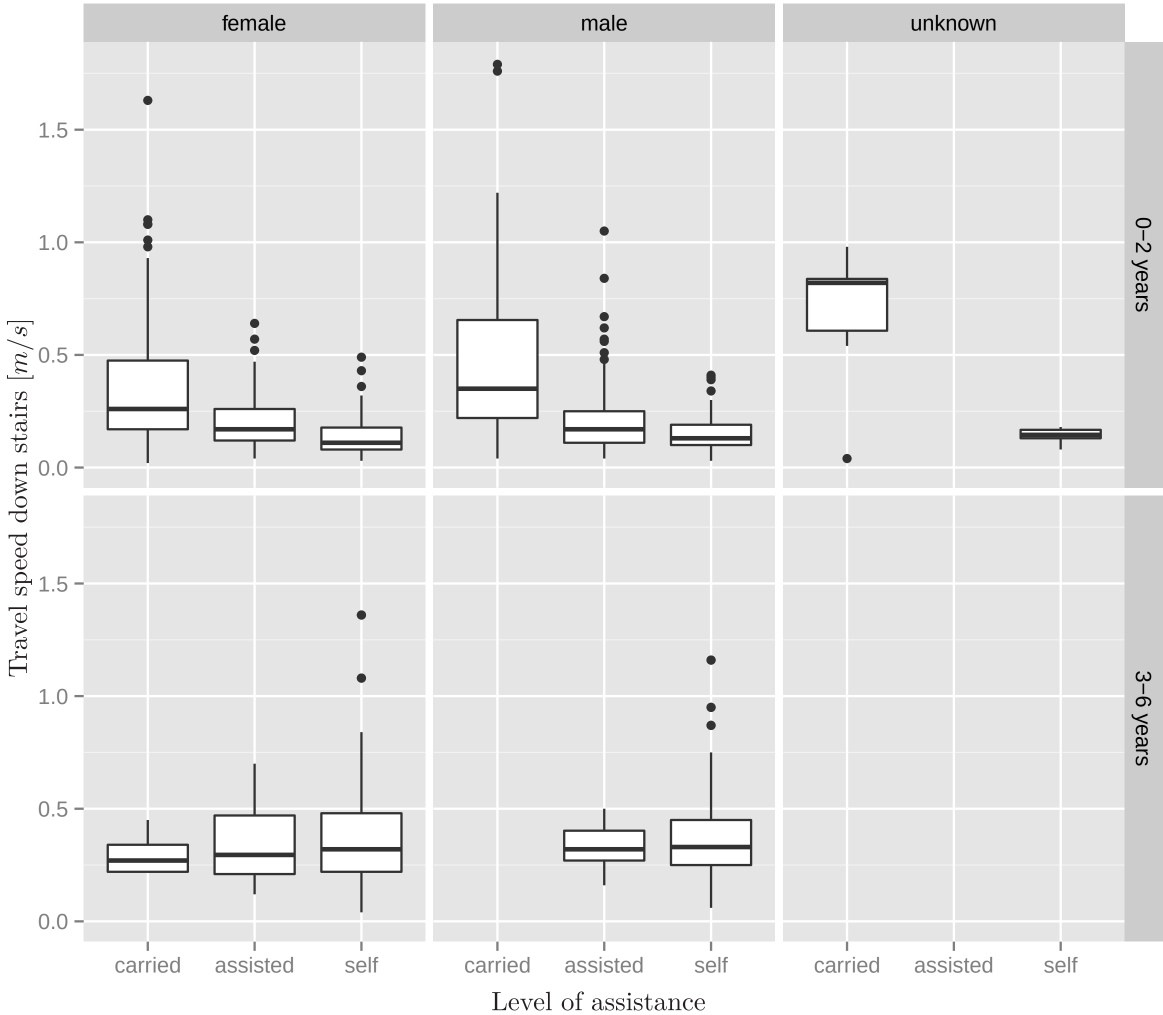


Figure 4.9: Boxplots showing travel speed down stairs with respect gender and level of assistance.

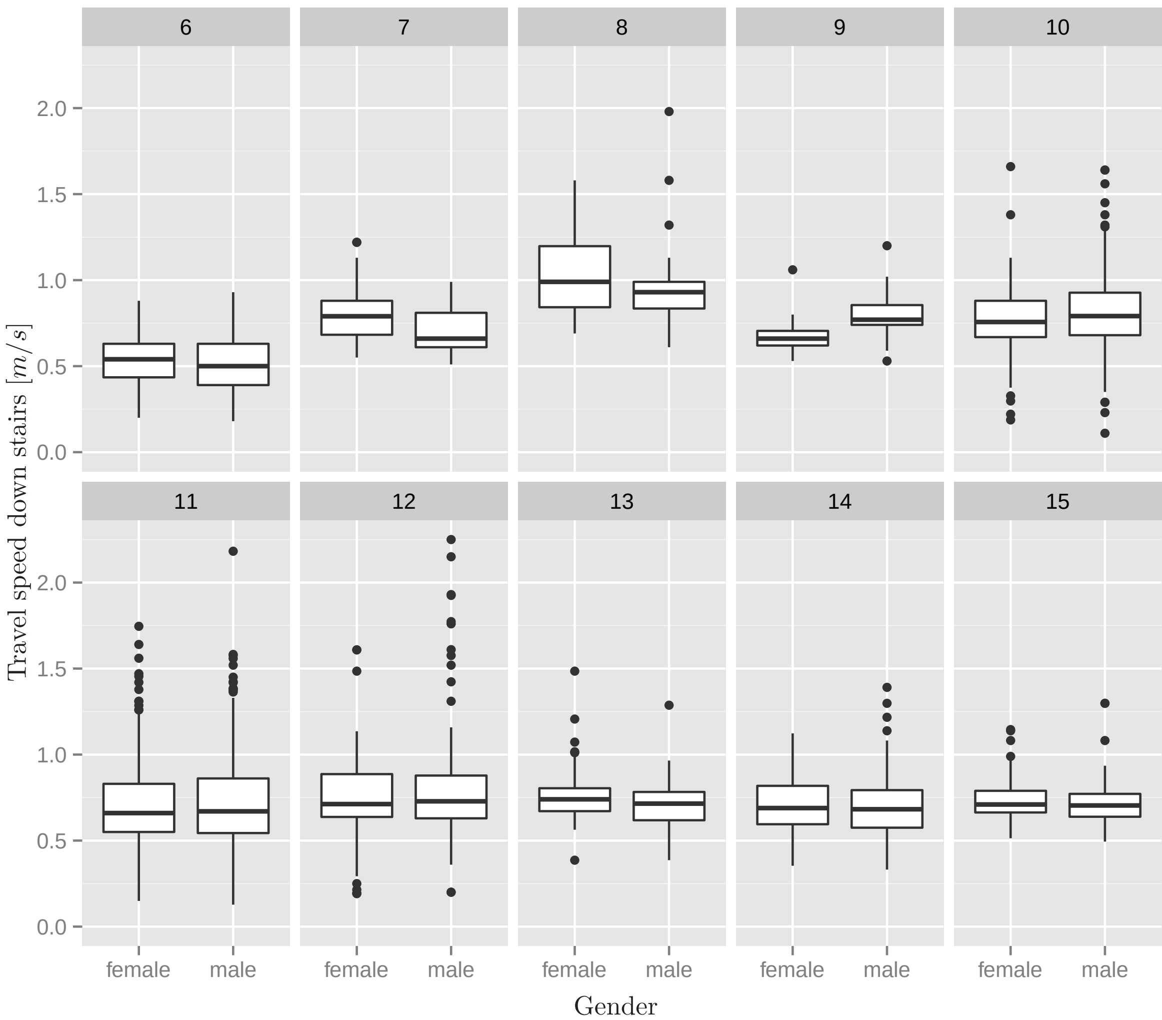


Figure 4.10: Boxplots showing travel speed down stairs with respect gender and level of assistance.

Figure 4.10 shows a boxplot for each age category for the school children. A quick look indicates no general gender difference and that is confirmed by an analysis of variance with the exceptions of 7 year old children where the girls were on average 0.11 m/s faster and 13 year old where the difference was marginal, but showing the girls being faster.

4.11 Behavioral aspects

A number of interesting behaviors were noticed during the fire drills. Some of whom relate directly to what can be expected from adults, while other might be more identifying of children.

4.11.1 Affiliation

Like adults, children are most comfortable with familiar people and routes. When told to go outside some children ran towards the main exit, although the plan was to use the direct emergency exit to outdoor. This is natural as that is the most used door and the door they entered through. Children could also be seen following the adults and children form their own group, throughout the evacuation where possible, indicating a preference.

4.11.2 Family bonds

Two examples of impact of family bonds could be seen during the fire drills. One example was when parents were arriving with their children when the fire drill started, they could be seen evacuating independently of the other daycare occupants, assisting their own child.

Another example was when children in the older age group asked the staff about their younger siblings who were located in another part of the facility. Even though they did not act on the family bond, they did express their concern.

4.11.3 Gathering belongings

A few children took belongings with them out and at least one child was seen getting upset over not being allowed to go get a favorite item.

Adults could be seen taking some personal belongings before leaving the rooms or grabbing them on the way out.

4.11.4 Helping others

On one occasion, children from the older age group in a daycare center were located in a room next to the younger children's department when the alarm was raised. That meant that they evacuated along with the younger children. The older children were keen to assist and ended up holding hands with younger children to support them.

During a school evacuation a student on crutches received help from a fellow student.

4.11.5 Investment

In some cases children were reluctant to stop their activities which can be related to investment theory, where people do not want to evacuate due to their financial or time investment in something. Examples of this could be that a child would lose a good spot or a toy by leaving.

In the cases where adults finished their coffee, they were saving their investment, since it would get cold during the evacuation.

4.11.6 Redirecting

In the school evacuations it could occasionally be seen that children or groups of children redirected to an other exit or stair due to congestion.

4.11.7 Rules and routines

It could be seen through several examples that children in daycares are used to a structured environment, where certain rules and routines are followed during the day. Children could be seen starting to change from indoor shoes to outdoor shoes, as that is what normally is done when going outside. Children could also be seen stopping by the outside door to zip up a jacket and to put on a hat for the same reason and stopping by the door or by a stair, waiting for adults permission to proceed.

4.11.8 Social influence

Young children did not seem to mind what the people around them were doing and a few examples could be seen where children kept playing even though everyone left the room. They only evacuated when an adult came to get them.

Older children seemed more aware of their surroundings and what their peers were doing. Children could be seen making jokes about the fire drills, perhaps not wanting to seem too serious or uptight. However, social influence was most obvious amongst the adults, who showed hesitation to evacuate without confirming that other groups were doing so as well.

4.12 Design perspectives

Looking at design perspectives it is important to identify what design supported efficient evacuation and what design most likely delayed it.

4.12.1 Alarm systems

Results indicate that alarm systems with an audio signal shorten the pre-evacuation time and ensure simultaneous warning. Some problems with the audio signal strength were noticed during activities behind closed doors. It should be ensured that the alarm can be heard at all locations with doors shut.

Research has shown that identifying and noticing a fire alarm correctly is not a matter of course [72, 73]. The task has not become easier as more and more sound alarms are used to notify us of different things. It was noticed that the fire alarms were different between the daycares (one even had a different warning signal inside the facility than in the staircase) and that some of the schools did not have specific fire alarm, but used the normal school bell either ringing in intervals or having a spoken message before. The fact that alarm sounds differ makes it even more important to train evacuations so that the children can be conditioned to associate the alarm with an evacuation.

The optimal would be to have a uniform fire alarm signal in all institutions to be able to limit the number of sounds that a child should connect to an emergency evacuation. Ideally children would be able to recognize a fire alarm in other buildings after training in a daycare or school.

4.12.2 Handrail

The results indicate that children prefer to use a handrail for support when descending stairs. Handrails could therefore be recommended on both sides of stairs. The travel speeds are likely to be higher if handrails are available at children's height.

Design of the low handrails could been improved by having them longer than the stairs, that is having the handrail start before the stair and ending a bit into the landing. This is suggested because the video footage showed children struggling with reaching forward to the low handrail, as the children seemed to want to get a firm grip on it before entering the stair. This resulted in stretching and knee bending as the children tried to grab the low handrail, causing a delay in entering the stair. A similar problem was seen at the end of the handrail, where the children did not want to let go before both feet were safe on the landing, this resulted in leaning back and backward arm stretching. This is a simple adjustment that could potentially improve the movement down stairs for young children.

4.12.3 People load

In schools it was noticed that the people load in the stairs varied, due to location of the offices and teachers' study rooms within the schools. In some schools these were all grouped together, resulting in uneven use of the school's two stairs, one only being used by a few members of staff, while the other stair was used by hundreds of children causing congestion on the stairs. Some thought should be given to the people load of each emergency route, to avoid overloading.

An alternative could be to implement this into the evacuation plan, by directing some classrooms to use the less occupied stair, if safe.

4.12.4 Stairs

It was observed that straight stairs caused less problems than half turn stairs. This is most likely due to the fact that the half turn stairs do not have a uniform step dimension throughout the stair. The steps are narrower on the inner side (similar to spiral stairs) and since the handrail was positioned on the inner side it encouraged the children to choose that travel path. Travel speeds on the two half turn stairs were below the average.

It was also observed that stairs with landings caused less problems than those without.

This was reflected in more frequent carrying of young children in stairs without landing(s). Even though the results on travel speed do not directly reflect this problem with stairs without landings, it did cause more delay on the landings between floors. Children hesitated to enter the stair and adults hesitated to allow the children to enter the stair without assistance most likely due to higher risk of injury in case of falling.

The results did not indicate that the steeper the stair, the lower the travel speed. In fact the relationship was opposite to what was expected, that is higher travel speeds were measured at steeper stairs. Assuming that the theory for adults is correct, a possible explanation to why this relation is different or not as strong for children could be that children have smaller feet, so the run of the steps can be smaller without causing such discomfort that it effects the walking speed.

4.13 Procedures

Some potential flaws in the evacuation procedures were observed during the fire drills. Three examples will be described and discussed in the following subsections.

4.13.1 Locked door delayed evacuation

During one evacuation, adults instructed the children (aged 3-6 years) to evacuate and opened a door to a back stair. The children walked down but could not open the door to the outside because it was locked and they did not know how or did not have the strength to unlock it. The children piled up in front of the door until an adult came down, squeezing through the group of children and opened the door.

Furthermore, and not less worrying, was that one child could be seen continuing down the stair to the basement. That child came up again shortly afterwards and evacuated with the other children. No adult observed this and it is worrying that a child could have been left behind.

This situation could have been avoided by sending one of the adults down first to open the door and guide the children through it, instead of the adults grouping up at last.

4.13.2 Staff pre-evacuation actions delayed evacuation

In one case, already mentioned in connection with the pre-evacuation, the evacuation procedure required a few members of staff to take on the role of controlling the evacuation. The first task after putting on an identifying vest was to gather at the fire alarm control panel and find out where the fire was located. They should then inform the other occupants in the group rooms, who should be waiting ready to evacuate, of which evacuation route to take.

The remaining adults gathered the children when the alarm sounded but then waited in the rooms for confirmation and instructions. In fact, they waited up to five minutes for instructions about which route to take. The delay was due to difficulties reading and understanding the fire alarm control panel.

It can be said that the benefits of having an audio alarm, that normally should shorten the pre-evacuation time, were minimized in this case.

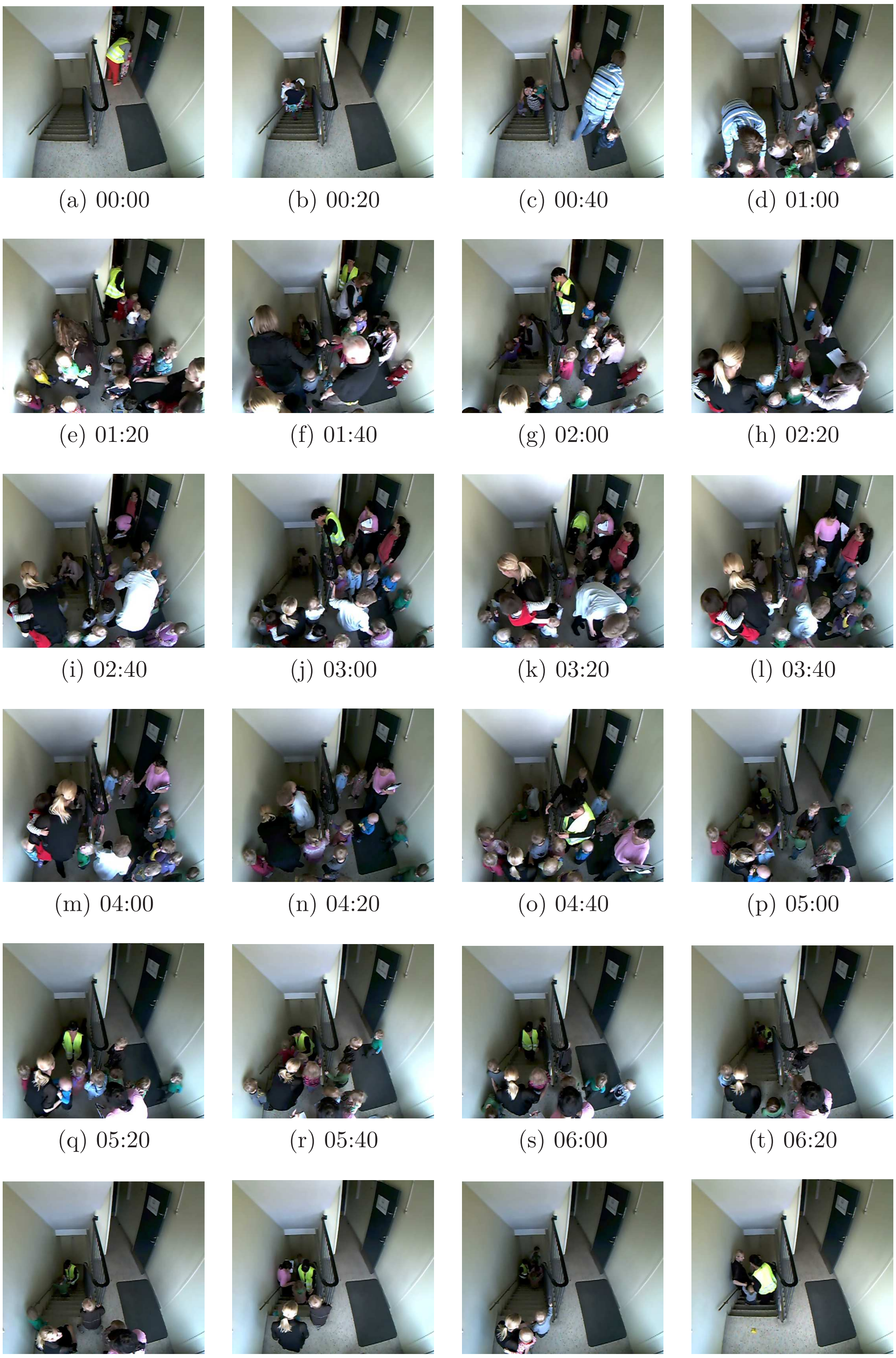
The delay could be shortened by training the staff in reading the panel and/or replacing it with one with a more user friendly interface. Another option is to rely on the staff for choosing a safe route for each group, depending on the fire cues available and recognized on the way.

4.13.3 Limited staff and multiple stairs delayed evacuation

A third example is the challenge of getting a large number of children down multiple flights of stairs. As the results showed regarding assistance, the younger children needed it the most. In one of the daycare centers around 100 children aged 0-2 years and 25 adults evacuated using the daycarecenter's two stairs. The daycare center was located on fourth floor so the evacuation plan stated that each staff member was responsible of helping children between two particular floors to avoid needing to go up and down the whole stairwell multiple times. This procedure however, resulted in adults leaving for their positions further down the stairwell with only one or two children or even no children with them. This meant that the remaining staff had even more children per person. On several occasions the flow into the stair came to a stop due to lack of staff to assist the children.

Figure 4.11 shows snapshots taken every 20 seconds on the landing where 45 children and 11 adults enter a stair on the fourth floor. It can be seen that it takes over 7 minutes to get everyone into the 0.95 m wide stair. On a number of snapshots, adults can be seen waiting with children while another adult runs up and down the stair assisting children.

This example shows how important every adult is and that evacuation plans need to be carefully considered and tested to ensure efficiency.



(a) 00:00 (b) 00:20 (c) 00:40 (d) 01:00

(e) 01:20 (f) 01:40 (g) 02:00 (h) 02:20

(i) 02:40 (j) 03:00 (k) 03:20 (l) 03:40

(m) 04:00 (n) 04:20 (o) 04:40 (p) 05:00

(q) 05:20 (r) 05:40 (s) 06:00 (t) 06:20

(u) 06:40 (v) 07:00 (w) 07:20 (x) 07:40

Figure 4.11: Snapshots taken every 20 seconds on the platform in a daycare for children 0-2 years on fourth floor.

4.14 Training

Training can both be direct and indirect. Direct training is where fire drills are used to train the procedures and evacuation of buildings and indirect training can be passing the evacuation route or a part of it in another context. An example of this could be to have a group of children use a fire escape stair or a back stair once a week when exiting the building. This would make the children aware of the location of the stair and make them comfortable using it. Surprises could therefore be minimized if it becomes necessary to use it in an emergency. Back stairs or fire escape stairs are typically not as user friendly as main stairs, even though it might be especially important for them to be easy to use.

This indirect training effect was identified during a fire drill in a daycare center, where two spiral stairs were used during a fire drill. The average travel speed for the children on an internal spiral stair, which the children used daily, was over four times higher than for the children using the external fire escape stair for the first time. Due to difference in stair design it was not possible to isolate the training effect from the design effect, but it was clearly observed that in addition to difficulties walking down the children were distracted by the new situation and view.

The effect of direct training could be measured on one occasion, where a daycare center made two similar evacuation experiments during the same month. The total evacuation time was reduced from 3:35 min to 2:38 min, or more than 25 % and behaviors that indicated lack of training and knowledge of evacuation procedure were not seen during the second fire drill.

Although more data on the effect of training is needed, there are indications that both direct and indirect training are beneficial during evacuation. Furthermore, training can be useful for detecting flaws and weaknesses in the evacuation plan and procedure which can then be improved accordingly.

Chapter 5

Conclusion

This chapter includes a summary of the results, overview of the limitations of the research, suggestions for future work and concluding remarks.

5.1 Summary of results

The volume of available literature focusing on children in relation to fire safety and evacuation has increased in recent years. In the past couple of years, publications show ongoing studies in at least three countries in addition to Denmark, namely Brazil, Spain and Russia (chapter 2).

This project provides a large amount of new data and findings on children's evacuation from daycare centers and schools, covering children aged 0-15 years. The data was gathered during fire drills in daycare centers and schools which were filmed and analyzed afterwards. The results touch on three areas, namely measurable parameters, human behavior and process, all of which are related when it comes to fire safety and evacuations and influence each other. The main results are summarized below.

It has been shown that staff in daycares and schools play a leading role in initiating an evacuation and assisting the children throughout evacuations. The role of the staff is more important for younger children (chapter 4, section 4.1).

Pre-evacuation activities and times depended on the warning method, the adult's reactions and the local evacuation procedures. Simultaneous audio warning signal had a positive effect on the pre-evacuation time in daycare centers compared to verbal warning (chapter 4, sections 4.2 and 4.3).

Children generally achieve higher flow though doors than existing handbooks state for adults. The flow rate for children increased with age, peaking in the age group 9-11 years and for the age group 12-15 years it started approaching theoretical values for adults.

Since no measurements were under the reference curve for adults after the age of 12 years, it can be considered safe to use adult values from that age. Person densities for children 3-6 years reached 10 $pers/m^2$ but for school children aged 6-15 years 4 $pers/m^2$ was the highest person density measured. Effective width was found to being equal to the free width as children used the whole width of doors and stairs and did not leave a boundary layer, as theory suggests for adults (chapter 4, section 4.4).

Free walking speed in horizontal plane was lower than for adults and lower for 0-2 year old children than for 3-6 year old children. Running occurred more frequently amongst children 3-6 years, where their travel speed exceeded adults' typical walking speed (chapter 4, section 4.5).

Travel speed on stairs increased with age. At the age of 12 years the travel speed was rarely below the reference curve for adults and it can be considered representative from that age. Travel speed on stairs was found to be dependant on person density for all age groups, although the density had less effect on the travel speed of children in daycares compared to the other age groups (chapter 4, section 4.6 .

Children aged 6 years were consistently slower on stairs and achieved lower flow rates than other students of the schools which can partly be explained by them having attended school for less than two months, not knowing the procedures and surroundings as well as the others.

While the travel speed of children 0-2 years was affected by the level of assistance received, where children that were carried traveled fastest, followed by children assisted by handholding and children descending the stairs without physical assistance were slowest. This was not the case for children aged 3-6 years, where there was not a statistical difference in the travel speed with respect to level of assistance (chapter 4, section 4.7).

Majority of children in daycares used a handrail for support when descending the stairs, the younger ones more than the older ones and the handrail use decreased if the children were assisted by handholding. It was found that children using a handrail at children's height moved on average 23.5 % faster than those using a handrail at traditional height (designed for adults) (chapter 4, section 4.8).

Handholding amongst students was seen in the lower classes in schools, where children evacuated in double lines holding hands. The frequency of handholding went from 100 % for 6 year old children down to 29 % for 9 year old children. Only occasional handholding appeared amongst older children (chapter 4, section 4.9).

No general difference could be seen in the travel speed down stairs between boys and girls. Boys and girls furthermore received similar level of assistance in the daycares (chapter 4, section 4.10).

Examples were found in the results where procedures or failures in procedures caused a delay in the evacuation at some point. These could be adjusted accordingly to avoid such delays (chapter 4, section 4.13.

Examples where found where the design of the evacuation route influenced the evacuation. By optimizing the design to fit the use and occupants of the building valuable time can be saved (chapter 4, section 4.12).

Training had a positive effect on the evacuation time and procedure and is highly recommended. This comprehends both direct training through fire drills but also indirect training where alternative exits or stairs are used to make the children aware of their existence and comfortable using them (chapter 4, section 4.14).

5.2 Limitations

When implementing or using data produced in this project, the method used during collection and analyzing needs to be kept in mind, ensuring compatibility with the situation of interest. Details have been described when relevant but some of the more important limitations will be highlighted here.

The results are collected during partly announced fire drills where unannounced fire drill would have been preferred, using more discrete cameras. The effect of the participants knowledge of the drill or partial knowledge is not known.

As the results show a lot of difference between the age groups 0-2 years and 3-6 years it would be preferable to have smaller ager groups and potentially identifying how the change develops with age as large jumps are seen between the two groups. This might be achieved by marking the children using colored vests or a more discrete marking such as a sticker. An other option would be to target daycare centers, where children are divided into groups by the year, to participate.

For some of the age groups there is a lack of data on travel down stairs, where the results only base on a single class or travel down a single flight of stairs. This might not be representative for the age group in whole.

The practical side has been a learning process where by every experiment conducted the routine became smoother, less stressing and fewer mistakes were made. One of the most important lessons learnt is the value of planning, organizing and documenting. Furthermore it was found out that too many pictures cannot be taken of the setup, stairs and buildings. As the last of the practical things mentioned here is that the camera location should not be underestimated, avoiding disturbance by changing conditions such as sunlight and doors positions which might influence the view of the camera is essential.

5.3 Future work

A lot of new data has been gathered and many questions have been answered, however many new questions have been raised simultaneously. This is not uncommon when research is involved and is perhaps the key to continuous development in many research fields, where indeed the new questions drive the field forward.

It is strange to think of not being able to "finish" what has been started. That continuing the progress on this particular subject, evacuation of children, is most likely in the hands of others. Hopefully someone is ready to take on the challenge because there is plenty of work to be done.

The video files, over 1.5 TB, still contain a lot of information that has not been extracted and documented. Also the data that has been retrieved from the videos already, still has room for analyzing. Then further experiments provide endless possibilities.

The following list is not in any way completed, it only represents some of the interesting things that could be investigated, using the already collected video material.

- The video recordings from the elementary schools include children going out for recess/break in addition to the fire drill. Analyzing the walking speeds and noting the behavior and comparing to the fire drills would be interesting. The result could conclude if data from schools could be collected on normal school days when the children go outside and used to extend the experimental data collected during fire drills.
- The video recordings from the daycares have a near full coverage of the facilities meaning that each individual's evacuation path can be tracked from beginning to end. This could be used in a number of ways. One is to map the evacuation in a way so the evacuation progress could be viewed graphically at perhaps 30 s time steps.
- Compare the empirical results to results of simulation software could be very interesting. Plan drawings with dimensions to a reasonable accuracy already exist.
- A comprehensive analysis using the person density unit m^2/m^2 as presented in [4] where different size of individuals are accounted for. This would ease comparison between adult data and data on children, when looking at parameters dependant on density.
- A more structured collection of occurring behavior to be able to map it in some extend and estimate frequency of occurrence.

Then many interesting questions need further gathering of data. Those could be:

- Further extension of the data set focusing on the largest gaps such as travel speed in horizontal plane at different densities and the travel speed on stairs for the age groups lacking data.
- The effect of training on total evacuation time as well as the evacuation process, by repeating fire drills in the same institutes. Even though this project aimed on answering this question, only fractional answers were found.
- The effect of adult/child ratio on total evacuation time as well as the evacuation process, by varying this ratio throughout multiple fire drills.
- Investigating the different acoustic fire alarm signals used in daycares and educational buildings in Denmark and investigate if people recognize the sound as fire alarms.

5.4 Concluding remarks

The original aims of the thesis were to bring focus to the topic of evacuation of children and to provide new data and knowledge on children's evacuation. This thesis applied the research method described in chapter 3 in order to achieve these aims, resulting in the novel contribution in the data in chapter 4, as also published at international conferences and in a journal. This project has also been critically assessed by identifying its limitations. Finally, this thesis lays foundation for further research by also identifying candidate future work.

Bibliography

[1] Erhverfs og Byggestyrelsen. Bygningsreglement for erhverfs- og etagebyggeri, inkl. tillæg 14., 2006. (in Danish).

[2] Mannvirkjastofnun. Byggingarreglugerð nr.112/2012, 2012. (in Icelandic).

[3] National Fire Protection Association. Nfpa 101 - life safety code, 2012.

[4] V.M. Predtechenskii and A.I. Milinskii. *Planning for Foot Traffic Flow in Buildings*. Stroiizdat Publishers, Moscow, 1969.

[5] J.J. Fruin. *Pedestrian Planning and Design*. Metropolitan Association of Urban Designers and Environmental Planners Inc., New York, 1971.

[6] *Nordic statistical yearbook*. Nordic Council of Ministers, 2009.

[7] M. Koelch. Ethical issues in psychopharmacology of children and adolescents. *Curr Opin Psychiatry*, 21(6):598–605, 2008.

[8] B. Evarts. Structure fires in educational properties. Report, National Fire Protection Association, June 2011.

[9] C.I. Babcock. The chicago school fire. Nfpa quarterly report, National Fire Protection Association, January 1959.

[10] G. Srinivasan. 87 children die in school fire. Online edition of India's National Newspaper, July 17th 2004. News article retreved September 19th 2013(http://www.hindu.com/2004/07/17/stories/2004071707570100.htm).

[11] Xinhua. Death toll from Mexico's daycare center fire rises to 47. People's Daily Online, June 23rd 2009. News article retreved September 19th 2013(http://english.peopledaily.com.cn/90001/90777/90852/6684347.html).

[12] Collins. Doha mall fire: Tragic list of characters in a terrible, terrible tale. The National, May 30th 2012. News article, retreved September 19th 2013 (http://www.thenational.ae/news/uae-news/doha-mall-fire-tragic-list-of-characters-in-a-terrible-terrible-tale).

[13] A.L. Szachnowicz. Balancing safety and security in the school environment. *Fire Protection Engineering*, October 2003.

[14] J. L. Bryan. *SFPE Handbook of Fire Protection Engineering, Behavioral Response to Fire and Smoke*. National Fire Protection Association, USA, third edition, 2002.

[15] G. Proulx. *SFPE Handbook of Fire Protection Engineering, Movement of People - The Evacuation Timing*. National Fire Protection Association, USA, third edition, 2002.

[16] H. E. Nelson and F. W. Mowrer. *SFPE Handbook of Fire Protection Engineering, Emergency Movement*. National Fire Protection Association, USA, third edition, 2002.

[17] J.L. Pauls. Evacuation and other fire safety measures in high rise buildings. *Ashrae Transactions*, 81:528–534, 1975.

[18] G. Prolux. Critical factors in high-rise evacuations. *Fire Prevention*, pages 24–27, 1996.

[19] J.R. Hall. High-rise building fires. Technical report, National Fire Protection Agency, USA, December 2011.

[20] F. B. et al Steffensen. Brand og brandsikkerhed i forsamlingslokaler - et fælles ansvar. Technical report, Københavns Brandvæsen, Forebyggende afdeling, Projekt- og udviklingssektionen., May 2000. (In Danish).

[21] G. Prolux. Occupant responce during a residential fire. *Fire and Materials*, 23(6):317–323, 1999.

[22] G. Prolux and C. McQueen. Evacuation timing in apartment buildings. Internal Report 660, National Reseach Council Canada, June 1994.

[23] G. Prolux. How to initiate evacuation movement in public buildings. *Facilities*, 17(9/10):331–335, 1999.

[24] J.L. Pauls. Effective-width model for evacuation flow in buildings. *Proceedings of Engineering Applications of Fire Technology Workshop*, pages 215–232, April 1980.

[25] R.F. Fahy and G. Prolux. 'panic'and human behaviour in fire. *Proceedings of Human Behaviour in Fire Symposium*, pages 387–398, July 2009.

[26] R.F. Fahy, G. Prolux, and L. Aiman. Panic or not in fire: Clarifying the misconception. *Fire and Materials*, 2011.

[27] E.D. Kuligowski, R.D. Peacock, and B.L. Hoskins. A review of buliding evacuation models 2nd edition. Technical Note 1680, National Institute of Standards and Technology, 2010.

[28] S. Gwynne and E.R. Galea. A review of the methodologies and critical apprasial of computer models used inthe simulation of evacuation from the built environment. Technical Report 97/IM/21, Centre for Numerical Modelling and Process Analysis, University of Greenwich, 1997.

[29] G. Hallberg. Defining care and residential buildings with respect to the evacuation capabiliry of occupants. *Fire Safety Science 3*, pages 825–834, 1991.

[30] S.M.V. Gwynne, D.L. Boswell, and G. Proulx. Understanding the effectiveness of notification technologies in assisting vulnerable populations. *Fire Protection Engineering*, 19:31–49, February 2009.

[31] K.E. Boyce, T.J.Shields, and G.W.H. Silcock. Toward the characterization of building occupancies for fire safety engineering: Prevalence, type and mobility of disabled people. *Fire Technology*, 35(1):35–50, 1999.

[32] K.E. Boyce, T.J.Shields, and G.W.H. Silcock. Toward the characterization of building occupancies for fire safety engineering: Capabilities of disabled people moving horizontally and on incline. *Fire Technology*, 35(1):51–67, 1999.

[33] K.E. Boyce, T.J.Shields, and G.W.H. Silcock. Toward the characterization of building occupancies for fire safety engineering: Capability of disabled people to negotiate doors. *Fire Technology*, 35(1):68–78, 1999.

[34] K.E. Boyce, T.J.Shields, and G.W.H. Silcock. Toward the characterization of building occupancies for fire safety engineering: Capability of people with disabilities to read and locate exit signs. *Fire Technology*, 35(1):79–86, 1999.

[35] A. Chalmers. Improving the fire safety knowledge and practices of vulnerable groups. New Zealand Fire Service Commision Research Report 8, New Zealand Council for Education Research, June 2000.

[36] E. Kuligowski. Elevators for occupant evacuation and fire department access. *Proceedings of the CIB-CTBUH International Conference on Tall Buildings*, May 2003.

[37] G. Prolux. Evacuation by elevators- who goes first? *Workshop on the Use for Elevators in Fires and Other Emergencies, Atlanta, Georgia*, pages 1–13, March 2004.

[38] G. Prolux, E. Heyes, G. Hedman, J. Averill, J. Paules, D. MCColl, and P. Johnson. The use of elevators for egress. *Proceedings of Human Behaviour in Fire Symposium*, pages 97–110, July 2009.

[39] M.J. Kinsey, E.R. Galea, and P.J. Lawrence. Investigating the use of elevators for high-rise building evacuation through computer simulation. *Proceedings of Human Behaviour in Fire Symposium*, pages 85–96, July 2009.

[40] J.J. O'Donoghue. Evolution of an elevator task group project. *Fire Engneering*, 2010.

[41] S.J. Kravontka. A fire signal system for deaf school children. *Fire Technology*, 11(1):23–28, 1975.

[42] Y. Murozaki and K. Ohnishi. A study of fire safety and evacuation planning for pre-schools and day care centers. *Memoirs of the Faculty of Engineering Kobe University*, 32:99–109, 1985.

[43] A.F. Van Bogaert. Evacuating schools on fire. *Fire Safety Science 1*, pages 551–560, 1986.

[44] A.F. Van Bogaert. Fire safety research and measures in schools in belgium. *Fire Safety Science 1*, pages 819–828, 1986.

[45] M. Horasan and Bruck D. Investigation of a behavioural response model for fire emergency situations in secondary schools. *Fire Safety Science 4*, pages 715–726, 1994.

[46] D. Bruck. Non-awakening in children in response to a smoke detector alarm. *Fire Safety Journal*, pages 369–376, 1998.

[47] D. Gamache, S. andPorth. The development of an education program effective in reducing the fire deaths of preschool children. *Proceedings of Human Behaviour in Fire Symposium*, 2001.

[48] H. Klüpfel, T. Meyer-König, and M. Schrecjenberg. Comparison of an evacuation exercise in a primary school to simulation results. *Traffic and Granular Flow '01*, pages 549–554, 2003.

[49] R. Ono and K. Tatebe. A study on school children's attitude towards firesafety and evacuation behaviour in brazil and the comparison with data from japanese children. *Proceedings of Human Behaviour in Fire Symposium*, 2004.

[50] M.A. Hassanain. Towards the design and operation of fire safe school facilities. *Disaster and prevention management*, 15(5):838–846, 2006.

[51] R. Ono and M.V. Valentin. A study on evacuation of school buildings for elementary education. *Proceedings of Human Behaviour in Fire Symposium*, pages 231–242, 2009.

[52] Kholshevnikov V.V., D.A. Samoshin, and A.P. Parfenenko. Pre-school and school children building evacuation. *Proceedings of Human Behaviour in Fire Symposium*, pages 231–242, 2009.

[53] A.R. Larusdottir and A.S. Dederichs. Evacuation dynamics of children - walking speeds, flow through doors in daycare centers. *Proceedings of Pedestrian and Evacuation Dynamics Symposium*, pages 139–147, 2010.

[54] C. Lu. The evacuate training problems of earthquake in china. *Proceedings of Pedestrian and Evacuation Dynamics Symposium*, pages 121–127, 2010.

[55] A.R. Larusdottir and A.S. Dederichs. A step towards including children's evacuation parameters and behavior in fire safe building design. *Fire Safety Science 10*, pages 187–195, 2011.

[56] M.C. Campanella, A.R. Larusdottir, W. Daamen, and A.S. Dederichs. Empirical data analysis and modelling of the evacuation of children from three multi-storey day-care centres. *Proceedings of Evacuation and Human Behavior in Emergency Situations, Santander*, 2011.

[57] A.R. Larusdottir and A.S. Dederichs. Evacuation of children - movement on stairs and on horizontal plane. *Fire Technology*, 48(1):43–53, 2012.

[58] V.V. Kholshevnikov, D.A. Samoshin, A.P. Parfenenko, and I.P. Belosokhov. Study of children evacuation from pre-school education institutions. *Fire and Materials*, 36:349–366, 2012.

[59] A.R. Larusdottir and A.S. Dederichs. Behavioural aspects of movement down stairs during elementary school fire drills. *Proceedings of Human Behaviour in Fire Symposium*, 2012.

[60] J.A. Capote, D. Alvear, O. Abreu, A. Cuesta, and J. Hernando. Children evacuation: Empirical data and egress modelling. *Proceedings of Human Behaviour in Fire Symposium*, 2012.

[61] R. Ono, M.V. Valentin, and F. Vittorino. Walking speed data of fire drills at an elementary school. *Proceedings of Human Behaviour in Fire Symposium*, 2012.

[62] J.A. Capote, D. Alvear, O. Abreu, A. Cuesta, and F. Ancona. Children behaviour during evacation process in school buildings. *Proceedings of the International Congress Fire Computer Modelling, Santander*, pages 441–456, 2012.

[63] G. Proulx. Evacuation time and movement in apartment buildings. *Fire Safety Journal*, 24:229–246, 1995.

[64] A. Taciuc and A.S. Dederichs. Determining self-preservation capability in pre-school children. Technical note, The Fire Protection Research Foundation, 2013. (To be published).

[65] A.E. Cote, editor. *Fire Protection Handbook, Principles and Techniques of Fire and Life Safety Education (Section 5, chapter 1)*. National Fire Protection Association, twentieth edition, 2008.

[66] S.M.V. Gwynne. Helping people on their own terms: Developing inclusive emergency procedures. *Fire Technology*, 44:439–461, September 2008.

[67] A.R. Larusdottir. Evacuation process of daycare centers for children 0-6 years. Master's thesis, Technical University of Denmark, August 2009.

[68] B.A. Pedersen. Grundlag for designkriterier til brandsikring ad bygninger for børn og unge 6-15 år. Master's thesis, Technical University of Denmark, February 2011. (In Danish).

[69] Brandskyddshandboken. Report 3134, Department of Fire Safety Engineering, Lund University, 2005. (In Swedish).

[70] B.L. Hoskins. Effective density measurements methods on stairs. *Proceedings of Human Behaviour in Fire Symposium*, 2012.

[71] B.L. Hoskins and J.A. Milke. Differences in measurement methods for travel distance and area for estimates of occupant speed on stairs. *Fire Safety Journal*, 48:49 – 57, 2012. doi:http://dx.doi.org/10.1016/j.firesaf.2011.12.009.

[72] L. Benthorn and H. Frantzich. Fire alarm in a public building: How do people evaluate information and choose evacuation exit? Technical Report ISSN 1102-8246, Department of Fire Safety Engineering, Lund University, June 1996.

[73] R. Palmgren, J. Åberg, and D. Nilsson. Which acoustic and optical signals are best suited for evacuaiton alarms? *Proceedings of Human Behaviour in Fire Symposium*, 2012. (Poster).

Appendices

Appendix A

Icelandic program for 5 year old children

In Iceland a fire safety educational programme for 5 year old children (last year of daycare/kindergarten) started in 2007. The name of the programme is Flame (Icelandinc boy's name: Logi) and Ember (Icelandic girl's name: Glóð) which are the names of fictional characters (elfish) that are the fire department's helpers.

Every year two staff members of the local fire department visit daycare centers and meet with the 5 year old children. While one does the annual fire inspection the other one goes through the educational program with the children.

The children are asked to join Flame and Ember in helping the fire department, where their task will be to take turns in inspecting the daycare facility on a monthly basis. The points to be inspected are explained carefully to the children using pictures and demonstrations. The children learn about emergency exits and signs, importance of keeping exits clear, fire alarms, smoke detectors, fire extinguishers, door pumps and to minimize garbage inside.

They are told what to do if they need to evacuate the daycare and the message is simple, stop what they are doing and quickly form a line and the teacher will lead them out, choosing a safe route.

Then the importance of smoke detectors and to have a fire extinguisher in homes are discussed and the children are asked to check or ask their parents if their home has smoke detectors and a fire extinguisher.

Then the children are told about the emergency line and learn a way to memorize the emergency number 1-1-2. Then the children see the fire man take on his protective suit and his smoke equipment on to see how a fire man would look and how a fire man would sound like if ever in the need of help. They are told that they always come to help and should never be afraid of one.

At last the group goes outside to take a look at the ambulance or fire truck they arrived in. The children get some material with pictures to color and information for the parents.

This project has been a success, it has become very welcomed among the daycares and they claim to be more aware of fire safety after the yearly reminder. According to response to the fire department from parents it is also likely to have good affect on smoke detector installation in homes, although not proven.

The fire department also visits every class with eight year old children annually. They receive some general fire safety education and get a small story book about Flame and Ember and their adventures. The book also includes useful information on fire safety in homes.

The school project for eight year old children started several years before the daycare project for five year old children. Although not investigated, it can be mentioned that the fire department felt a jump up in level of knowledge, when the first children receiving education in their daycare, came through to the school education programmes.

Appendix B

Extended flow tables

Table B.1: Flow table for children 0-2 years.

daycare (0-2 years)								
density				95 % confidence interval				
interval	n	mean flow	SD	lower bound	upper bound	min	median	max
$[pers/m^2]$	[#]	$[pers/sm]$	$[pers/sm]$	$[pers/sm]$	$[pers/sm]$	$[pers/sm]$	$[pers/sm]$	$[pers/sm]$
$[0,1)$								
$[1,2)$	1	0.67		0.67	0.67	0.67	0.67	0.67
$[2,3)$	2	0.84	0.09	0.77	0.90	0.77	0.84	0.90
$[3,4)$	7	0.95	0.24	0.68	1.28	0.68	0.93	1.29
$[4,5)$	5	1.08	0.37	0.74	1.61	0.74	1.09	1.67
$[5,10)$	5	1.23	0.28	0.90	1.53	0.89	1.31	1.54

Table B.2: Flow table for children 3-6 years.

daycare (3-6 years)								
density				95 % confidence interval				
interval	n	mean flow	SD	lower bound	upper bound	min	median	max
$[pers/m^2]$	[#]	$[pers/sm]$	$[pers/sm]$	$[pers/sm]$	$[pers/sm]$	$[pers/sm]$	$[pers/sm]$	$[pers/sm]$
$[0,1)$								
$[1,2)$	4	1.09	0.35	0.78	1.43	0.78	1.08	1.43
$[2,3)$	3	1.39	0.16	1.23	1.52	1.22	1.43	1.53
$[3,4)$	9	1.42	0.26	1.19	1.93	1.17	1.31	2.00
$[4,5)$	11	1.89	0.42	1.37	2.58	1.34	1.75	2.68
$[5,10]$	17	2.34	0.45	1.59	3.10	1.52	2.38	3.25

Table B.3: Flow table for children 6-8 years.

school (6-8 years)								
density				95 % confidence interval				
interval	n	mean flow	SD	lower bound	upper bound	min	median	max
$[pers/m^2]$	[#]	$[pers/sm]$	$[pers/sm]$	$[pers/sm]$	$[pers/sm]$	$[pers/sm]$	$[pers/sm]$	$[pers/sm]$
$[0, 1)$								
$[1, 2)$	4	1.09	0.35	0.78	1.43	0.78	1.08	1.43
$[2, 3)$	3	1.39	0.16	1.23	1.52	1.22	1.43	1.53
$[3, 4)$	9	1.42	0.26	1.19	1.93	1.17	1.31	2.00
$[4, 5)$	11	1.89	0.42	1.37	2.58	1.34	1.75	2.68
$[5, 10)$	17	2.34	0.45	1.59	3.10	1.52	2.38	3.25

Table B.4: Flow table for children 9-11 years.

school (9-11 years)								
density				95 % confidence interval				
interval	n	mean flow	SD	lower bound	upper bound	min	median	max
$[pers/m^2]$	[#]	$[pers/sm]$	$[pers/sm]$	$[pers/sm]$	$[pers/sm]$	$[pers/sm]$	$[pers/sm]$	$[pers/sm]$
$[0, 1)$								
$[1, 2)$	4	1.09	0.35	0.78	1.43	0.78	1.08	1.43
$[2, 3)$	3	1.39	0.16	1.23	1.52	1.22	1.43	1.53
$[3, 4)$	9	1.42	0.26	1.19	1.93	1.17	1.31	2.00
$[4, 5)$	11	1.89	0.42	1.37	2.58	1.34	1.75	2.68
$[5, 10)$	17	2.34	0.45	1.59	3.10	1.52	2.38	3.25

Table B.5: Flow table for children 12-15 years.

school (12-15 years)								
density				95 % confidence interval				
interval	n	mean flow	SD	lower bound	upper bound	min	median	max
$[pers/m^2]$	[#]	$[pers/sm]$	$[pers/sm]$	$[pers/sm]$	$[pers/sm]$	$[pers/sm]$	$[pers/sm]$	$[pers/sm]$
$[0, 1)$								
$[1, 2)$	4	1.09	0.35	0.78	1.43	0.78	1.08	1.43
$[2, 3)$	3	1.39	0.16	1.23	1.52	1.22	1.43	1.53
$[3, 4)$	9	1.42	0.26	1.19	1.93	1.17	1.31	2.00
$[4, 5)$	11	1.89	0.42	1.37	2.58	1.34	1.75	2.68
$[5, 10)$	17	2.34	0.45	1.59	3.10	1.52	2.38	3.25

Table B.6: Flow table for children 6 years.

school (6 years)								
density				95 % confidence interval				
interval	n	mean flow	SD	lower bound	upper bound	min	median	max
$[pers/m^2]$	[#]	$[pers/sm]$	$[pers/sm]$	$[pers/sm]$	$[pers/sm]$	$[pers/sm]$	$[pers/sm]$	$[pers/sm]$
$[0, 1)$								
$[1, 2)$	2	1.82	0.55	1.45	2.19	1.43	1.82	2.21
$[2, 3)$	5	2.00	0.32	1.62	2.40	1.59	1.94	2.42
$[3, 4)$	4	1.21	0.56	0.54	1.80	0.48	1.25	1.84
$[4, 5)$								
$[5, 10)$								

Table B.7: Flow table for children 7 years.

				school (7 years)				
density				95 % confidence interval				
interval	n	mean flow	SD	lower bound	upper bound	min	median	max
$[pers/m^2]$	[#]	$[pers/sm]$	$[pers/sm]$	$[pers/sm]$	$[pers/sm]$	$[pers/sm]$	$[pers/sm]$	$[pers/sm]$
$[0, 1)$								
$[1, 2)$	1	1.17		1.17	1.17	1.17	1.17	1.17
$[2, 3)$	2	1.89	0.45	1.59	2.18	1.57	1.89	2.20
$[3, 4)$	5	2.74	0.76	2.02	3.71	2.00	2.36	3.75
$[4, 5)$								
$[5, 10)$								

Table B.8: Flow table for children 8 years.

				school (8 years)				
density				95 % confidence interval				
interval	n	mean flow	SD	lower bound	upper bound	min	median	max
$[pers/m^2]$	[#]	$[pers/sm]$	$[pers/sm]$	$[pers/sm]$	$[pers/sm]$	$[pers/sm]$	$[pers/sm]$	$[pers/sm]$
$[0, 1)$								
$[1, 2)$	6	1.94	0.67	1.11	2.92	1.04	1.92	3.04
$[2, 3)$	3	2.10	0.11	2.00	2.20	2.00	2.10	2.21
$[3, 4)$	2	2.21	1.12	1.45	2.96	1.41	2.21	3.00
$[4, 5)$								
$[5, 10)$								

Table B.9: Flow table for children 9 years.

				school (9 years)				
density				95 % confidence interval				
interval	n	mean flow	SD	lower bound	upper bound	min	median	max
$[pers/m^2]$	[#]	$[pers/sm]$	$[pers/sm]$	$[pers/sm]$	$[pers/sm]$	$[pers/sm]$	$[pers/sm]$	$[pers/sm]$
$[0, 1)$								
$[1, 2)$	2	2.68	0.30	2.48	2.88	2.47	2.68	2.89
$[2, 3)$								
$[3, 4)$								
$[4, 5)$								
$[5, 10)$								

Table B.10: Flow table for children 10 years.

				school (10 years)				
density				95 % confidence interval				
interval	n	mean flow	SD	lower bound	upper bound	min	median	max
$[pers/m^2]$	[#]	$[pers/sm]$	$[pers/sm]$	$[pers/sm]$	$[pers/sm]$	$[pers/sm]$	$[pers/sm]$	$[pers/sm]$
$[0, 1)$	2	1.15	0.54	0.78	1.51	0.76	1.15	1.53
$[1, 2)$	6	2.50	0.49	1.83	3.00	1.80	2.58	3.00
$[2, 3)$	4	2.30	0.51	1.77	2.91	1.73	2.25	2.96
$[3, 4)$	2	2.54	0.25	2.37	2.70	2.36	2.54	2.71
$[4, 5)$								
$[5, 10)$								

Table B.11: Flow table for children 11 years.

				school (11 years)				
density				95 % confidence interval				
interval	n	mean flow	SD	lower bound	upper bound	min	median	max
[$pers/m^2$]	[#]	[$pers/sm$]	[$pers/sm$]	[$pers/sm$]	[$pers/sm$]	[$pers/sm$]	[$pers/sm$]	[$pers/sm$]
$[0,1)$	2	1.15	0.54	0.78	1.51	0.76	1.15	1.53
$[1,2)$	5	1.89	0.99	0.77	3.14	0.72	1.80	3.21
$[2,3)$	3	2.22	0.46	1.76	2.62	1.73	2.29	2.64
$[3,4)$	2	2.54	0.25	2.37	2.70	2.36	2.54	2.71
$[4,5)$								
$[5,10)$								

Table B.12: Flow table for children 12 years.

				school (12 years)				
density				95 % confidence interval				
interval	n	mean flow	SD	lower bound	upper bound	min	median	max
[$pers/m^2$]	[#]	[$pers/sm$]	[$pers/sm$]	[$pers/sm$]	[$pers/sm$]	[$pers/sm$]	[$pers/sm$]	[$pers/sm$]
$[0,1)$	1	1.74		1.74	1.74	1.74	1.74	1.74
$[1,2)$	3	1.84	0.16	1.68	1.97	1.67	1.88	1.98
$[2,3)$	3	1.80	0.46	1.43	2.29	1.42	1.67	2.32
$[3,4)$	1	2.27		2.27	2.27	2.27	2.27	2.27
$[4,5)$								
$[5,10)$								

Table B.13: Flow table for children 13 years.

				school (13 years)				
density				95 % confidence interval				
interval	n	mean flow	SD	lower bound	upper bound	min	median	max
[$pers/m^2$]	[#]	[$pers/sm$]	[$pers/sm$]	[$pers/sm$]	[$pers/sm$]	[$pers/sm$]	[$pers/sm$]	[$pers/sm$]
$[0,1)$								
$[1,2)$	6	1.75	0.24	1.44	2.04	1.41	1.70	2.05
$[2,3)$	2	2.21	0.17	2.10	2.32	2.09	2.21	2.33
$[3,4)$								
$[4,5)$								
$[5,10)$								

Table B.14: Flow table for children 14 years.

				school (14 years)				
density				95 % confidence interval				
interval	n	mean flow	SD	lower bound	upper bound	min	median	max
[$pers/m^2$]	[#]	[$pers/sm$]	[$pers/sm$]	[$pers/sm$]	[$pers/sm$]	[$pers/sm$]	[$pers/sm$]	[$pers/sm$]
$[0,1)$								
$[1,2)$	1	1.72		1.72	1.72	1.72	1.72	1.72
$[2,3)$	2	1.90	0.41	1.62	2.18	1.61	1.90	2.19
$[3,4)$								
$[4,5)$								
$[5,10)$								

Table B.15: Flow table for children 15 years.

				school (15 years)				
density				95 % confidence interval				
interval	n	mean flow	SD	lower bound	upper bound	min	median	max
$[pers/m^2]$	[#]	$[pers/sm]$	$[pers/sm]$	$[pers/sm]$	$[pers/sm]$	$[pers/sm]$	$[pers/sm]$	$[pers/sm]$
$[0,1)$								
$[1,2)$	2	2.09	0.08	2.04	2.15	2.04	2.09	2.15
$[2,3)$	1	2.16		2.16	2.16	2.16	2.16	2.16
$[3,4)$								
$[4,5)$								
$[5,10)$								

Table B.16: Flow table for children 0-6 years.

				daycare (0-6 years)				
density				95 % confidence interval				
interval	n	mean flow	SD	lower bound	upper bound	min	median	max
$[pers/m^2]$	[#]	$[pers/sm]$	$[pers/sm]$	$[pers/sm]$	$[pers/sm]$	$[pers/sm]$	$[pers/sm]$	$[pers/sm]$
$[0,1)$								
$[1,2)$	5	1.01	0.36	0.68	1.42	0.67	0.80	1.43
$[2,3)$	5	1.17	0.33	0.78	1.52	0.77	1.22	1.53
$[3,4)$	17	1.20	0.34	0.68	1.87	0.68	1.25	2.00
$[4,5)$	17	1.62	0.54	0.76	2.52	0.74	1.67	2.68
$[5,10]$	25	1.99	0.65	0.90	3.02	0.89	2.15	3.25

Table B.17: Flow table for children 6-15 years.

				school (6-15 years)				
density				95 % confidence interval				
interval	n	mean flow	SD	lower bound	upper bound	min	median	max
$[pers/m^2]$	[#]	$[pers/sm]$	$[pers/sm]$	$[pers/sm]$	$[pers/sm]$	$[pers/sm]$	$[pers/sm]$	$[pers/sm]$
$[0,1)$	5	1.26	0.47	0.76	1.72	0.76	1.53	1.74
$[1,2)$	39	1.98	0.57	1.02	3.05	0.72	1.92	3.21
$[2,3)$	30	2.22	0.61	1.53	3.96	1.42	2.20	4.00
$[3,4)$	21	2.13	0.79	0.85	3.54	0.48	2.27	3.75
$[4,5)$	1	1.61		1.61	1.61	1.61	1.61	1.61
$[5,10)$								

Appendix C

Extended speed tables

Table C.1: Travel speed down stairs for children 0-2 years.

daycare (0-2 years)								
density				95 % confidence interval				
interval	n	mean speed	SD	lower bound	upper bound	min	median	max
$[pers/m^2]$	[#]	$[m/s]$	$[m/s]$	$[m/s]$	$[m/s]$	$[m/s]$	$[m/s]$	$[m/s]$
$[0, 1)$	46	0.19	0.10	0.06	0.38	0.06	0.18	0.50
$[1, 2)$	365	0.31	0.27	0.06	1.04	0.02	0.20	1.79
$[2, 3)$	400	0.27	0.22	0.05	0.88	0.03	0.21	1.76
$[3, 4)$	195	0.20	0.17	0.04	0.68	0.03	0.15	1.02
$[4, 5)$	64	0.16	0.09	0.06	0.39	0.04	0.14	0.49
$[5, 10)$	19	0.14	0.06	0.07	0.29	0.07	0.12	0.32

Table C.2: Travel speed down stairs for children 3-6 years.

daycare (3-6 years)								
density				95 % confidence interval				
interval	n	mean speed	SD	lower bound	upper bound	min	median	max
$[pers/m^2]$	[#]	$[m/s]$	$[m/s]$	$[m/s]$	$[m/s]$	$[m/s]$	$[m/s]$	$[m/s]$
$[0, 1)$	65	0.41	0.28	0.07	1.19	0.06	0.36	1.36
$[1, 2)$	203	0.39	0.19	0.13	0.75	0.04	0.34	1.16
$[2, 3)$	112	0.37	0.15	0.14	0.68	0.08	0.35	0.68
$[3, 4)$	87	0.28	0.11	0.14	0.57	0.11	0.26	0.67
$[4, 5)$	53	0.32	0.12	0.16	0.50	0.16	0.30	0.95
$[5, 10)$	27	0.34	0.13	0.17	0.59	0.16	0.29	0.63

Table C.3: Travel speed down stairs for children 6-8 years.

				school (6-8 years)				
density				95 % confidence interval				
interval	n	mean speed	SD	lower bound	upper bound	min	median	max
$[pers/m^2]$	[#]	$[m/s]$	$[m/s]$	$[m/s]$	$[m/s]$	$[m/s]$	$[m/s]$	$[m/s]$
$[0, 1)$	15	0.63	0.21	0.38	1.05	0.34	0.57	1.05
$[1, 2)$	208	0.68	0.25	0.35	1.30	0.29	0.63	1.98
$[2, 3)$	95	0.52	0.25	0.20	0.99	0.18	0.52	1.22
$[3, 4)$								
$[4, 5)$								
$[5, 10)$								

Table C.4: Travel speed down stairs for children 9-11 years.

				school (9-11 years)				
density				95 % confidence interval				
interval	n	mean speed	SD	lower bound	upper bound	min	median	max
$[pers/m^2]$	[#]	$[m/s]$	$[m/s]$	$[m/s]$	$[m/s]$	$[m/s]$	$[m/s]$	$[m/s]$
$[0, 1)$	112	1.00	0.34	0.46	1.64	0.34	1.00	2.18
$[1, 2)$	628	0.76	0.20	0.46	1.22	0.29	0.72	1.66
$[2, 3)$	116	0.66	0.15	0.25	0.93	0.18	0.67	1.05
$[3, 4)$	42	0.45	0.17	0.30	0.65		0.41	1.38
$[4, 5)$	26	0.22	0.07	0.12	0.36		0.20	0.38
$[5, 10)$	3	0.21	0.01	0.19	0.22		0.22	0.22

Table C.5: Travel speed down stairs for children 12-15 years.

				school (12-15 years)				
density				95 % confidence interval				
interval	n	mean speed	SD	lower bound	upper bound	min	median	max
$[pers/m^2]$	[#]	$[m/s]$	$[m/s]$	$[m/s]$	$[m/s]$	$[m/s]$	$[m/s]$	$[m/s]$
$[0, 1)$	64	1.01	0.38	0.66	2.02	0.56	0.87	2.25
$[1, 2)$	537	0.75	0.15	0.55	1.10	0.39	0.72	1.61
$[2, 3)$	96	0.70	0.18	0.42	1.09	0.35	0.67	1.31
$[3, 4)$	58	0.53	0.11	0.36	0.74	0.33	0.52	0.77
$[4, 5)$	8	0.27	0.09	0.19	0.41	0.19	0.23	0.42
$[5, 10)$	1	0.20		0.20	0.20	0.20	0.20	0.20

Table C.6: Travel speed down stairs for children 6 years.

				school (6 years)				
density				95 % confidence interval				
interval	n	mean speed	SD	lower bound	upper bound	min	median	max
$[pers/m^2]$	[#]	$[m/s]$	$[m/s]$	$[m/s]$	$[m/s]$	$[m/s]$	$[m/s]$	$[m/s]$
$[0, 1)$	11	0.53	0.10	0.37	0.70	0.34	0.52	0.72
$[1, 2)$	150	0.58	0.13	0.32	0.80	0.29	0.57	0.93
$[2, 3)$	49	0.31	0.11	0.19	0.56	0.18	0.27	0.59
$[3, 4)$								
$[4, 5)$								
$[5, 10)$								

Table C.7: Travel speed down stairs for children 7 years.

				school (7 years)				
density				95 % confidence interval				
interval	n	mean speed	SD	lower bound	upper bound	min	median	max
$[pers/m^2]$	[#]	$[m/s]$	$[m/s]$	$[m/s]$	$[m/s]$	$[m/s]$	$[m/s]$	$[m/s]$
$[0,1)$								
$[1,2)$	17	0.83	0.19	0.57	1.18	0.55	0.83	1.22
$[2,3)$	46	0.74	0.15	0.55	0.99	0.51	0.69	1.22
$[3,4)$								
$[4,5)$								
$[5,10)$								

Table C.8: Travel speed down stairs for children 8 years.

				school (8 years)				
density				95 % confidence interval				
interval	n	mean speed	SD	lower bound	upper bound	min	median	max
$[pers/m^2]$	[#]	$[m/s]$	$[m/s]$	$[m/s]$	$[m/s]$	$[m/s]$	$[m/s]$	$[m/s]$
$[0,1)$	4	0.92	0.17	0.70	1.05	0.69	0.97	1.05
$[1,2)$	41	1.00	0.28	0.63	1.58	0.61	0.93	1.98
$[2,3)$								
$[3,4)$								
$[4,5)$								
$[5,10)$								

Table C.9: Travel speed down stairs for children 9 years.

				school (9 years)				
density				95 % confidence interval				
interval	n	mean speed	SD	lower bound	upper bound	min	median	max
$[pers/m^2]$	[#]	$[m/s]$	$[m/s]$	$[m/s]$	$[m/s]$	$[m/s]$	$[m/s]$	$[m/s]$
$[0,1)$								
$[1,2)$	28	0.75	0.16	0.53	1.11	0.53	0.76	1.20
$[2,3)$								
$[3,4)$								
$[4,5)$								
$[5,10)$								

Table C.10: Travel speed down stairs for children 10 years.

				school (10 years)				
density				95 % confidence interval				
interval	n	mean speed	SD	lower bound	upper bound	min	median	max
$[pers/m^2]$	[#]	$[m/s]$	$[m/s]$	$[m/s]$	$[m/s]$	$[m/s]$	$[m/s]$	$[m/s]$
$[0,1)$	33	1.00	0.26	0.69	1.64	0.66	0.92	1.64
$[1,2)$	189	0.83	0.16	0.54	1.16	0.48	0.81	1.66
$[2,3)$	65	0.71	0.12	0.52	0.95	0.49	0.69	1.05
$[3,4)$	17	0.53	0.24	0.32	1.09	0.29	0.44	1.38
$[4,5)$	8	0.27	0.09	0.12	0.37	0.11	0.29	0.38
$[5,10)$	1	0.22		0.22	0.22	0.22	0.22	0.22

Table C.11: Travel speed down stairs for children 11 years.

				school (11 years)				
density				95 % confidence interval				
interval	n	mean speed	SD	lower bound	upper bound	min	median	max
$[pers/m^2]$	[#]	$[m/s]$	$[m/s]$	$[m/s]$	$[m/s]$	$[m/s]$	$[m/s]$	$[m/s]$
$[0, 1)$	79	1.00	0.37	0.42	1.65	0.39	1.06	2.18
$[1, 2)$	411	0.72	0.21	0.40	1.25	0.23	0.67	1.58
$[2, 3)$	51	0.60	0.17	0.24	0.86	0.19	0.62	0.94
$[3, 4)$	25	0.39	0.05	0.31	0.49	0.30	0.40	0.52
$[4, 5)$	18	0.20	0.04	0.14	0.29	0.13	0.19	0.30
$[5, 10)$	2	0.21	0.02	0.19	0.22	0.19	0.21	0.22

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Table C.12: Travel speed down stairs for children 12 years.

				school (12 years)				
density				95 % confidence interval				
interval	n	mean speed	SD	lower bound	upper bound	min	median	max
$[pers/m^2]$	[#]	$[m/s]$	$[m/s]$	$[m/s]$	$[m/s]$	$[m/s]$	$[m/s]$	$[m/s]$
$[0, 1)$	29	1.18	0.48	0.61	2.18	0.56	1.02	2.25
$[1, 2)$	127	0.79	0.19	0.58	1.44	0.52	0.73	1.61
$[2, 3)$	41	0.76	0.19	0.52	1.09	0.51	0.71	1.31
$[3, 4)$	22	0.55	0.12	0.37	0.76	0.36	0.56	0.77
$[4, 5)$	8	0.27	0.09	0.19	0.41	0.19	0.23	0.42
$[5, 10)$	1	0.20		0.20	0.20	0.20	0.20	0.20

Table C.13: Travel speed down stairs for children 13 years.

				school (13 years)				
density				95 % confidence interval				
interval	n	mean speed	SD	lower bound	upper bound	min	median	max
$[pers/m^2]$	[#]	$[m/s]$	$[m/s]$	$[m/s]$	$[m/s]$	$[m/s]$	$[m/s]$	$[m/s]$
$[0, 1)$	17	0.89	0.21	0.68	1.37	0.68	0.84	1.49
$[1, 2)$	184	0.73	0.12	0.53	0.97	0.39	0.72	1.29
$[2, 3)$	15	0.65	0.08	0.56	0.82	0.56	0.64	0.84
$[3, 4)$								
$[4, 5)$								
$[5, 10)$								

Table C.14: Travel speed down stairs for children 14 years.

				school (14 years)				
density				95 % confidence interval				
interval	n	mean speed	SD	lower bound	upper bound	min	median	max
$[pers/m^2]$	[#]	$[m/s]$	$[m/s]$	$[m/s]$	$[m/s]$	$[m/s]$	$[m/s]$	$[m/s]$
$[0, 1)$	14	0.88	0.16	0.70	1.19	0.70	0.85	1.22
$[1, 2)$	129	0.73	0.14	0.55	1.07	0.44	0.70	1.39
$[2, 3)$	17	0.64	0.20	0.36	0.98	0.35	0.60	1.01
$[3, 4)$	30	0.50	0.10	0.35	0.69	0.33	0.49	0.73
$[4, 5)$								
$[5, 10)$								

Table C.15: Travel speed down stairs for children 15 years.

				school (15 years)				
density				95 % confidence interval				
interval	n	mean speed	SD	lower bound	upper bound	min	median	max
$[pers/m^2]$	[#]	$[m/s]$	$[m/s]$	$[m/s]$	$[m/s]$	$[m/s]$	$[m/s]$	$[m/s]$
$[0, 1)$	4	0.77	0.02	0.75	0.79	0.75	0.78	0.79
$[1, 2)$	97	0.75	0.14	0.56	1.12	0.53	0.72	1.30
$[2, 3)$	23	0.67	0.15	0.50	1.03	0.49	0.64	1.14
$[3, 4)$	6	0.62	0.03	0.58	0.67	0.58	0.61	0.67
$[4, 5)$								
$[5, 10)$								

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PART II

Paper I

Paper I is an extended version of a paper presented at Pedestrian Evacuation Dynamics 2010. It was published in a special issue of Fire Technology in 2012 (online in 2010).

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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.

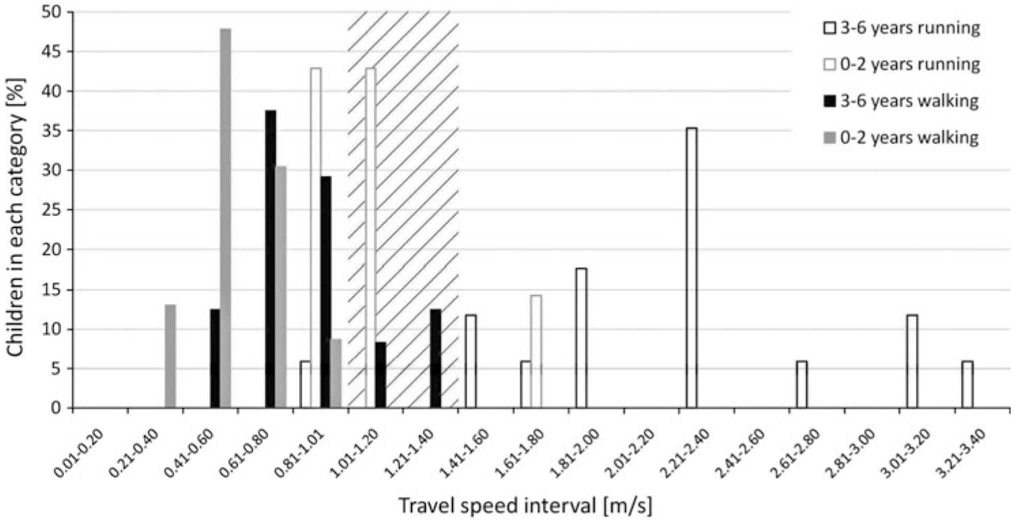

Figure 1. Travel speed (intervals of 0.20 m/s) for differentiated age groups 0 to 2 years (*grey*) and 3 to 6 years (*black*) running (*empty box*) and walking (*filled box*). A range of commonly used average walking speeds for adults is hatched.

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].

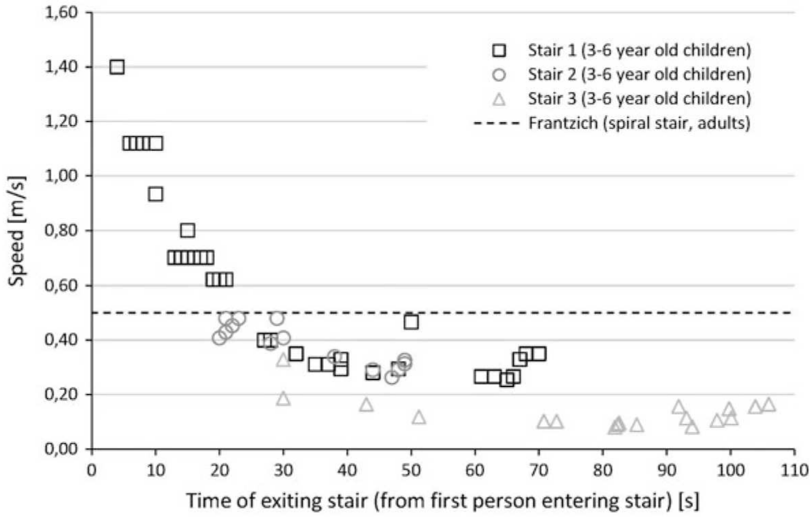

Figure 2. The individual travel speeds with respect to time of individuals exiting the stair. A *dashed line* marks the 0.5 m/s which literature suggests as an average travel speed for adults.

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

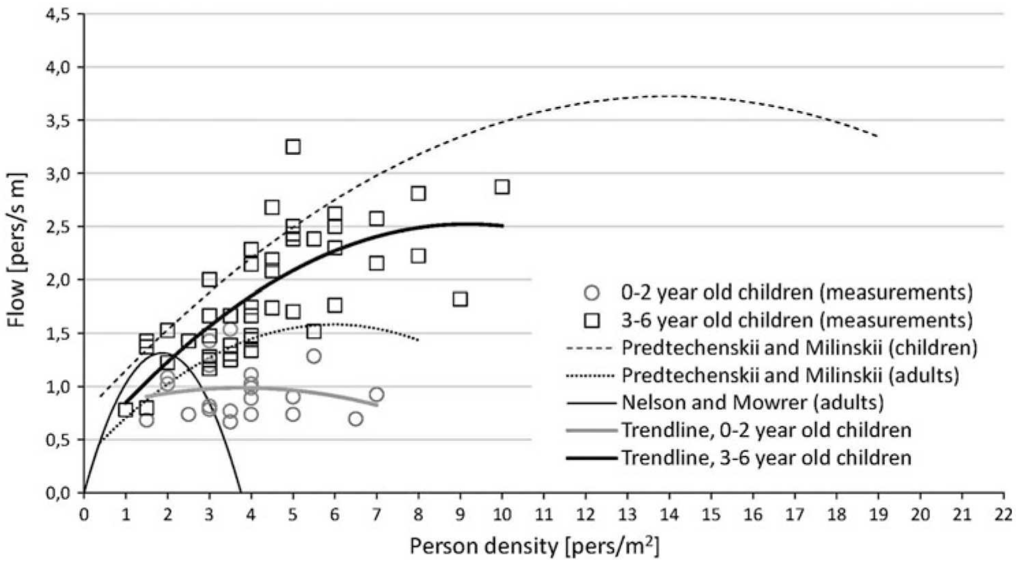

Figure 3. Flow through doors, measured during evacuation experiments, with respect to person density in pers/m^2. Trend lines (2nd degree polynomial) for the two age groups, 0 to 2 years (*thick grey line*) and 3 to 6 years (*thick black line*) are shown. For reference two transformed curves from Predtechneskii 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.

References

1. Nordic Council of Ministers (2009) Nordic statistical Yearbook. Nordic Council of Ministers, Nordic Council, Nordic

2. Larusdottir AR, Dederichs AS (2010) Evacuation dynamics of children, walking speeds, flows through doors in daycare centers. In: Proceedings of the fifth international conference on pedestrian and evacuation dynamics. NIST, Gaithersburg
3. Kimland E, Bergman U, Lindemalm S, Bottiger Y (2006) Drug related problems and off-label drug treatment in children as seen at a drug information centre. Eur J Pediatr 166:527–532
4. Lehmann B (2009) Klinische Prüfung an Kindern im Spannungsfeld zwischen wissenschaftlichen Anforderungen, der Sicherstellung der korrekten Behandlung und ethischen Aspekten. Bundesgesundheitsblatt - Gesundheitsforschung – Gesundheitsschutz, (In German)
5. Koelch M (2008) Ethical issues in psychopharmacology of children and adolescents. Curr Opin Psychiatry 21(6):598–605
6. Proulx G (1995) Evacuation time and movement in apartment buildings. Fire Safety J 24:229–246
7. Proulx G (2002) Movement of people: the evacuation timing. In: DiNenno PJ, Walton WD (eds), The SFPE handbook of fire protection engineering, Third edn. Society of Fire Protection Engineers, Bethesda, MD, pp 3-341–3-366
8. Nilsson D (2009) Exit choice in fire emergencies. Ph.D. thesis, Department of Fire Safety Engineering and Systems Safety, Lund, Sweden
9. Frantzich H (1994) En modell för dimensionering av förbindelser för utrymning utifrån funktionsbaserede krav, Technical report, Department of Fire Safety Engineering, Lund University, (In Swedish)
10. Frantzich H (1993) Utrymningsvägars fysiska kapacitet, sammanställning och utvärdering av kunskapsläget, Technical report, Department of Fire Safety Engineering, Lund University, (In Swedish)
11. Proulx G, Reid IMA (2006) Occupant behavior and evacuation during the Chicago cook county administration building fire. Fire Prot Eng 16:283–309
12. Steffensen FB (2000) Brand og brandsikkerhed i forsamlingslokaler et fælles ansvar. Technical report, Københavns Brandvæsen, May 2000 (In Danish)
13. Ravn K (2008) Undersøgelse af Reaktions-og Beslutningstid. Master thesis, Technical University of Denmark (in Danish)
14. Bryan JL (2002) Behavioral response to fire and smoke. In: Denno PJ, Walton WD (eds) The SFPE handbook of fire protection engineering, Third edn. Society of Fire Protection Engineers, Bethesda, MD, pp 3-315–3-341
15. Shields TJ, Smyth B, Boyce KE, Silcock WH (1999) Towards the prediction of evacuation behaviours for people with learning difficulties. Facilities 17(9–10):336–344
16. Nisser M (2001) Utrymningssäkerhet för rörelsehindrade. Technical report, Räddningsverket, Sverige (In Swedish)
17. Gwynne SMV, Boswell DL, Proulx G (2009) Understanding the effectiveness of notification technologies in assisting vulnerable populations. J Fire Prot Eng 19:31–48
18. Bruck D, Thomas I (2008) Comparison of the effectiveness of different fire notification signals in sleeping older adults. Fire Technol 44:15–38
19. Bruck D (1999) Non-awakening in children in response to a smoke detector alarm. Fire Safety J 32(4):369–376
20. Murozaki Y, Ohnishi K (1985) A study of fire safety and evacuation planning for preschools and day care centers. Mem Faculty Eng Kobe Univ 32:99–109
21. Kholshevnikov VV, Samoshin DA, Parfenenko AP (2009) Pre-school and school children building evacuation. State Moscow University of Civil Engineering, Academy of State Fire Service of Russia, Moscow, Russia

22. Predtechenskii VM, Milinskii AI (1969) Planning for foot traffic flow in buildings, Stroiizdat Publishers, Moscow
23. Nelson HE, Mowrer FW (2002) Emergency Movement. In: Denno PJ, Walton WD (eds) The SFPE handbook of fire protection engineering, Third edn. Society of Fire Protection Engineers, Bethesda, MD, pp 3-367–3-380
24. Brandskyddshandboken (2005) Rapport 3134. Department of Fire Safety Engineering, Lund University (In Swedish)

Paper II

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A Step Towards Including Children's Evacuation Parameters and Behavior in Fire Safe Building Design

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ABSTRACT

An important part the world's population is neglected in today's fire safety design – children. The vast amounts of data as well as the empirical models applied describe adults. This paper embraces the fact that there is a difference between children and adults, regarding evacuation and that children's movement parameters are age dependent. On the basis of 16 full scale evacuation experiments made in 10 Danish daycare centers the present paper gives input data applicable in fire safety design on flow through doors, walking speed in horizontal plane and spiral stairs. Parameters distinguish small children in the age of 0–2 years from older ones in the age 3–6 years. An empirical model of children´s flow through doors is introduced. The effect of using alarm/warning system on pre-evacuation time is briefly discussed. Behavioral aspects are also considered where possible. It is found that there is a higher need of physical assistance during evacuation for children in the age of 0–2 years, than for children aged 3–6. Children aged 3–6 years are keen to run during evacuations. Furthermore it was observed that children are used to following rules and routines which they continue doing during the evacuation. At last the effect of affiliation during the evacuation was seen among the children.

KEYWORDS: egress, children, flow, person density, behavior.

INTRODUCTION

The population of the western world comprises of between 15 and 20% children aged 0–14 years [1,2]. However, information on this part of the population is often neglected in fire safety design even in case of school buildings [3]. Buildings should be safe for all occupants whether they are designed according to prescriptive fire codes or performance-based codes. Building traditions, materials and technology have changed drastically throughout decades, forcing fire safety design to keep up. However, the fire society's main focus of new measures lays on the technical design focusing on the physics of the fire and the buildings rather than on the human beings which are to be protected. Many drastic changes to regulations and practice have been made after large fires, were valuable lessons were learned [4,5]. Important information on the subject has also been collected throughout studies and experiments, which all together are the fundamentals of today´s fire safety design.

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 account 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 on real fire incidents as well as experiments concerning fire and evacuations [1,5,6]. However, they provide design parameters and models on walking speed in horizontal plan and in stairs and flow through doors as well as other aspects relevant for evacuation. The results are applied in models and introduced in simulation programs 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 [1]. 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 [6–16]. 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 [17–21].

Another aspect is that society has developed through time in many ways. One is that it is more and more common for both parents having a working career outside of the home. This means that more children and younger children are in daycare centers during the day. Still few studies exist on evacuation of young children, such as daycare centers or other places were a large number of children are located [1,22–24] Hence, there exists very little data and no model describing walking speeds, flow or densities particularly of children of this young age.

The aim of this paper is to bring the fire safety community a step closer to including children in fire safety design, by introducing movement parameters and an empirical model describing evacuation of young children. Attention is also brought to the difference between adults and children, when it comes to evacuation. Behavioral aspects are investigated and discussed to increase the understanding of children´s evacuation dynamics and therefore contribute to safer buildings for children. The parameters investigated are velocities and flow on stairs and through doors as well as the relevance on automatic fire alarms, and the need of aid during the evacuation. It shall be seen whether the current data on adults is conservative enough to keep children safe in buildings.

METHOD

The data presented in this paper are the results from a study on fire evacuations of Danish daycare centers. It is not obligatory to have fire drills in daycare centers in Denmark. Hence, this was the first time for many of the daycare centers to perform a full scale evacuation. In fact, the fire drill was a first time experience for all children which were currently enrolled in the daycare centers and many of the staff. Ten daycare centers all located in Lyngby municipality, a suburb of 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 1017 persons, where 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.

All in all there were performed sixteen full scale evacuation experiments, in the form of fire drills. The evacuations were filmed in order to collect data; other forms for data collection were interviews with staff, time taking, measurements and observation on site. The fire drills were more or less unannounced for the children, but most of the daycare centers staff was prepared.

The course of action was typically:

- Arriving at the daycare center and talking to the contact person.
- Setting up cameras, focusing on the exits.
- Turning the cameras on, one by one.
- Fire drill starts, fire alarm/verbal warning.
- Evacuation to outside.
- Gathering at assembly point, waiting for "all clear".
- Discussing the fire drill with the older children.

In order to make fire safety design cover children and daycare centers, the relevant evacuation characteristics for the group need to be described. The goal of this study is to deliver empirical relevant design parameters as well as a few guidelines to consider in fire safety design for children.

Most of the data was collected using cameras, the basic set-ups and measurement techniques will now be briefly described. The recorders were partially exposed and out of reach for the children.

The densities measured during the flow measurements are local person densities in front of the doors, where tape markings or standard size mats were used as reference. Each measuring point marks a continuous flow of 6–51 people, which occurred during the experiments. The walking and running speeds were calculated by measuring the time it took children to pass fixed points. A child was defined as running if both feet left the ground simultaneously.

The travel speed on the three spiral stairs was calculated by measuring the length of the travel path and dividing with the time each person spend on the staircase. The travel speeds on spiral stairs are therefore individual averages, where fluctuations within the stair are neglected.

The films were analyzed for walking speed in horizontal plane and spiral stairs and flow through doors as described above as well as behavioral pattern. In general it must be stated that more data is necessary to prove statistical validity. Hence the results presented in this work are not general, but indicate trends. The data and model refer to homogeneous population of children only.

RESULTS AND DISCUSSION

The results presented in this section give information on flow through doors, walking speed in a horizontal plane and spiral stairs. An empirical model is developed, which enables the description of flow through doors. In Danish daycare centers children are divided into the two age groups, 0–2 years and 3–6 years. This enabled a separation of the results describing these two age groups.

Flow Through Doors – Empirical Model

The flow through doors is presented in Fig. 1. The boxes mark measuring points for the older age group, aged 3–6 years and the circles mark the measuring points for the younger children, aged 0–2 years. Trend lines for each of these measurement series are also plotted as well as Nelson and Mowrer's widely used flow curve for comparison [7].

It can be seen in Fig. 1 that for the older children the highest flow measured in a single measurement was above 3 pers/s m at a person density 5 pers/m², but the trend line peaks at a person density around 8 pers/m² with a flow of around 2.5 pers/s m. For the younger children the highest flow measurement was also made at a person density 5 pers/m² but here the flow was just above 1.5 pers/s m and here the trend line has a peak with a flow of around 1.25 pers/s m at a person density of approximately 6.5 pers/m².

For the age group 3–6, adults were rarely a part of the measured flow, because the children were in most cases eager to evacuate and the staff waited until last to exit. However more adults evacuated among the children aged 0–2 years, since many needed assistance and guidance. There are also more adults caring for the younger children on a daily basis. When comparing to Nelson and Mowrer's flow curve it is clear that the older children exceed that curve while the younger children do not. This comparison does not take into account different sizes of people, the fact that physically there can be more children located in one square meter than adults.

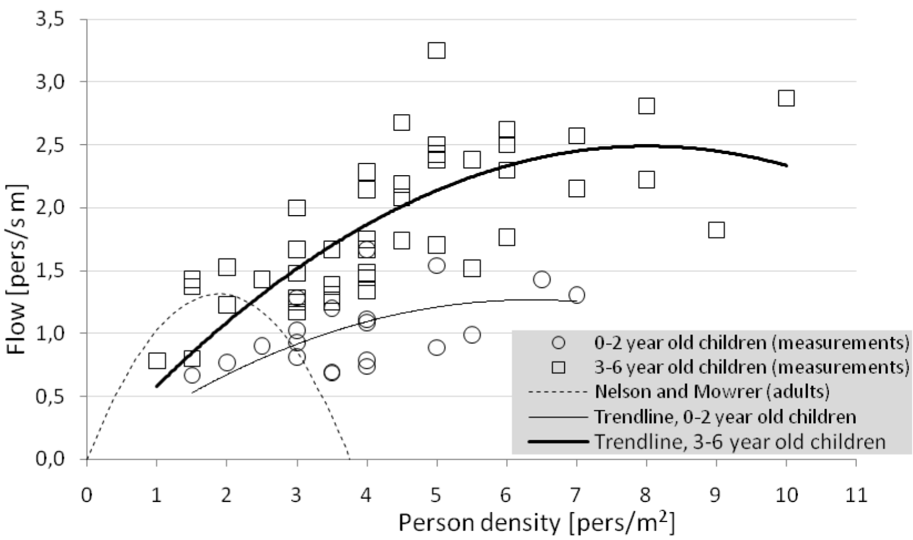

Fig. 1. Flow through doors. Mesurements on children [1] and their trendlines, compared to Nelson and Mowrers flow curve [7].

Nelson and Mowrer's flow curve has been published in numerous handbooks and other relevant publications on fire safety [7,25] where flow in the unit pers/s per meter effective width is shown with respect to person density in the unit pers/m². This formulation applies to homogenous populations only. Due to the nature of daycare centers, there will always be some adults among the children when evacuating and the results on flow presented in Fig.1 include 5–10% adults for the older children and 20–30% adults for the younger children. Even though populations (size wise) cannot be mixed using the approach above, it is more adaptive and easier to relate to than the correlations by Predtechenskii and Milinskii [16].

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.

The trend lines shown in Fig. 1 can be expressed by second degree polynomials (Eq. 1) with a fixed intersection at 0.0. The polynomial follows the expression of the SFPE Handbook [7]. Values relevant for age group 0–2 and 3–6 could be found for the constants *a* and *k*. Equation 1 gives the relation between the specific flow, F_S, in pers/s m and person density, D, in pers/m² for the two age groups. The equations for the trend lines are found by inserting $a_{0\text{-}2/3\text{-}6}$ and $k_{0\text{-}2/3\text{-}6}$ respectively.

$$F_s = (1 - aD)kD \qquad (1)$$

where:

$a_{0-2} = 0.079 \qquad a_{3-6} = 0.062$

$k_{0-2} = 0.399 \qquad k_{3-6} = 0.622$

The presented model is more conservative than the model of Nelson and Mowrer's flow curve for a density below 3 pers/m².

Movement Parameters

The results of the movement parameters found in the current study have been gathered and Table 1 shows an overview of those.

The flow was discussed in the previous section but is included in Table 1 to complete the overview. Walking speeds were measured in the horizontal plane at low person densities (< 0.5 pers/m²), where the children could move freely and independently of others. This also applies for the running measurements. Three spiral stairs were analyzed, and the results for all three are included in Table 1.

Table 1. Parameters for children´s movement during evacuation.

Parameter		**Children 0–2 years**				**Children 3–6 years**			
Flow (pers/s m)		$-0.031\,D^2 + 0.399\,D$				$-0.039\,D^2 + 0.622\,D$			
		Mean (m/s)	**Min.** (m/s)	**Max.** (m/s)	**SD** (m/s)	**Mean** (m/s)	**Min.** (m/s)	**Max.** (m/s)	**SD** (m/s)
Walking	Plane	0.60	0.30	0.98	0.17	0.84	0.42	1.36	0.25
	Stair 1	-	-	-	-	0.58	0.25	1.40	0.31
	Stair 2	-	-	-	-	0.38	0.29	0.48	0.07
	Stair 3	-	-	-	-	0.13	0.08	0.33	0.06
Running	Plane	1.14	0.90	1.80	0.30	2.23	0.83	3.24	0.64

A frequently used values used for adults' average walking speed in a horizontal plane at low person densities is 1.2–1.3 m/s [8,25]. Compared to the children's movement speeds presented here it can be stated that adults move faster. This difference can be linked to the body's proportions, as well as general physical development. However, Table 1 shows that when the older children run they exceed the common average walking speeds for adults, mentioned above.

Not all children in the younger age group were able to walk by themselves; hence fewer measurements were available for that age. This especially applies for running, since children cannot be expected to run efficiently until around age 2 or 3 [24]. The movement speed of children carried by adults or holding an adult's hand was excluded in this analysis, since in that case the child does not move freely and independent of others.

To give a better understanding of the results on the spiral stairs the three stairs will be briefly described. Stair 1 is an internal stair used by the children daily. It also has an extra handrail at a 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 compared to the other two stairs. The walking path was defined 0.25 m from the wider end of the stair.

Table 1 shows a remarkable difference in the movement speed on the stairs, despite their similar dimensions. The highest speeds were obtained in Stair 1, the stair frequently used by the children and with an extra handrail. This indicates that the children's familiarity of the stair and the stairs' child-friendly design, affected the movement speed to the better. This is supported by the extremely low speeds measured in Stair 3 which the children were using for the first time and was not specially designed for children. The difference in variation can also be seen in Table 1. Again Stair 1 stands out with a high standard deviation. The recordings revealed that the first children rushed down the stair at very high speeds, but as more children gathered in and by the stair the movement speed dropped. Both Stair 2 and Stair 3 have a more steady movement speed, which is reflected in the low standard deviation.

A general average value for adults, travelling on spiral stairs of 0.5 m/s is suggested [25], nondependent on the width of the stair [10]. The width is not relevant since persons usually walk in a single row in spiral stairs, because of the narrow steps near the center. This was confirmed in this study; although a few passes were made when a child stopped in the middle of a stair.

When comparing the results presented in Table 1 to the known literature for adults it can be seen that the children generally move slower than adults.

The high movement speeds achieved on Stair 1 and the slow speeds on the other two stairs supports the conclusion of Murozaki's and Ohnishi's study [23], which states that familiarity with the evacuation route is a leading factor to a achieve a fast evacuation.

The Effect of Alarm System on Pre-evacuation Time

The effect of automatic fire alarm on pre-evacuation time was studied, that is the time from "detection" until evacuation started. In this analysis the definition on when a person starts to evacuate is that when it leaves the current room, and is therefore clearly started to evacuate. This definition has been used when studying apartment buildings [6] and is convenient in this case, as the cameras were focused on the doors. Another advantage is that the definition is clear, and no interpretation is needed during the analysis on whether or not the movement is connected to the evacuation or not.

Figure 2 shows a box plot for the pre-movement times, where pre-movement times in daycare centers with an alarm/warning system can be compared to the pre-movement times in the daycare centers that do not have any. Having no alarm or warning system meant that an adult went around the daycare center and gave a verbal warning or a message to evacuate. In one case an internal phone system was used as aid, and in one case a small hand bell was used to get attention. These were categorized in the no alarm group, along with three other daycare centers. In three daycare centers a smoke detector was used for warning and those are categorized in the alarm group along with two daycare centers with automatic alarm and warning systems, who also call the fire department and close some doors.

The horizontal lines in the box plot represent the lower quartile (25th percentile), the median (50th percentile) and the upper quartile (75th percentile) respectively. The whiskers show the lowest/highest value still within 1.5 IQR (inter-quartile range) of respectively the lower/higher quartile. The outlier (× mark) represents the maximum value since it is outside the range of the whisker.

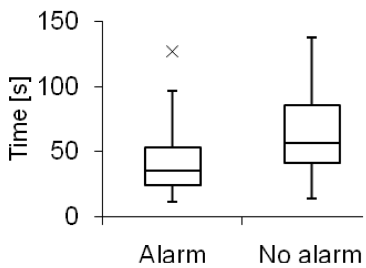

Fig. 2. A box plot showing the pre-evacuation time seperately for daycare centers with an alarm and without an alarm.

Figure 2 indicates that there is longer pre-movement time if no alarm or warning system is installed. The analysis revealed that the difference mainly lies in the warning time and not the reaction or decision making. The reason for this might be that in both cases (alarm or no alarm) an adult verbalized the evacuation signal. That is few children started to evacuate before verbally getting instructions on doing so from a nearby adult.

The size and design of the daycare center as well as the warning procedure itself were key factors in the total warning time, where there were no alarms. The pre-movement time varied also more as can be seen in Fig. 2, since some received the warning simultaneously with the start, while the ones located far from the initial starting point got a delayed warning. The maximum delay of warning registered in this study was 95 s.

Need of Assistance

In this section the involvement of adults in the evacuation process is described. Fig. 3 presents the amount of assistance provided to the children during the evacuation, separately for the two age groups. The vertical axis shows the amount of children as a percentage and the horizontal axis shows the three different levels of assistance. The white boxes represent the younger age group and the gray boxes present the older age group.

There is a difference between the three levels of assistance. Some children were carried by an adult, which provides the most assistance available. Some received physical help, which includes handholding, gently pushing towards exit or assistance in steps or standing up, in fact all forms of physical help, except for carrying. The third level consisted of verbal commands only, which categorizes the children who evacuated after receiving verbal instruction on doing so but without any physical assistance.

Figure 3 shows a clear difference between the ages as mentioned earlier. While more than 80% of the older children evacuated without physical assistance only around 20% of the younger children did the same. This shows how important the adults are during evacuations of children.

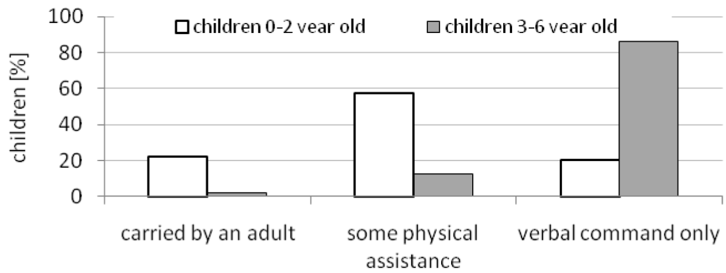

Fig. 3. Comparison of level of assistance during evacuation for the two age groups. Vertical axis: amount of children in %. Horizontal axis: three levels of assistance.

The level of assistance during evacuation might be reduced with training. As mentioned earlier the evacuations made in this study, were the first fire drills the children participated in. The films showed cases where children most likely needed more assistance because they were not familiar with the evacuation procedure. In one case some children stood still after the fire alarm sounded, because they had never heard the alarm before. In another case a child was carried outside because it did not want to leave their favorite hat behind.

Behavioral Considerations

It was found that the two age groups (younger children aged 6 months to 2 years and older children aged 3–6 years) not only vary from each other when it comes to travel speed and flow through doors, but also when looking at the behavior. An example of a behavioral difference is that very few of the younger children ran during the evacuations (about 5%) compared to the older children (about 40%). This may be caused by several reasons. The recordings indicate that one factor might be that while the younger children were hesitating on evacuating, seeming a bit confused or surprised, many of the older children were excited and raced to the exits. However 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.

Another behavior that was noticed is that the children were keen to follow the rules and daily routines of their daycare center, during the evacuation, and some were reluctant to make exceptions. Some children started changing to outdoor shoes, others stopped in front of the door to zip up their coats. This also meant that most of the children obeyed the adults, without questioning their reasons. This form for role-rule model is likely at its strongest level, due to the young age of the children.

It was interesting to see other behaviors, known from general evacuation theory. Some children initially went for the main door of their group room, when receiving instructions on evacuating, even though the room had a direct exit to the outside. This is well known as affiliation theory, when people tend to use the evacuation paths and exits they are most familiar with, even though others might be closer or safer. There were also a few children who worried about their younger siblings, located elsewhere in the building. This behavior is seen where people will not evacuate without a family member, although in this case the children did not act on it, but only expressed their concern.

CONCLUSION

This paper presents an overview of characteristics relevant for children's evacuation, who in the long term can contribute to fire safety design guidelines and practice. The data was originally collected from sixteen full scale evacuation experiments, in ten Danish daycare centers. The evacuations were filmed and analyzed to collect information on movement speeds in a horizontal plane and in spiral stairs as well as flow through doors. Assistance during the evacuations was also investigated as well as alarm system's effect on pre-evacuation time. Interesting findings were also made concerning the children´s behavior during the evacuations.

All in all the results show that there is a difference between adult's movement characteristics and children's. Regarding the flow through doors, the children´s flow exceeded Nelson and Mowrer´s flow curve for adults, but only at person densities above 3 pers/m^2. An empirical model is developed for the flow in a form of a second degree polynomial, describing the flow through doors. The equation has the same format as the equation for specific flow in the SFPE Handbook [7] but new values are provided for the constants, fitting it to either 0–2 year old children or 3–6 year old children.

Looking at movement speed in horizontal planes it can be said that children move slower than adults and that younger children move slower than older ones. When running, the children were however able to exceed the commonly average walking speed for adults. A large variation could also be seen in the dataset concerning the older children running. This can most likely be explained by the large variation in motor skills at that age, and the relatively large age gap. It can be concluded that the walking speed for children deviates from the data obtained and applied from literature.

The results on the movement 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.

The effect of alarm systems or warning systems on the pre-evacuation time was investigated. It was seen that a system of such kind decreased the pre-evacuation time.

The level of assistance was also analyzed and a great difference between the two age groups was discovered, showing that most of the children aged 3–6 years old evacuated on verbal command only while most of the children 0–2 were either carried or received other physical help.

When looking at the behavior one of the interesting findings was that there was a clear difference between the younger and older age groups during the evacuations. The older children ran much more frequently towards the exit than the younger ones. Behaviors known from evacuation theory could also be spotted among the children such as role-rule model and affiliation theory.

Coming back to Nelson and Mowrer's flow curve, which generally is considered conservative it can be seen from the data presented in this paper that this is not the case at person densities below 3 pers/m^2, when it comes to children.

Evacuation models rarely consider children mainly due to lack of data and information on the field. This indicates that children's safety in buildings can be improved by providing the necessary data and knowledge on this important topic. More data is needed for further understanding on the subject and for future models to describe children's evacuation pattern and behavior.

ACKNOWLEDGEMENTS

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REFERENCES

[1] Larusdottir, A.R. and Dederichs, A.S., (2010) Evacuation of Children: Movement on Stairs and on Horizontal Plane, Fire Technology special issue. http://dx.doi.org/10.1007/s10694-010-0177-6

[2] *Nordic statistical Yearbook*, Nordic Council of Ministers, Nordic Council, 2009.

[3] Building Bulleting 100: Design for fire safety in schools, Department for Children, Schools and Families, EC2P 2EA, RIBA Enterprises Ltd (NBS), London, 2007.

[4] Wermiel, S.E., *The fire prove building*, The Johnson University press, London, 2000.

[5] Sørensen, L.S., *Brandfysik og brandteknisk design af bygninger*, Politeknisk Forlag, 2004.

[6] Proulx, G., (1995) Evacuation time and movement in apartment buildings, Fire Safety Journal 24, 229-246, http://dx.doi.org/10.1016/0379-7112(95)00023-M

[7] Nelson, H. E and Mowrer, F.W., "Emergency Movement," The SFPE Handbook of Fire Protection Engineering (3rd ed), DiNenno, P.J. and Walton, W.D. (ed), Society of Fire Protection Engineers, Bethesda, MD, 2002, pp. 3-367-3-380.

[8] Proulx, G., "Movement of People: The Evacuation Timing," The SFPE Handbook of Fire Protection Engineering (3rd ed), DiNenno, P.J. and Walton, W.D. (ed), Society of Fire Protection Engineers, Bethesda, MD, 2002, pp. 3-341-3-366.

[9] Nilsson, D., "Exit choice in fire emergencies," Ph.D. thesis, Department of Fire Safety Engineering and Systems Safety, Lund, Sweden, 2009.

[10] Frantzich, H., "En modell för dimensionering av förbindelser för utrymning utifrån funktionsbaserede krav," Technical report 1011, Department of Fire Safety Engineering, Lund University, 1994.

[11] Frantzich, H., "Utrymningsvägars fysiska kapacitet, sammanställning och utvärdering av kunskapsläget," Technical Report 3069, Department of Fire Safety Engineering, Lund University, 1993.

[12] Proulx, G. and Reid, I.M.A., (2006) Occupant behavior and evacuation during the Chicago cook county administration building fire, Fire Protection Engineering 16: 283-309, http://dx.doi.org/10.1177/1042391506065951

[13] Steffensen, F. B., "Brand og brandsikkerhed i forsamlingslokaler et fælles ansvar," Technical report, Københavns Brandvæsen, 2000.

[14] Ravn, K., "Undersøgelse af Reaktions- og Beslutningstid," Master thesis, Technical University of Denmark , 2008.

[15] Bryan, J. L., "Behavioral Response to Fire and Smoke," The SFPE Handbook of Fire Protection Engineering (3rd ed), DiNenno, P.J. and Walton, W.D. (ed), Society of Fire Protection Engineers, Bethesda, MD, 2002, pp. 3-315-3-341.

[16] Predtechenskii, V.M. and Milinskii, A.I., *Planning for Foot Traffic Flow in Buildings*, Stroiizdat Publishers, Moscow, 1969.

[17] Shields, T.J., Smyth, B., Boyce, K.E. and Silcock, W.H., (1999) Towards the prediction of evacuation behaviours for people with learning difficulties, Facilities 17 (9/10): 336-344, http://dx.doi.org/10.1108/02632779910278746

[18] Nisser, M., "Utrymningssäkerhet för rörelsehindrade," Technical Report, Räddningsverket, Sverige, 2001.

[19] Gwynne, S.M.V., Boswell, D.L. and Proulx, G., (2009) Understanding the Effectiveness of Notification Technologies in Assisting Vulnerable Populations, Journal of Fire Protection Engineering 19: 31-48, http://dx.doi.org/10.1177/1042391508095094

[20] Bruck, D. and Thomas, I., (2008) Comparison of the Effectiveness of Different Fire Notification Signals in Sleeping Older Adults, Fire Technology 44: 15-38, http://dx.doi.org/10.1007/s10694-007-0017-5

[21] Bruc*k, D.*, (1999) Non-awakening in children in response to a smoke detector alarm, Fire Safety Journal 32 (4):369-376, http://dx.doi.org/10.1016/S0379-7112(98)00035-6

[22] Larusdottir, A.R. and Dederichs, A.S., "Evacuation dynamics of children: Walking speeds, flow through doors in daycare centers," Proceedings of the Fifth International Conference on Pedestrian and Evacuation Dynamics 2010, NIST, Gaithersburg, USA, 2010.

[23] Murozaki, Y. and Ohnishi, K. (1985) A study of fire safety and evacuation planning for pre-schools and day care centers, Memoirs of the Faculty of Engineering Kobe University 32: 99-109.

[24] Kholshevnikov,V.V., Samoshin, D.A. and Parfenenko, A.P., "Pre-School and School Children Building Evacuation," Proceedings of the Fourth International Symposium on Human Behaviour in Fire 2009, Robinson College, Cambridge, UK, 2009.

[25] *Brandskyddshandboken*, Rapport 3134, Department of Fire Safety Engineering, Lund University, 2005.

Paper III

Paper III focuses on evacuation of school children when descending stairs. It has been submitted to Fire and Materials.

Movement down stairs during elementary school fire drills

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ABSTRACT

Fire Safety within building design is required to be flexible to meet the demand of user and architects; fire safety within building design is also required to be sustainable and even fulfill social aspects of sustainability as well as Universal Design – a requirement posed by society. This is done by applying performance based codes and accounting for the fire safety for the entire population in a building irrespective age. Knowledge on the evacuation characteristics of the entire population, covering all ages, is needed in order to provide an equal safety level for all. The current experimental study provides qualitative and quantitative information regarding evacuation on stairs for children and youth aged 6-15 years. The study bases on full scale fire drills performed in Denmark. It was found that the walking speed of children changes with age and converges towards the walking speed of adults with increased age. It was found that handholding decreased with age, going from 100% for class 0 (6 six year old children) to 29% for class 2 (9 year old children). For higher classes the frequency of handholding was less than 5%. Amongst children in class 0 it was observed that 19% of the children either descended placing both feet on each step or occasionally did so. This walking pattern could not be seen amongst older students. The results of the present study indicate that it is not conservative to apply adult´s models for children at low person densities. On the other hand children generally obtained higher speeds, at high densities, than adults do according to nowadays models.

KEYWORDS: *Children, elementary school, evacuation, fire drill, stairs.*

INTRODUCTION

6260 fires in educational properties occurred during the years 2005-2009 in the United States where 72% of these fires happened in nursery, primary and high schools. The fires cost 68 civilian injuries. 83% of the fires occurred in the hours between 6am and 6pm, when children and students might be in the buildings [1].

Building regulations applying performance based codes, demand that people can escape to safety in case of fire, as in Denmark [2]. The required safety level can be achieved by following prescriptive rules providing a certain empiric level of safety or by applying fire safety engineering methods. The latter demands that no one may be exposed to critical conditions, regardless of age and physical condition. This includes schools, private or public, where a majority (97.8% in the US) of children spend a large part of the day [1]. School buildings are often designed in a traditional way, where prescriptive codes are used. However, for designing by performance based codes being a safe option it is important to have information concerning evacuation characteristics of children and youth available.

Furthermore, the demand for sustainable building design is outspoken in society. Besides environmental factors, sustainability comprises social factors [3]. Social quality implies the consideration of all users of a building in the design, ensuring equal opportunities for all occupants. In the context of fire safety design, this means egressibility. In sustainable fire safety design no parts of the population are disabled when it comes to egress. To meet these requirements, the evacuation of all parts of the heterogeneous population needs to be investigated qualitatively and quantitatively.

Still, most available data and qualitative studies are on abled-bodied adults. This means that children and youth spend a lot of time in buildings, which perhaps are most suited for adults when it comes to evacuation. Previous studies have shown that data based on adult's movements differ from data from children in preschool [4] as well as school [5]. Even though some handbooks and design guides mention special measures regarding children, there is a lack of research supporting the statements and quantifying the difference. At the time being there exists neither an explicit evacuation theory including movement parameters that applies for children nor a guideline stating when it is appropriate or realistic to apply adult´s values regarding evacuation, on children and youth. All in all literature provides very limited data on children´s movement parameters and evacuation behavior.

An increasing number of studies on evacuation consider groups of the population, which earlier have been neglected, including children. The aim and scope of the existing studies are different. One of the studies is by Shaobo et al [6] and contains results from experiments and cellular automaton evacuation simulations on the flow of schoolroom evacuation. Neither age nor the behavior of the participating children is discussed. The focus here is on geometric aspects and obstacles in the evacuated room.

In 2002 Klüpfel et al [7], performed a comparison of an evacuation exercise in a primary school to simulation results. The two goals of the work are stated to be the validation of model assumptions and the verification of simulation results. The data was taken applying video recordings of children in the age range 6-10 years. The total evacuation times were found to be 1.6 times larger than when the standard population was applied. It is also pointed out that the amount of taken data is too little for providing statistical validity. The age distribution affected the evacuation characteristics and times.

Kholshevnikov et al [8] presented data in 2009 on the evacuation of children from school buildings. Some data was presented on the velocity of children on stairs in the density range of 0.5-4.5 persons/m^2. The children were subdivided into two age groups of 6-10 years and 11-15 years. The velocities seemed to decrease with age, the opposite trend was found in a study by Lu [10]. Studies by Capote et al [9] and Ono et al [11], which base on fire drills in schools both include travel speed on stairs. Some similarities can be seen between those and the current study presented here, however some parts and results cannot be compared directly, either due to different methods or lack of detailed information. However, still more data on children is needed for model validation. Data with a more narrow differentiation in age would be preferable.

This paper presents new results on children´s and youth´s movement down stairs. The data was collected by filming fire drills in elementary schools in Lyngby, Denmark. The data collection was carried out in September and October 2010. The films were among other things analyzed for travel speed and evacuation behavior while moving down stairs.

METHOD

Seven elementary schools in Lyngby-Taarbæk municipally, a suburb north of Copenhagen, Denmark, participated in evacuation experiments in the present study. In Lyngby-Taarbæk municipally, less than 0.05 % of children are homeschooled according to the local educational office. The evacuation experiments were in the form of full scale fire drills, where all occupants evacuated to out-doors on a signal. The evacuations were carried out in the period of September 24th to October 26th 2010 on normal school days. The fire drills were partly unannounced, the teachers knew the day, but not the specific time. The students were not notified except for the youngest children who were told about the fire drill, since this was their first one. However, some students were suspicious due to the cameras, while others thought they were set up for security reasons.

The evacuations were filmed with up to 59 video cameras, which had been placed around the school, either the day before the drill or the same morning. Most of the cameras were used to film the staircases and doors in the common evacuation routes, but there were also a few cameras located in classrooms to observe behavioral aspects in the initial phase of the evacuation. As the experiments were performed in a natural environment, the schools, mounting options and locations were limited. Commonly used mounting devices were vacuum cups used on windows/glass walls, elastic bands used on lamps and clamps or velcro strips used on ceiling plates and other inventory.

For starting the fire drills the local fire alarms were used. The type of alarm varied between the seven schools where four schools had a specific fire alarm, that is an alarm only used in case of fire, and the other three used the school bell for alarming (ringing in intervals or as it would ring to indicate a break). Furthermore, three of the schools had a spoken message before the audio alarm (either fire alarm or school bell). The children generally evacuated in the clothes they had on when the fire drill started. Typical clothing consisted of long pants, a t-shirt or a sweater and shoes.

During the analysis, each individual was followed all the way down, giving one data point (speed/density) for each flight of stair on the way out. This means that for each individual 1-5 data points were collected. The total number of students used in analysis of stair data was 667, resulting in a total of 1943 data points. The stair data was collected from 4 of the seven elementary schools that participated in the project. Three of which had similar overall design with two staircases each that were also similar in design and dimensions. The fourth school used for stair data was smaller and only with one staircase, however the staircase was similar in design and dimensions to the other ones used. Figure 1 shows one staircase from each school.

Figure 1. Staircases from the four schools where stair data was collected from.

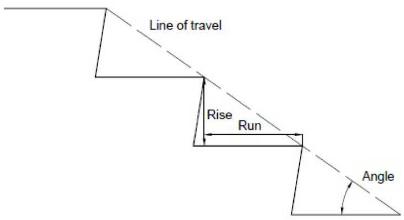

Figure 2: Definition of the line of travel, rise, run and angle of the stairs.

The definition of the steps and the stairs are explained in the following and can be seen in figure 2. The rise is the height of the steps, the vertical portion between each tread on the stair. The run is the depth. It is measured from the outer edge of the step to the vertical riser between steps or its vertical projection on the step. The stair dimensions were in the range of 16,5-18 cm rise and 27-28,5 cm run.

When determining the travel speed on stairs, the distance down a single flight of stairs, in line of travel (from floor to landing or vice versa) was divided by the time spent on the stair flight. The horizontal landings between flights of stairs are excluded from the stair data.

The average person density occurring on the stair over the time spent on the stair is used, when determining the person density belonging to a certain travel speed on the stairs. The person density on a flight of stairs is observed and registered every second. The appropriate average value is then calculated by using the person densities occurring the same seconds an individual spent on the flight of stairs. The person density was measured in pers/m^2 and the area used is the horizontal area (run in figure 2) of the steps in one stair flight added up. Each individual counts as one person in this analysis, regardless of age and size.

RESULTS & DISCUSSION

Figure 3 shows results for the travel speed down stairs, in m/s, in relation to person density, in pers/m^2. The results are displayed for two ages/classes in each graph. Linear trend lines are also displayed for each class. For reference a curve from Nelson and Mowrer [12] for travel speed down stair for adults is shown. The top graph in figure 3 shows experimental results for class 0 (6 years old), blue circle (O), blue thick solid trend line (–) and class 1 (7 years old), red triangle (Δ), red thin solid trend line (–). The distribution from literature, by Nelson and Mowrer, is shown with a thick black broken line (- -). The graph show the results for two classes at once, commencing with class 2 and class 3 and ending with class 8 and class 9.

The evacuation paths for classes 1 and 2 included only one flight of stair. Hence, the limited number of data points, 63 and 45 respectively. Furthermore, stair data for class 3 was retrieved from a single group of students using two flights of stairs on their way out, resulting in 28 measuring points. Data for other classes than 1, 2 and 3 (class 0 and class 4-9) base on 130-586 measurement points each.

Figure 3 shows that the speed for class 0 is generally below what literature suggests for adults. Only a few data points are above the curve from Nelson and Mowrer resulting in a trend line which is constantly below it. The children in class 0 are the youngest students in the Danish schools. They are therefore the smallest physically and relatively new to the surroundings, compared to older students. These factors are likely to have influenced the travel speed.

As mentioned earlier, there is limited data available for classes 1-3, whereas conclusions cannot be made with the same certainty. From the films it could be seen that class 1 and 3 travelled down the stair along with older students, which seemed to influence the travel speed of the younger ones, by making them more eager to keep up the pace.

For class 4 and 5 it can be seen that the trend lines are above the curve from literature. At the same time there are many measuring points located below it. It can also be seen that the data points are spread, even within the same density, indicating a large variation.

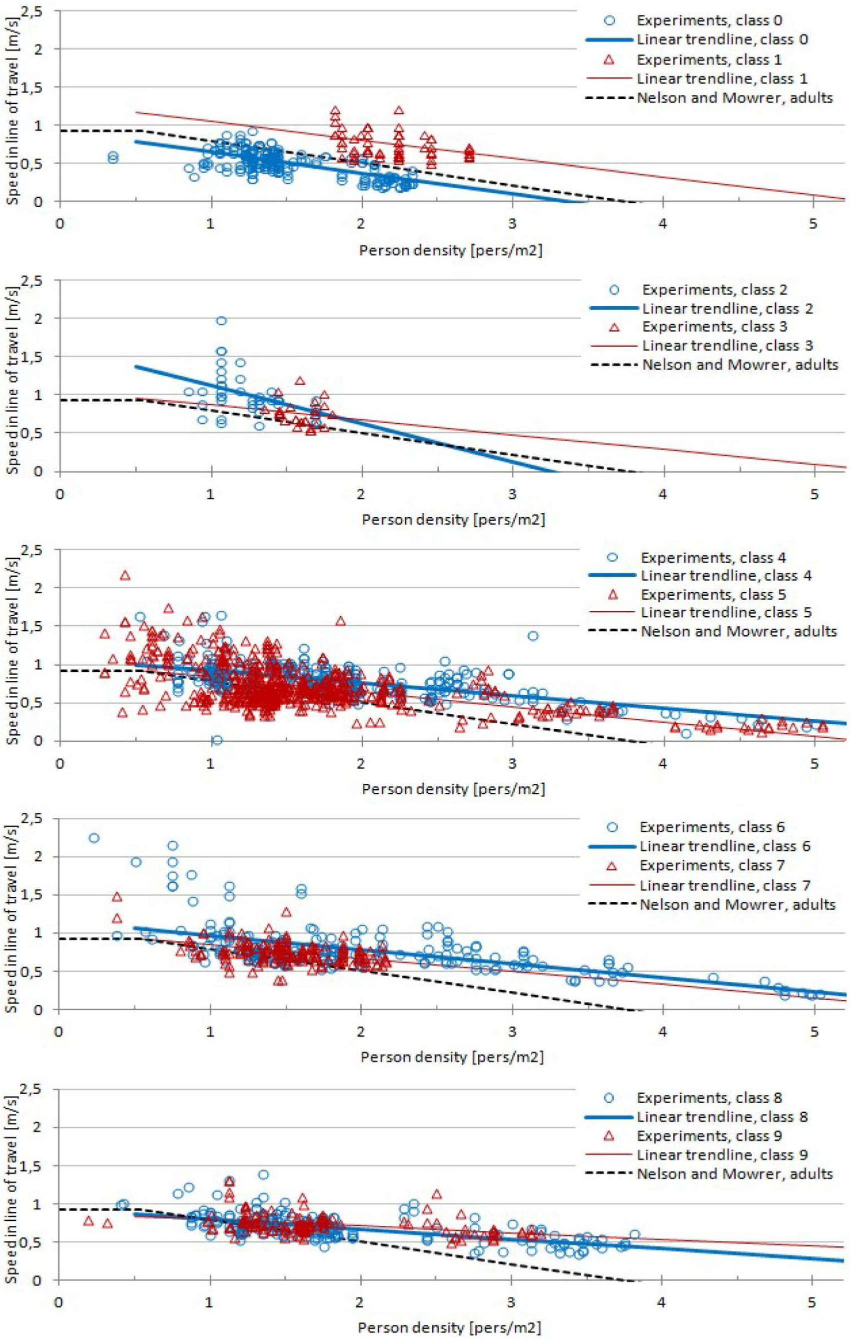

Figure 3. Travel speed down stairs for school children in classes 0-9 (6-15 years old) with respect to density. Two classes are displayed together in a graph along with the relevant linear trend lines. A curve from Nelson and Mowrer is also displayed in each graph with a thick broken line for reference [12].

Results for class 6-9 look somewhat alike, since there is only a limited number of measuring points below the curve from literature and the trend lines are relatively close to each other and above the curve from literature. Generally the results shown in figure 3 indicate that the travel speed on stairs increases with age and that by class 6 or age 12 it is reasonable conservative to use the Nelson and Mowrer curve to describe the travel speed. After that age the travel speed is somewhat constant. It can therefore be said that the children´s curves convergence towards the adult curve with age.

Figure 3 also shows that most measuring points are collected at a person density 1- 2 pers/m^2 and that classes 4-6 are the only ones with measuring points at a person density higher than 4 pers/m^2.

Results on handholding during school evacuations, previously introduced in [5], have been expanded and can be seen in Table 1. The table shows how the handholding decreases with age, where all students held hands in class 0 but in classes 4 and above only occasional handholding was observed. Furthermore, it can be seen that the children continue to walk in pairs, although they let go of the hands in classes 1, 2 and 3.

Table 1: Results on children´s handholding during elementary school evacuation.

	Class 0	**Class 1**	**Class 2**	**Class 3**	**Class 4-9**
Students holding hands [%]	100	82	48	29	< 5
Students walking in pairs but not holding hands [%]	0	18	44	29	
Students walking alone [%]	0	0	8	42	

The results shown in table 1 indicate that as the children get older, they do not to take the teacher´s instructions as literally, and in the same manner the teacher´s instruction becomes more general instead of detailed as the children in question are older.

When looking at the films it was observed that the degree of which the whole width of the stair was used varied. Two things were identified as main factors, age and merging flows. The age factor relates directly to the handholding, that is when the children are holding hands while travelling down the stairs, they walk in a double row close to one of the handrails. This means that almost half of the stair width is not occupied. However, if there were merging flows, the children occupied the whole stair width in most cases. When only occupying a part of the stair, the inner lane(s) were most frequently chosen. Figure 4 shows snap shots from the fire drills for different ages. All stairs have the width 1,70 ±0,05 m. It can clearly be seen that class 0 and class 2 do not occupy the whole width of the stair, in fact class 1 also only uses a part of the stair, but students form class 4 are using the other half. However, it can be seen that four students can use the stair parallel each other, two from class 4 and two from class 1. When taking a look at the snapshot from classes 4-5 evacuating it can also be seen that four children are walking down side by side. However, when looking at class 6-7 there were not seen more than three students walking side by side. It was also observed that even when only walking in pairs, as the younger children they tend to walk in the center of the stair, not using the handrails leaving little space for overtaking. Similar walking pattern was observed for classes 8-9; no more than three walked side by side, however, stacking pattern was more common. Every other step there were two students and in every other step there was only one in the center, making a quite equal distance between all students.

Class 0 Class 4 (left) class 1 (right) Class 2

Class 3 Class 4-5 Class 6-7 Class 8-9

Figure 4: Snap shots from the fire drills, showing how the width of the stairs was typically used. The stairs are all 1,70 ±0,05 m wide. This is the actual width of the stair and there has been no reduction made due to handrails, which in all cases are present on both sides.

Opposite to the handholding, overtaking in the stairs increased with age. At the ages where the children are holding hands and walking in pairs, there was no overtaking. However, as the age increased so did the overtaking.

Regarding walking pattern, as if the children step with one foot or two feet on each step, it was found that 75 % of the children in class 0 or 6 years old stepped with one foot on each step, 10 % occasionally stepped with two feet per step, 9% consistently stepped with both feet down on each step at last 6% of the children dissented the stairs by jumping down step by step or two steps at a time. For other classes, this walking pattern of stepping with both feet on the same step could not be seen. This was investigated in [9] where it was found that 33% and 56% of children aged 4-6 years placed two feet on each step in two fire drills made in Spain. A comparison between the results of the two studies shows that in the present study it was less common to walk placing both feet on the same step. It is likely that this can be explained by the age difference of the groups compared. This walking pattern is typical for young children that are restricted by the physical length of their legs. As the children grow and their motor skills develop they become more secure when walking on stairs, and do not need to place two feet on every step.

When looking at the procedure and the evacuations in whole it can be said that the course of action was similar between schools. The fire drill was initiated using the warning method in place, the teachers and students left their classrooms and continued evacuation until outside. When at the meeting place each teacher took headcount and reported to a superior. While the youngest children as described above evacuate in a double row typically holding hands, the older children move more freely and blend in with other classes. Furthermore, the teacher for the older classes often evacuate as the last, while the teachers for the youngest students walk in front and lead the way out.

CONCLUSION

In order to provide equal egress for people in buildings irrespective age qualitative and quantitative studies are needed on young and elderly people. This paper provides results on children´s and youth´s movement down stairs. Travel speed and evacuation behavior while moving down stairs was quantitatively using video footage.

This experimental study provides qualitative and quantitative information on the evacuation of children in the age 6-15 years on stairs. It was found that the walking speed of children changes with age and converges towards the walking speed and behavior of adults with age. Handholding during the evacuations could be seen to decrease with age. Starting at 100% amongst 6 year old children and it was down to 29% amongst 9 year olds. Handholding occurred only occasionally at an age over that.

Furthermore, 19% of 6 the year old children used two feet per step while ascending or occasionally used two feet per step and 6 % were jumping. This behavior was rarely seen for children in the age groups above.

The use of the width of the stair was different and increased with age. It was related to the handholding since when the children held hands and walked in pairs, they only used a part of the stair and were never more than two side by side. However, where there were merging flows with other classes the whole stair width was occupied, around half a stair width by each class.

The results regarding travel speed and behavior during the evacuations indicate that as the children get older they obtain more free will and are able to interpret the situation independently and the instructions they get in a more logical way. The youngest children can be seen taking instructions very literally such as the handholding, being careful of not letting go. As the children get older they tend to loosen the grip and letting the hands go but still staying in pairs. However, the instructions from the teachers also develop with increased age of the children, going from detailed instructions on how to proceed during the evacuation to a more general note to start evacuation.

While the standards used for adults are not conservative for children at low densities, it could be seen that children tend to move faster than expected from adults at high person densities. Here one child corresponds to one person in the current density calculations, even though the child occupies less space. When looking at the evacuations in whole it can be said that the youngest children have the lowest travel speed on stairs and that as the children get older their travel speed increases. By the age of 12 their travel speed can, with reasonable safety, be described with the standards used today for adults on stairs.

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REFERENCES

[1] Evarts, B., *Structure Fires in Educational Properties (2011) PKG14*, 6/11, NFPA Fire Analysis and Research, Quincy, MA.

[2] Danish building regulations 2010, The Danish Ministry of Economic and Business Affairs, Danish Enterprise and Construction Authority. 2010

[3] Zinke, T., Ummenhofer, T., Pfaffinger, M., & Mensinger, M. (2012). The social dimension of bridge sustainability assessment - Impacts on users and the public. In B. &. (Eds) (Ed.), *Bridge Maintenance, Safety, Management, Resilience and Sustainability* (pp. 1836-1843). London: © 2012 Taylor & Francis Gr

[4] Larusdottir, A., R. ; Dederichs, A. S., Evacuation of children - movement on stairs and on Horizontal Plane, Fire Technology, 48: 1, pages: 43-53, 2012 DOI: http://dx.doi.org/10.1007/s10694-010-0177-6),

[5] Larusdottir, A., R. ; Dederichs, A. S., Behavioral Aspects of Movement Down Stairs During Elementary School Fire Drills, Proceedings of the Human Behaviour in Fire Symposium 2012, 2012

[6] Shaobo, L., Lizhong, Y, Tingyong, F., Jian, L., Evacuation from a classroom considering the occupant density around exits, State Key Laboratory of Fire Science, University of Science and Technology of China, Hefei 230026, Anhui Province, PR China 2009

[7] Klüpfel H., Meyer-König, T., Schreckenberg, M., Comparison of an Evacuation Exercise in a Primary School to Simulation Results,Traffic and Granular Flow'01, 2003, pp 549-554.

[8] Kholshevnikov VV, Samoshin DA, Parfenenko AP (2009) Pre-school and school children building evacuation. State Moscow University of Civil Engineering, Academy of State Fire Service of Russia, Moscow, Russia

[9] Capote, J.A., Alvear, D., Abreu, O., Cuesta, A.; Hernando, J., Children Evacuation: Empirical Data And Egress Modelling , Fifth International Symposium on Human Behaviour in Fire, 2012.

[10] Lu, C., The Evacuation Training Problems of an Earthquake in China, Pedestrian and Evacuation Dynamics 2011, pp 121-127

[11] Ono, R. Valentin, M.V., Vittorine, F., Walking speed data of fire drills at an elementary school, Fifth International Symposium on Human Behaviour in Fire, 2012.

[12] Nelson, H.E. & Mowrer, F.W., 2002. Emergency Movement. In: *SFPE Handbook of Fire Protection Engineering.* Quincy, Massachusettes: National Fire Protection Association, pp. 3-367 - 3-380.

Paper IV

Paper IV focuses on evacuation of children from daycare centers when descending stairs. It has been submitted to Fire Technology.

Evacuation of young children from multistory daycare centers: Travel parameters down stairs

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Abstract

This study aims at filling in a gap, concerning young children´s travel parameters, where few previous studies account for children's travel speed down stairs. The study bases on fire drills that were performed in nine daycare centers located in Copenhagen, Denmark, with children aged 6 months to 6 years. The fire drills were filmed and data extracted on travel speed, assistance from adults and handrail use. Two age groups were analyzed separately, 0-2 years and 3-6 years. Seven of the daycare centers contribute to the results on travel speed down stairs. The findings confirm that there is a difference between the two age groups, where the younger age groups, children under 3 years have a lower travel speed, receive more assistance from adults and use the handrail more than the older age group. Travel speed for children under 3 depends on the level of assistance received, while the travel speed for children aged 3-6 years old is not related to the assistance in the same way. At person densities lower than 3 pers/m^2 the travel speeds for children are generally lower than what is suggested for adults, with the exception of when young children are carried. Comparison shows that the travel speeds found in the current study are on average lower than other studies have found for same or similar age groups. The results also show that when children travel down stair unassisted they achieve on average a higher travel speed when using a handrail which is at children´s height compared to using a handrail intended for adults.

1. Introduction

For decades very limited attention has been brought towards evacuation of children. Children at young age are not capable of moving like adults and show different behaviors than adults. However, there has not been a quantifying description of the difference with respect to fire safety engineering and evacuation. Most evacuation theories base on studies and experiments, where able bodied adults are the subjects [1][3]. Many other subgroups of the population have therefore also been neglected. However, for recent years the general evacuation theory has begun to expand by describing vulnerable populations [4][7] that were previously only mentioned at the most, children being one of them [8][9].

The term "children" covers a wide age range, legally from birth to eighteen years in most western countries. The same performance cannot be expected from all age groups, regardless of the field or subject in mind. When looking at fire safety a few important factors that affect the ability to evacuate safely can be mentioned. Firstly children´s anatomy and motor skills develop from a baby unable to move to the full grown body, also their communication skills, rational thinking and knowledge on fire safety increase throughout the childhood. A report from NFPA presents results on an investigation through online questionnaires regarding self-preservation of young children, where key questions to be answered were at what age children can be expected to walk down stairs without assistance and at what age children can be expected to follow simple instructions [10]. An example of differences between children and adults that has been proven is that children are less likely to wake up to the sound of smoke detectors, compared to adults [11].

Literature background

Studies that provide information on evacuation dynamics and behavior of children and focus on buildings with mass stay of children, such as daycare centers and schools are limited. The first one published is a study on daycare centers performed in Kobe, Japan in 1985 by Murozaki and Ohnishi [13]. The focus of the research was on evacuation of children aged 1-5 years using stairs and slides. A study by Kholshevnikov et al. from 2009 also investigates evacuation of daycare centers for children [8]. The focus of that study is on human behavior and travel parameters. A new paper by Kholshevnikov et al. [14] based on the same study represents the largest amount of data available so far on young children.

At least three recent studies provide new data on evacuation of elementary schools by Capote et al. [16] (including pre-school), by Ono et al. [17] and Larusdottir et al. [18]. The last mentioned suggests an age of where children´s movement down stairs can be described by the general evacuation theory for adults.

Objectives

The present study aims at filling in gaps of previous work on the subject evacuation of children from daycare centers, focusing on travel speed down straight stairs. Results on travel speed down spiral stairs were introduced for the age group 3-6 years old in [19][20] as well as flow through doors and free travel speed on horizontal plane for the age groups 0-2 years and 3-6 years old. Need of assistance, effect of fire alarm on pre-evacuation time and other behavioral aspects were described in [20]. As a part of the present study nine full-scale fire drills were performed in daycare centers located in down town Copenhagen. Results concerning evacuation of children aged 0-6 years down stairs are presented in this paper as well as some other findings regarding evacuation of young children. Where relevant the results will be compared to the data set mentioned above from Kholshevnikov et al. [14] as well as to Murozaki´s [13] and Capote´s results [16].

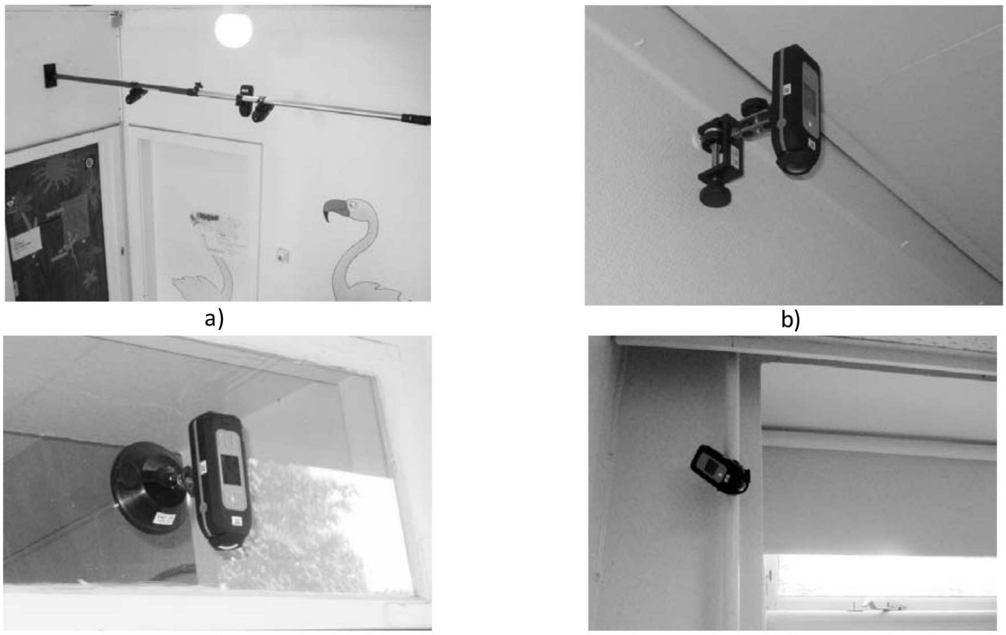
2. Method

To view the children in a natural environment, the data was collected during fire drills in nine daycare centers down town Copenhagen. The Copenhagen Fire Department assisted with finding daycare centers in multistory buildings. The goal was to gather data on travel speeds down stairs and to observe the evacuation.

Cameras and setup

The fire drills were filmed using up to 59 cameras located as discretely as possible covering most areas of the daycare centers, with special focus on the stairwells. Due to ethical reasons, the parents were consulted about the filming, since filming and taking pictures of children is a sensitive issue.

The cameras used for filming were compact action cameras with a 170° wide angle lens which made it possible to capture a large area with a single camera. As the experiments were performed in a natural environment the location of cameras was limited to temporary mounting solutions, meaning that no drilling was allowed. A number of different solutions were available. In the staircases the cameras were often located on vertical pressure bars that were temporary mounted over the landings. This ensured a good view of the stairs. This was also used in hallways. Figure 1 a) shows an example of a pressure bar with three cameras, one pointing straight down to view the landing and two cameras each focused towards one flight of stairs. Other options were multipurpose clamps, vacuum cups for windows and pipe fasteners. Examples of these can be seen in figure 1 b) c) and d). At last there were velcro stips (not shown) that could be connected together depending on the need at each time, these were typically used around columns or even trees if filming outside.



a) b)

c) d)

Figure 1. Four examples of mounting devices for the cameras.

Stairs

Eight stairs in seven different daycare centers were used to produce the data presented here. The main dimensions and characteristics of each stair are described in table 1. It can be seen that the slope of the stairs varies from 30°- 41°.

Table 1. List of stairs used in this study.

Stair	# floors	Type	# landings between floors	Users age [years]	Width [m]	Slope [°]
A	5	three flight of stairs with quarter landings	2	0-2	1.15	30
B	5	straight stair flight	0	0-2	0.95	41
C	2	half-turn staircase	0	0-2	0.90	35
D	5	two flight of stairs with half landing	1	0-2 & 3-6	0.91	35
E	3	two flight of stairs with half landing	1	0-2 & 3-6	1.00	29
F	2	straight stair flight	1	3-6	1.00	33
G	3	half-turn staircase	0	3-6	0.96	34
H	4	two flight of stairs with half landing	1	3-6	1.00	40

Figure 2 shows pictures of the eight stairs. The pictures also show if there are handrails present. It can be seen that three out of five stairs used by children aged 0-2 years have a low handrail on one side, namely stairs A, B and C. The height of the low handrails, measured perpendicular from the horizontal surface of the steps was 34-44 cm for stair A, 40-50 cm for stair B and 61 cm for stair C.

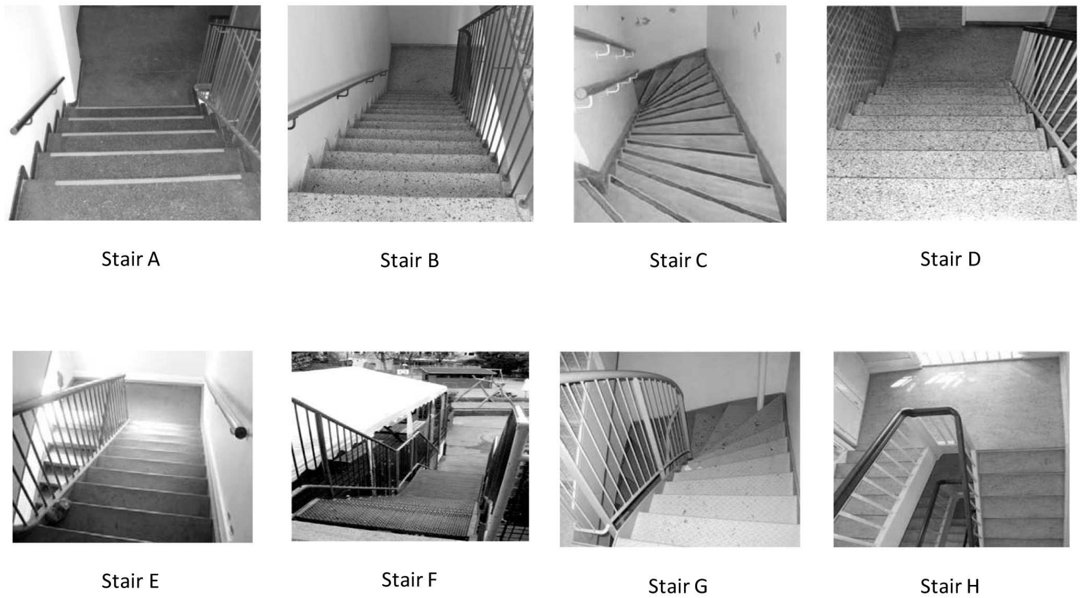


Figure 2. Pictures showing the eight stairs used in this study.

Analyzing of data

Video files from the drill were analyzed extensively with respect to evacuation down stairs, where differentiations were made between the age group 0-2 years old and 3-6 years old. Even though more detailed age differentiation would be preferable the Danish daycare system categorizes the facilities according to these two age groups, where some daycares are integrated to facilitate both age groups. It was evaluated that further deviation by marking of the children would interfere too much with the evacuation and compromise the validity of the evacuation data. In addition to speed and density the assistance from adults as well use of handrail was registered. Adobe Premiere Pro CS5 was used for analyzing/playback and Microsoft Excel was used for data organizing and processing.

The travel speed is measured as the distance travelled in line of travel divided with the time it took to cover the distance. The density belonging to each speed is the average density occurring on the stair while the travel speed was measured. This is found by keeping track of the number of persons located on the stair part at every time step, in this case every frame. The information from the time steps while a person in question is on the stair is used for taking the average. The area used in the density calculation is the horizontal area of the steps in one stair part added up. This is the same method used in [18] although the counting is made automatically with the help of excel instead of manually and the time steps are one frame instead of one second. For density calculations each individual was counted as one, irrespective of age or size which means that an adult carrying two children count as three.

For each child the assistance and use of handrail was noted. The assistance categories were carried, holding one adult´s hand, holding two adult´s hands or no assistance and the handrail categories were holding handrail or not holding handrail. If there were both high and low handrails present, it was noted which one was used.

3. Results & Discussion

The analysis resulted in a large amount of data points with travel speed down stairs for children and corresponding person densities. There are a total of 1089 data points for children aged 0-2 years and 547 data points for children aged 3-6 years. Each flight of stair passed by a child, or half a stair in cases where there were no landings between floors, produced a data point, meaning that each child has contributed with 2-10 data points depending on the evacuation route.

The travel speeds of the adults are excluded from the presented dataset, they have however contributed to the person densities measured. Data points are categorized by age group, 0-2 years or 3-6 years as well as by the level of assistance. The three categories of assistance are: children that are carried (so the travel speed is in fact the travel speed of the adult carrying the child), children that are assisted by handholding in one or two hands and children that travel down the stairs without adult´s assistance but might hold the handrails. In some cases adults guided the children towards the handrail where they then walked independently down the stairs, these cases are categorized as children walking by themselves even though they have received assistance during the evacuation.

Figure 3 shows the level of assistance within each age category. A difference between the age groups can clearly be seen where the younger children were carried and assisted by handholding in far greater extent than the age group 3-6 years old. These results comply with results from [19] where it was found that 85.9 % of the children aged 3-6 years evacuated on verbal command only (without physical assistance) and 20.2% of the children aged 0-2. Some physical assistance was received by 12.3% of children aged 3-6 and than the age group 3-6 years old. These results comply with results from [19] where it was found that 85.9 % of the children aged 3-6 years evacuated on verbal command only (without physical assistance) and 20.2% of the children aged 0-2. Some physical assistance was received by 12.3% of children aged 3-6 and 57.6 % of the 0-2 year old children. At last 1.8% and 22.2% of the children were carried in the age groups 3-6 and 0-2 respectively. The difference between the studies is that the present one only focuses on the stairs, while the previous looks at the initiation of the evacuation and the evacuation in general. The difference in results is mainly that more of the children in the younger age group are carried when on stairs, which also fits with the results of [10] stating that children are older when they can be expected to walk in stairs than on horizontal plane.

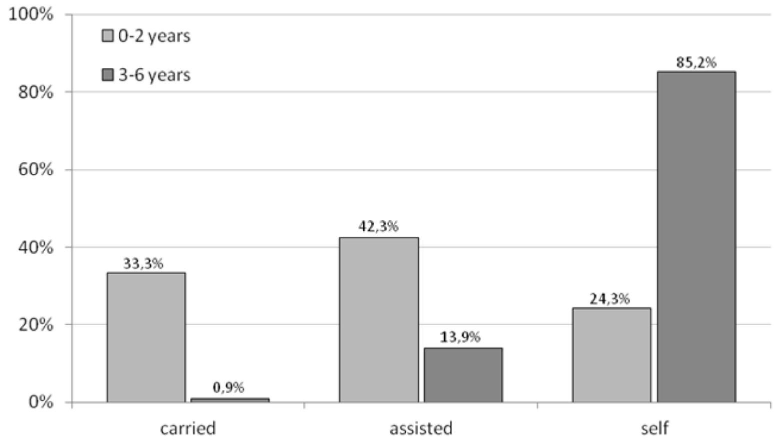


Figure 3. The level of assistance for the two age groups.

The graphs in figure 4 show travel speed down stairs in m/s with respect to person density in pers/m^2. As mentioned previously, there is no differentiation made between adults and children, when calculating the person density. A commonly used relationship between travel speed down stairs and person density is shown as reference in the six presented graphs [3].

To the left in figure 4, that is a), b) and c) data points for children aged 0-2 can be seen, starting with children being carried, then children being assisted and at last children descending the stair by themselves.

Figure 4 a) shows how the children that are carried have the highest travel speed. It can also be seen that there are many data points stacked at the densities 1.4 pers/m^2 and 2.1 pers/m^2, those data points come from one of the daycare centers where there are two on the stair (one adult carrying a child) and three on the stair (an adult carrying a child and holding the hand of another child). The figure shows a trend line, based on the assumption, of a linear development of the speeds as a function of density. The trend line shows that travel speed decreases with increased density as general evacuation theory suggests. The slope is however not nearly as steep as the slope for adults and the highest density measured was over 6 pers/m^2. The travel speed for the children who are assisted by handholding can be seen in figure 4 b), where the speed is clearly lower than for the ones carried. 83% of the data points are below the curve from literature, however at the higher densities the children´s travel speed exceeds the curve. The slope of the trend line for the children that are assisted is almost not existing, this indicates that the travel speed of children is not as effected by the person density as much as the travel speed of adults is according to literature. When looking at the travel speed of children walking themselves down the stairs in figure 4 c) it can be seen that most of the data points are below 0.2 m/s, in fact 81 % and 95 % below 0.3 m/s. Again the slope of the trend line is very little; supporting what was earlier seen indicating that children´s travel speed is less dependent of person density than adult´s travel speed. One explanation is that the children occupy less space than adults, meaning that an area does not feel dens. Another fact likely to influence is that young children do not mind being close to each other, even touching, while adults prefer having their private space intact.

Looking at figure 4 d) e) and f), showing the results for children 3-6 years it can first of all be seen that most of the children walked by themselves down the stairs and only five measurements on children 3-6 year old children being carried. It can also be seen that the data points are generally below the reference curve at person densities up to 2 pers/m^2. Between 2 and 3 pers/m^2 there are approximately equally many data points below and above the reference curve and at higher person densities than 3 pers/m^2 the children´s data points are generally above the reference curve. When comparing the children aged 3-6 walking by themselves, figure 4 f) to children aged 0-2 walking themselves, figure 4 c) it can both be seen that the older children generally walk faster but there is also a larger spread in the results. At last it can be noted that there occur higher person densities amongst the older children than the younger ones. The data points representing children 3-6 years who are assisted, figure 4 e) are about equally distributed on both sides of the reference curve. The trend line is almost horizontal but the slope of the line is opposite to the theory. This can most likely be explained by a few data points measuring relatively high speeds at high person densities. An analysis of variance failed to reject the null hypothesis that the means for children aged 3-6 were the same regardless of level of assistance, using α=0.05. The same null hypothesis was however rejected for children aged 0-2 years.

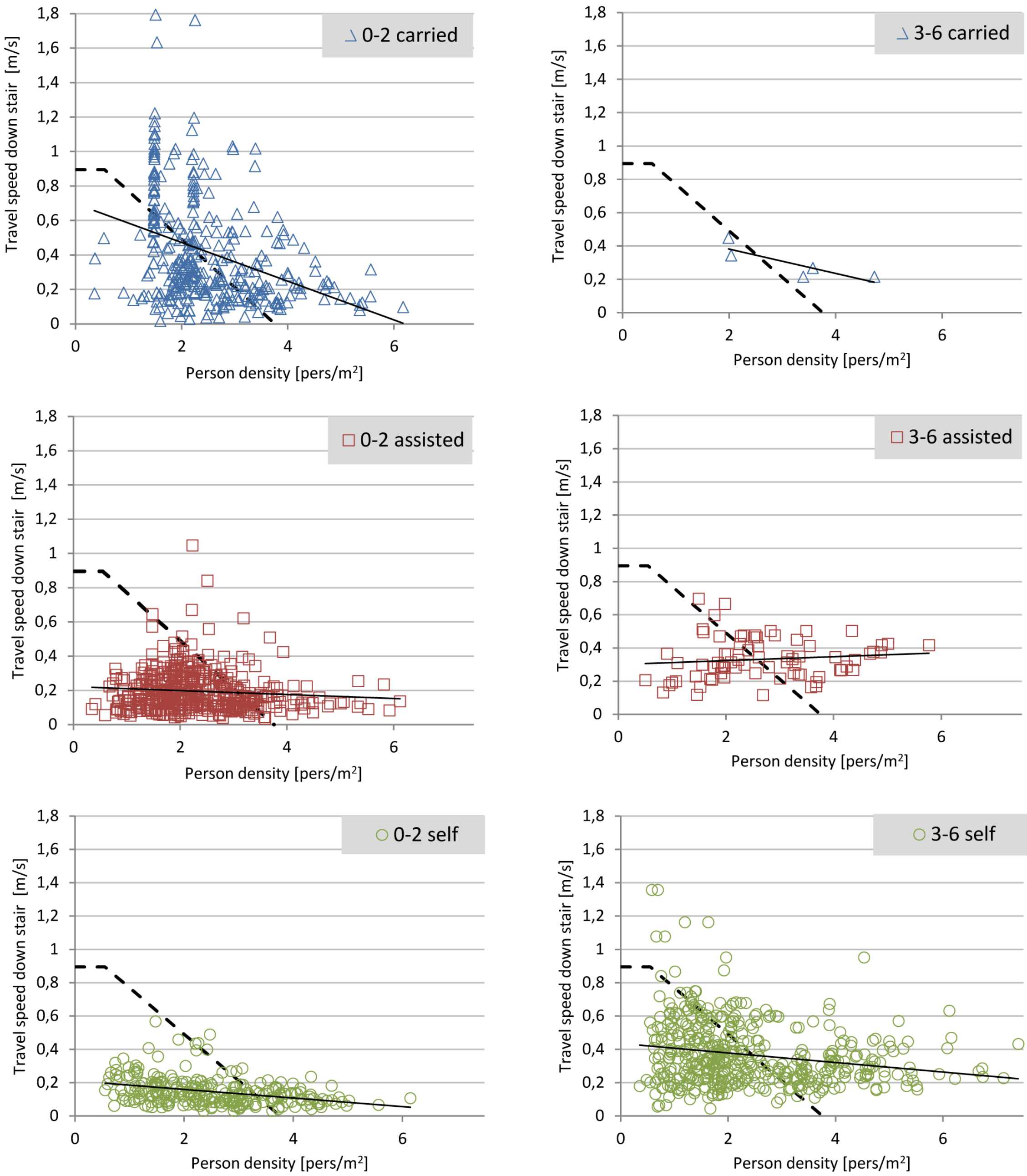


Figure 4. Results on travel speed down stairs as a function of person density. a), b) and c) represent results for children aged 0-2 years old and d), e and f) represent children aged 3-6. Data points are shown, linear trend lines for the presented data points is shown with a thin solid line and a reference curve from Nelson and Mowrer (typically used for adults) is shown as a thick dashed line[3].

Figure 5 shows the person density spread for the two different age groups. It can be seen that the frequency grows to a peak at the density interval [2,2.5) pers/m^2 for children 0-2 years and in [1.5,2) pers/m^2 for children aged 3-6, where the frequency rapidly lowers again, ending with less than 5% at person density 5 pers/m^2 and higher for both age groups. All in all it can be said that similar densities occur among children aged 0-2 and 3-6 years.

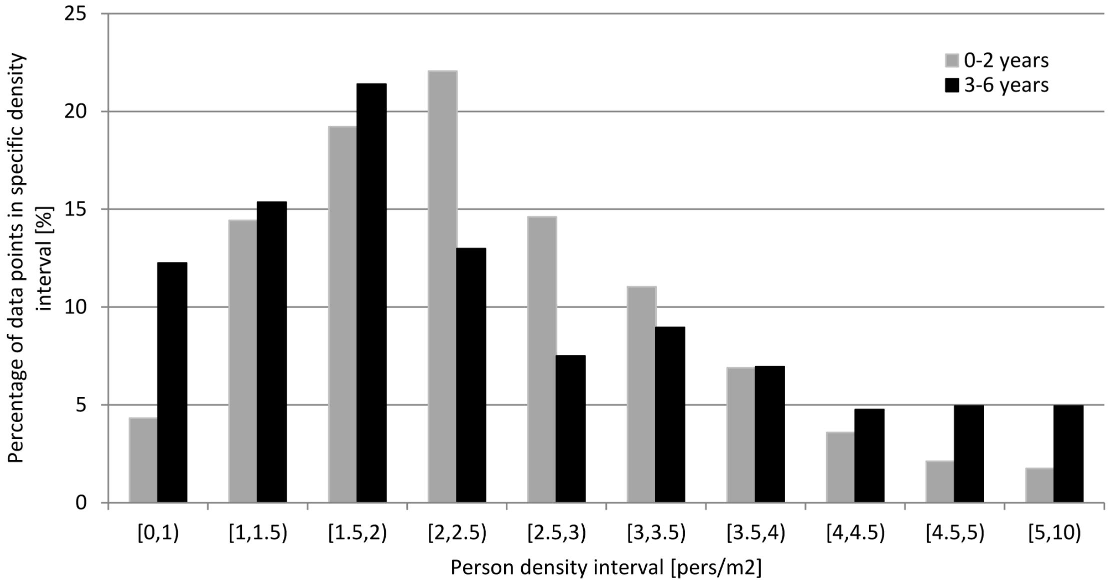


Figure 5. Frequency of occurring person densities for both age groups, according to defined intervals.

Figure 6 shows graphically the average speed, separately for the same density intervals as used in figure 5, with differentiation between the two age groups as well as the three levels of assistance. Data for children aged 3-6 that were carried are excluded, since there were only five data points for that group, all at different density intervals. The younger age group, 0-2 years are shown with shaded legends while children 3-6 years are shown with the outline only. To differentiate between the three different levels of assistance there are different shapes, a circle for “self”, a square for “assisted” and a triangle for “carried”. In addition to this there are different shades of grey for clearer view when overlap occurs. When looking at figure 6 and comparing the two age groups it can clearly be seen that the age group 3-6 travels faster than the group aged 0-2, both when walking self (grey circles) and when assisted (black squares). When comparing the average speed with respect to the assistance the difference is consistent for the younger children, that is the carried children have the highest travel speed and then the assisted children are a bit faster than the children walking by themselves. There are two exceptions from this, occurring at the end intervals.

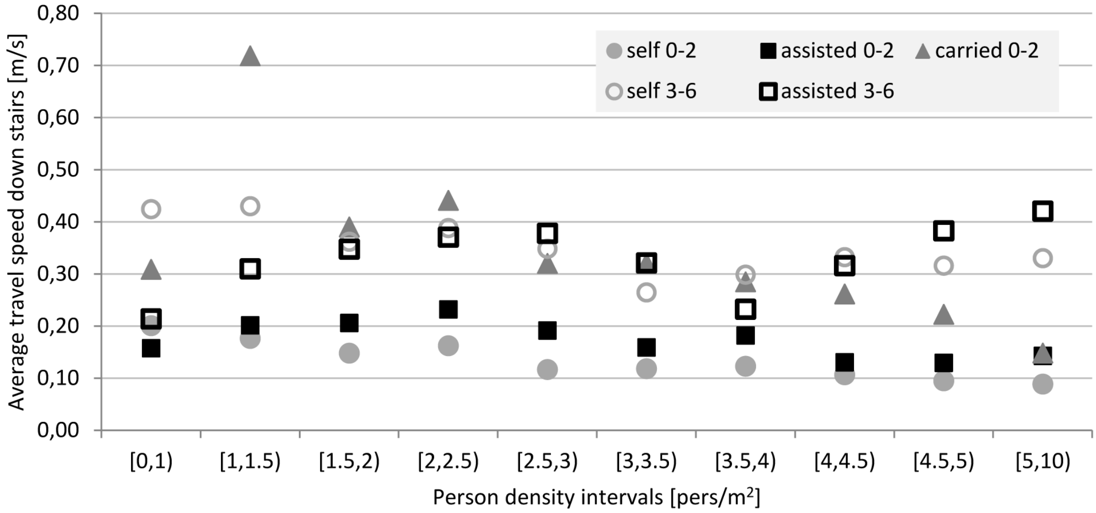


Figure 6. Average travel speed down stairs for different person density intervals. Differentiation is made between the two age groups and level of assistance.

The children who are carried down the stairs are in most cases slow walkers or unstable walkers. A few were non walkers. In some cases the children were carried for other reasons, where children were picked up when they stopped in the middle of a stair or didn´t continue after stopping on a landing. A few children were insecure, upset or didn´t follow the instructions and in rare cases the children tripped or fell and were therefore picked up to be carried. It should be mentioned that no injuries were obtained during the fire drills.

Table 2 and 3 show the results on travel speed down stairs according to density interval and age. Furthermore, it is distinguished between children that walked (either assisted or not) and children that were carried, for the younger age group. For comparison results from Kholshevnikov et al. [14] and Murozaki et al. [13] are shown in the same tables, the density intervals refer to those used by Kholshevnikov to improve compatibility.

When looking at table 2, which shows the mean travel speeds for the younger children it can be seen that the travel speeds from the two reference studies are between the values for children not carried and those carried. The results from Murozaki are the minimum and maximum means found among five measurements. The results include adults, which can explain why the travel speeds are on average higher than the travel speeds for children aged 0-2 years, not carried. Furthermore, the age group included older children or 0-5 years. The person density was not measured in that study. The assistance to the children is not specified for the study by Kholshevnikov so effects thereof cannot be estimated, however judging by the age group it can be assumed that a part of the children was not able to travel down stairs unassisted.

Table 2. Mean travel speed down stairs, number of measurements and standard deviation for chidren aged 0-2 years from the current study and numbers from two other studies for comparison.

	Current study 0-2 years (not carried)			Current study 0-2 years (carried)			Kholshevnikov et al. [14] under 3 years			Murozaki et al. [13] 0-5 years (including adults)		
density interval [pers/m2]	n [#]	speed [m/s]	SD [m/s]	n [#]	speed [m/s]	SD [m/s]	n [#]	speed [m/s]	SD [m/s]	n [#]	speed [m/s]	SD [m/s]
[0,1)	42	0.18	0.09	4	0.31	0.16	73	0.34	0.14	23 - 56	0.27 - 0.36	0.09 - 0.19
[1,2)	248	0.19	0.10	117	0.55	0.35	71	0.33	0.09			
[2,3)	259	0.19	0.13	141	0.40	0.28	43	0.34	0.11			
[3,4)	124	0.15	0.09	71	0.31	0.23	24	0.33	0.08			
[4,5)	41	0.11	0.05	23	0.24	0.09	-	-	-			
[5,10)	12	0.13	0.06	7	0.15	0.08	-	-	-			

Table 3. Mean travel speed down stairs, number of measurements and standard deviation for chidren aged 3-6 years from the current study and numbers from two other studies for comparison.

	Current study 3-6 years (not carried)			Kholshevnikov et al. [14] 3-4 years			Kholshevnikov et al. [14] 4-5 years			Kholshevnikov et al. [14] 5-7 years			Capote et al. [16] 4-6 years (drill 1 & drill 2)		
density interval [pers/m2]	n [#]	speed [m/s]	SD [m/s]	n [#]	speed [m/s]	SD [m/s]	n [#]	speed [m/s]	SD [m/s]	n [#]	speed [m/s]	SD [m/s]	n [#]	speed [m/s]	SD [m/s]
[0,1)	65	0.41	0.28	26	0.50	0.29	8	0.67	0.17	45	1.16	0.22	47 & 46	0.48 & 0.61	0.14 & 0.21
[1,2)	202	0.39	0.19	50	0.42	0.18	26	0.56	0.14	102	0.97	0.22			
[2,3)	111	0.37	0.15	38	0.38	0.16	37	0.50	0.12	122	0.88	0.20			
[3,4)	85	0.28	0.11	27	0.34	0.08	36	0.45	0.08	46	0.78	0.22			
[4,5)	52	0.33	0.12	4	0.32	0.08	12	0.42	0.08	26	0.72	0.19			
[5,10)	27	0.34	0.13	-	-	-	-	-	-	4	0.68	0.04			

Looking at table 3 it can be seen that the travel speeds achieved by children aged 3-6 years in this study are similar to travel speeds of children in the age group 3-4 years in Kholshevnikov´s study and that the age groups 4-5 years and 5-7 years exceed the travel speeds of the children in this study. The travel speeds from Capote measured from children 4-6 years old are close to Kholshevnikov´s travel speeds for 4-5 year old children, although Capote did not identify the densities, making comparison difficult. Overall it can be seen that the travel speeds measured in this study are at the lower when comparing to other studies for children in the same or similar age range. This could be due to different reasons such as difference in measurement methods, training, stair design and culture or different evacuation procedures.

Handrail usage

Table 4 shows results on handrail usage amongst the children that were not carried down the stairs. It can be seen that the younger age group uses the handrail more than the older age group. Furthermore, it can be seen that amongst children walking without assistance from adults 92.7 % and 58.6 % of the younger and older children respectively, use the handrail. The third category, after handrail and no handrail are exceptional cases, named other, where handrail usage was not an option for the child. For the younger age group the reason was that the children crawled backwards down the stairs, using both hands on the steps and for the older age group both hands were occupied by handholding.

Table 4. Results on use of handrail for the children that were not carried down the stairs.

		handrail	no handrail	other	total
0-2 years	self	92.7 %	6.5 %	0.8 % [1]	100%
	assisted	75.0 %	21.8 %	3.2 % [2]	100%
3-6 years	self	58.6 %	41.4 %	-	100%
	assisted	44.7 %	55.3 %	-	100%

[1] children that crawled backwards down

[2] children that held adults in both hands

It was observed that there was at times free space in the middle of the stair (width wise). This was more evident amongst the younger age group. This can be explained by the frequent handrail use of children aged 0-2, where they walked on either side of the stair where there was a handrail available, leaving space in between. However, the adults frequently used the center space, either to overtake or to support the children walking on the stair.

As mentioned earlier there was a low handrail installed in three stairs used by the younger age group. Comparison of the travel speeds achieved by children 0-2, depending on the handrail used (low, high or the only available) can be seen in figure 7. It shows a box plot, where the thick line is the mean, the upper and lower sides of the boxes are the lower and upper quartiles, the lines out of the boxes represent 1.5 IQR (interquartile range) and the points are outliers. Figure 7 indicates that children using a low handrail for support when descending stairs walk faster than the ones using a high handrail.

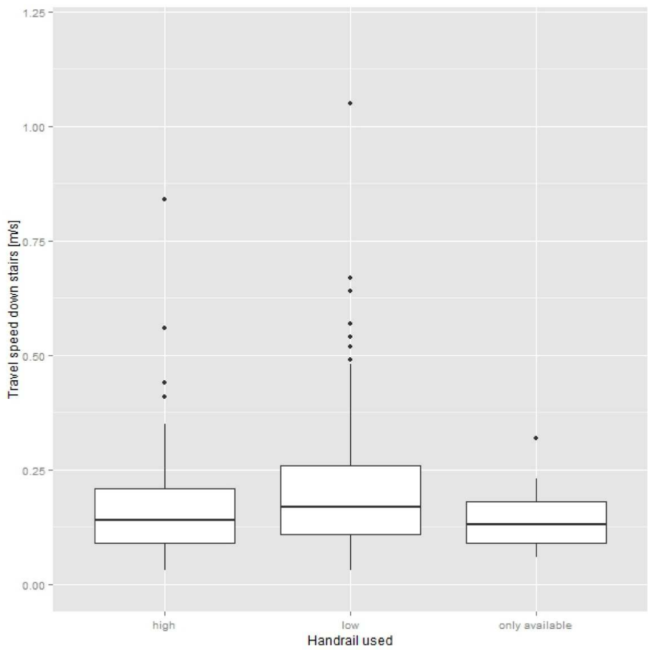


Figure 7. Boxplot showing travel speed for children 0-2 years using different handrails.

An analysis of variance, using α=0.05 rejected the null hypothesis that the means are equal for the tree handrails. To compare each of the handrails a Tukey test was performed and it confirmed that there is a consistence difference between the low handrail and the other handrails. In fact on average the children achieved a 23.5 % higher travel speed than when using the other handrails.

4. Conclusion

The current work deals with evacuation of children from daycare centers. New data on travel speed down straight stairs are introduced as well as need of assistance and use of handrail. The study confirmed that the younger age group (0-2 years) are more dependent on the adults and need more assistance to carry through the evacuation.

It could be found that more than 3/4 of the 3-6 year old children and less than 1/4 of the 0-2 year old children walked by themselves down stairs (self-preservation). Furthermore, 1/3 of the younger children were carried and almost half assisted by handholding. This complied with the results of a previous study on assistance. It was clearly shown that children in age group 0-2 years that were carried moved faster down the stair than the ones walking, however the results were much spread. It was common for adults to carry one child while assisting another by handholding; this process slowed the adult (and thereby the child) down. Children in the younger age group also moved faster on average when assisted than when walking by themselves. This different was not consistent when looking at the older children aged 3-6 years.

The results on travel speed with relation to density indicate that children's travel speed is not as affected by increased density as suggested for adults as children occupy less space than adults. At person densities below 3 pers/m^2 the majority of data points are below the reference curve, suggested for adults, with the exception of when children are carried.

The person density spread for the travel speed differs for the age groups. It can be seen that the frequency grows to a peak at the density interval [2,2.5) pers/m^2 for children 0-2 years and in [1.5,2) pers/m^2 for children aged 3-6. The average travel speeds achieved by children in this study were lower than speeds found in other studies for children at same or similar age range.

When looking at children walking without assistance from adults almost all of the younger and more than half of older children, use the handrail. When holding an adults hand the frequency of using the handrail lowers.

Children aged 0-2 years using a low handrail achieved on average 23.5 % higher travel speed down stairs than children using a high handrail.

All in all the results show than young children´s evacuation parameters differ from adults´. The term "children" also spans a wide age range, where the same does not apply for all. When designing buildings and evacuation procedures the age and composition of the occupants should be considered in order to ensure their comfort in daily use and safety in emergencies.

Acknowledgements

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References

[1] Bryan, J. L., *SFPE Handbook of Fire Protection Engineering, Behavioral Response to Fire and Smoke*. National Fire Protection Association, USA, third edition, 2002.

[2] Proulx, G., *SFPE Handbook of Fire Protection Engineering, Movement of People -The Evacuation Timing*. National Fire Protection Assosiation, USA, third edition, 2002.

[3] Nelson, H.E., Mowrer, F.W., Emergency Movement. In: *SFPE Handbook of Fire Protection Engineering.* Quincy, Massachusettes: National Fire Protection Association, 2002.

[4] Boyce, K.E., Shields ,T.J.,Silcock, G.W.H., Toward the Characterization of Building Occupancies for Fire Safety Engineering: Prevalence, Type and Mobility of Diabled People. Fire Technology, 35:35-50, 1999.

[5] Boyce, K.E., Shields ,T.J., Silcock, G.W.H., Toward the Characterization of Building Occupancies for Fire Safety Engineering: Capabilities of Disabled People Moving Horizontally and on Incline. Fire Technology, 35:51-67, 1999.

[6] Boyce, K.E., Shields ,T.J., Silcock, G.W.H., Toward the Characterization of Building Occupancies for Fire Safety Engineering: Capabilities of Disabled People to Negotiate Doors. Fire Technology, 35:68-78, 1999.

[7] Boyce, K.E., Shields ,T.J., Silcock, G.W.H., Toward the Characterization of Building Occupancies for Fire Safety Engineering: Capabilities of Disabled People to Read and Locate Exit Signs. Fire Technology, 35:79-86, 1999.

[8] Kholshevnikov VV, Samoshin DA, Parfenenko AP, Pre-school and school children building evacuation. Fourth International Symposium on Human Behaviour in Fire, 2009.

[9] Lu, C., The Evacuation Training Problems of an Earthquake in China, Pedestrian and Evacuation Dynamics, pp 121-127, 2011.

[10] Taciuc, A., Dederichs, A.S., Determining Self-Preservation Capability in Pre-School Children. Technical Note, Fire Protection Research Foundation, 2013.

[11] Bruck, D.. Non-awakening in children in response to a smoke detector alarm. *Fire Safety Journal*, pp. 369–376, 1998.

[12] Proulx, G., Evacuation time and movement in apartment buildings. *Fire Safety Journal*, 24:229–246, 1995.

[13] Murozaki, Y., Ohnishi, K.. A study of fire safety and evacuation planning for preschools and day care centers. Memoirs of the Faculty of Engineering Kobe University, 32:99–109, 1985.

[14] Kholshevnikov V.V., Samoshin, D.A., Parfenenko, A.P. and. Belosokhov, I.P. Study of children evacuation from pre-school education institutions. *Fire and Materials*, 36:349–366, 2012.

[15] Predtechenskii, V.M., Milinskii, A.I.. Planning for Foot Traffic Flow in Buildings. Stroiizdat Publishers, Moscow, 1969.

[16] Capote, J.A., Alvear, D., Abreu, O., Cuesta, A.; Hernando, J., Children Evacuation: Empirical Data And Egress Modelling , Fifth International Symposium on Human Behaviour in Fire, 2012.

[17] Ono, R. Valentin, M.V., Vittorine, F., Walking speed data of fire drills at an elementary school, Fifth International Symposium on Human Behaviour in Fire, 2012.

[18] Larusdottir, A., R. ; Dederichs, A. S., Behavioral Aspects of Movement Down Stairs During Elementary School Fire Drills, Fifth International Symposium on Human Behaviour in Fire, 2012.

[19] Larusdottir, A., R. ; Dederichs, A. S., Evacuation of children - movement on stairs and on Horizontal Plane, Fire Technology, 48: 1, pages: 43-53, 2012. DOI: http://dx.doi.org/10.1007/s10694-010-0177-6,

[20] Larusdottir, A.R., Dederichs, A.S.. A step towards including children´s evacuation parameters and behavior in fire safe building design. *Fire Safety Science 10*, pp.187–195, 2011.