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Human factors in evacuation simulation, planning, and guidance

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Abstract

Evacuation research shows growing interest in human factors and psychology. Before, humans were mostly modelled as homogeneous, without individual emotion, motivation or physical needs. Human factors had mainly been taken into account as physical characteristics or space requirements. In this paper, we give examples of relevant human factors from the literature and our own field research. Human factors include physical, cognitive, motivational and social variables. As yet, there is no validated set of variables most relevant for safe and fast evacuation. Models for classifying human factors from other domains are introduced for use in future research.

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1. Introduction

In research on evacuation, recent years have seen growing interest in human factors and psychology. Real evacuations in the past have taught the importance of human factors: Even where physical wellbeing and spatial aspects of the escape route were not a problem, they did not always run smooth. In a derailing accident in the Moscow Subway system in 2014, some passengers stated afterwards to the media that they had assumed it would be their end. In contrast to that other passengers took their time to take pictures of the derailed subway train instead of leaving the site immediately. Consequently, evacuation was slow and difficult to coordinate as people were injured, in shock waiting for help, or were actively searching for a way out through the dark subway tunnel by themselves.

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Incidents like that have inspired a long-standing tradition of research on behavior of humans in evacuation, especially from fires. Researchers often have addressed behavior that may seem irrational or not understandable, like delayed evacuation. Fridolf (2010) summarizes factors explaining the unwillingness to evacuate a subway train or subway station: information processing and social influence seem to be among the most important. After more than 20 years of research, a lot is known about human behavior in real events. But holistic collection and analysis of data on individual behavior or reasoning in real events is difficult and seldom tried. Field experiments give the opportunity of observing behavior, but here the problem is that usually participants know that there is no danger (e.g. in Zinke et al. (2014)). Field studies sometimes work with unannounced evacuation (e.g. Schmidt and Galea (2013)). As no real danger is present, even in this type of experiment, consequences of real threats and danger cannot be assessed. Also from analysis of real events and field studies, a lot is known about human behavior. Not all of analyses have been integrated into evacuation planning and modelling.

Due to practical and ethical problems of field studies, much evacuation research has been done by simulation and other modelling approaches (Peacock et al. (2011)). In the beginning of modelling research, human factors had not been in the focus; humans were modelled more or less as homogeneous quantity, without individual emotion, motivation or physical needs. Human factors had mainly been taken into account as physical characteristics or physical space requirements. These aspects are integrated into different calculating approaches when the overall time needed for the evacuation is determined (cf. for public transport systems: NFPA 2000; Predtetschenski and Milinski (1971)). In the last decade, also evacuation simulation and modelling have started to take human factors into account (cf. Galea (2014); Schäfer et al. (2013)). The primary motivation for that is expressed by Schatz et al. (2014, p. 1113) describing the performance-based approach: “Since the protection of human life is the primary aim […], predicting the behavior of people on danger is an essential purpose of such modeling”.

Many simulations take into account behavioral tendencies (cf. e.g. Galea (2014); Kostas et al. (2014); Schneider and Könnecke (2007)), e.g. walking towards a goal, taking the nearest exit, avoiding obstacles or following leaders. Even if operationalization is not always transparent, it seems that usually only a few of these variables are integrated. The reason might be that complex agents would not be scalable for larger crowds (Sung et al. (2004)). With advancing computer performance it will be possible to regard also more complex behavioral patterns.

Simulation of crowd behavior and pedestrian dynamics are closely related to evacuation modelling. As these approaches focus on normal conditions rather than emergencies, it is not clear which of their results can be transferred to evacuations. In this type of modelling, some aspects of human factors have been included, especially when regarding models of human behavior. Examples can be found e.g. Moussaïd et al. (2011), in Schadschneider et al. (2008), Helbing et al. (2001). But even though human factors meanwhile are generally accepted as relevant a rather limited range of human factors is integrated. There is a tendency for uniformities and thus oversimplification with respect to the complexity of human individuals (e.g. Klingsch et al. (2010)).

When trying to integrate, in addition to empirical restrictions and modelling limitations, the problem of selecting the right variables arises: “Human factors” include a great variety of different physical, cognitive, motivational and social variables, always regarded in relation to the socio-technical system, the task at hand, and the physical environment (cf. Karwowksi (2012); Badke-Schaub et al. (2012)). Although the need for integrating human factors has been widely recognized, there is yet no set of variables most relevant for safe and fast evacuation.

In section 2, we will discuss the relevance of human factors in evacuation planning and modelling. In section 3, we will give examples of evacuation research considering human factors. They show the broad range of relevant human factors. We also add some results from our own field studies. In section 4, we argue that human factors knowledge from psychology and human factors sciences can be valuable for establishing a set of relevant human factor variables. We also take a look on human factors classifications that could be helpful for evacuation research.

2. Human factors in evacuation - why are they relevant?

Planning for evacuations is a requirement for all infrastructures. Models used for practical evacuation planning, usually take into account mainly three dimensions (e.g. Kirchberger (2006)): The type of building or infrastructure and its environment, the incident with the rapidness of its impact / the type of danger, and human physical aspects.

Let us assume an office building as infrastructure and a fire originating from a printer in an office as an incident with a moderate level of imminent danger. There might be a number of different reactions by the occupants of the office building: Some persons will leave the building immediately full of fear. Some of those will experience problems on the stairs due to mobility impairments. Some might have problems with orientation in the building. Others will first finish their present work, saving the status quo and shutting down the computer and then leave. Another group may try to extinguish the fire themselves until the fire fighters arrive or will inform their colleagues and help them leave the building. And then there are those who stay in their office because they believe it's one of those false alarms again. And of course, someone could not hear the alarm because they were listening to the radio. Even this small example shows that a successful evacuation depends on many different factors apart from reliable infrastructure, structural protection, and accessible escape routes. Although it almost seems trivial to stress the relevance of human factors when talking to researchers, in practical work, they are still not well known. Tubbs and Meacham (2007) aggregated typical assumptions about human behavior by engineers, fire fighters and others responsible for evacuation. These assumptions which the authors call "myths" seem to be used in many types of modelling behavior or in the calculation of escape route dimensions. Three examples of this collection of "myths" which we have often been confronted with ourselves, may serve as an illustration.

2.1. Delayed evacuation

A first myth is that all occupants of a building or an infrastructure leave immediately when hearing an alarm. Just like in the fictional example above, case studies analyzing delay in evacuations showed the opposite (e.g. McClintock et al. (2001); Breznitz (1984)): People do many things before or instead of complying to an alarm. According to these case studies, delays of evacuations can be attributed to:

- recognition of the alarm and threat identification (What is it? Is that an alarm?)
- assessment of relevance (cry-wolf-syndrome, Breznitz (1984); "learnt irrelevance", McClintock et al. (2001))
- threat recognition ("It can't happen to me.", because a fire is such a rare occasion);
- need for information and orientation
- commitment to other task

Pre-Movement time is one of the main factors for delays and has been given consideration in evacuation research. Fitzpatrick and Mileti (1994) show that people must hear, understand, believe, personalize, and react to a warning or alarm in disaster. The reaction consists of several steps in the evacuation action chain, as a person will have to interrupt activities before deciding to leave the respective building. These steps in the evacuation chain (cf. Hofinger, Künzer and Zinke 2013) represent different individual cognitive human factors (perception, appraisal and assessment, knowledge, motivation) that interact with design of alarms, group behavior and other influences. Thus, the example of delayed evacuation shows that information processing and also social behavior need to be understood thoroughly for safer evacuation.

In our own field studies (Zinke et al. (2014)) in underground transportation systems, we used interviews about previous evacuation experiences and observational data from field experiments (informed participants in situations without threat). Three types of behavior in reaction to an emergency alert were identified which can be attributed to different cognitive or social motivations. Our findings correspond with the literature:

- "Wait-and-see": Social motivation seemed to be most important, as participants were either waiting for further instructions (i.e. need for leadership and guidance) or they were waiting for other group members (affiliation).
- "Information seeking": Participants searches for additional information, e.g. a plan of the station, or exit signage. Here, control over the situation and reduction of uncertainty seem to be the relevant motivation.
- "Get out of here": Participants started to evacuate immediately after hearing the alarm message. In the field study without real danger, the motivation behind that behavior might have been being a "good participant". In real evacuations, avoidance of pain and insecurity might be the driving forces.

2.2. Walking through smoke

Another myth is that people will not move through smoke (Tubbs and Meacham (2007)). This belief is shared by many fire fighters as they know how dangerous smoke is – a few deep breaths in smoke cause unconsciousness or even death. But case studies over the past 30 years have shown that people will continue to move through smoke even in worsening conditions (e.g. Proulx (1995)). Fahy and Proulx (2009) obtained data from evacuees of the World Trade Centre Bombing in 1993. Most of them (94% of subjects evacuating from Tower One and 70% from Tower Two) reported having moved through smoke. The reasons they gave for this behavior were among others: trying to help and warn others, trying to fight the fire, or curiosity. So, the human factors behind the seemingly irrational behavior (walk through smoke) can be found at the social level and also on the individual level (lack of knowledge, motivation). In one of our filed studies we could observe an unannounced evacuation of a university building. 165 occupants (roughly 85% of all occupants) answered a questionnaire afterwards. Of these, 65% answered that they would move through a smoke filled section of the building to get outside.

2.3. Not using the closest available emergency exit

A third example for evacuation myths is that people use all available exits evenly. Yet, occupants of an infrastructure tend to leave it by the same way they entered it (“common path of travel”, Sime (1995)). In the field studies by Norén and Winér (2003) and Nilsson (2009) analyzing evacuation from street tunnels, participants preferred the closest exit. Again, a whole range of human factors can be responsible for that behavior: one important factor is action regulation, as humans tend to use routines rather than conscious decisions (“skill-based behavior”, Rasmussen (1983)). Another reason might be learnt irrelevance again, as people ignore (emergency) exits that they may see every day but never use (McClintock et al. (2001)). Additionally, not using available doors might also be due to the fact that emergency exits often are secured by an alarm: so using it would mean disobeying a rule. “Cognitive economics” (Dörner (2008)) may play a role, too, as humans avoid detours, during evacuations but also in everyday life.

3. Some examples of human factors in evacuation research

Time needed for evacuation is crucial for safety or even the life of evacuees. Therefore, different parameters affecting the time needed for evacuation are elaborated on in the literature. These include the influence of infrastructural elements, e.g. obstacles, narrow passages or staircases (e.g. Fujiyama and Tyler (2010)). Research on pedestrian flow in crowds under normal and emergency conditions (e.g. Galea (2014); Helbing et al. (2002); Schreckenberg (2002)) has yielded results that have helped to improve safety e.g. by reducing congestions at exits. Much of the literature in evacuation time focuses on delayed evacuation, either by pre-movement time (detection and reaction, Fitzpatrick and Mileti (1994)) or suboptimal flow caused by human behavior. In this section, we assemble some findings from the literature, of course without any claim to completeness. Our aim is to show how broadly evacuation research has embraced the idea of human factors, although without sharing a definition, or a model of human factors. We focus on physical characteristics, cognitive processes and needs, and group phenomena –many other relevant human factors have been addressed in recent research but can’t be dealt with in this paper. Examples would be orientation in buildings (Lovas (1998); Steigenberger (2013)), decision-making processes in evacuation (Schatz et al. (2014); Hofinger et al. (2013)); or the influence of culture (e.g. Schmidt and Galea (2013)). Also, extreme behavior like panic (which has been given considerable attention by many researchers, e.g. Fahy and Proulx (2009)) cannot be dealt with here.

3.1. Physical characteristics

The characteristics of the human body are part of calculating escape routes in buildings. Examples are average shoulder width or depth of the human body. These have to be seen in relation to average walking speed and other factors. Since the seminal work of Predtetschenski and Milinsky (1971) and Sime (1995), the influence of additional physical characteristics on evacuation time has been known. Clothing or heavy luggage are among the aspect that are relevant here as they increase the space occupied by each person. These factors are human-centered but not psychological. Samples for gathering data on these aspects mainly included healthy young men. Only in recent times, persons with mobility impairments, handicaps, or other special needs have been regarded in evacuation research, e.g. DeJong (2012) for mobility impairments, Huang (2006) for senior citizens. Mobility impairments of all kinds sometimes are considered in evacuation modelling and simulation by reducing walking speed, but the behavior of the agents or their interaction is not changed. Ulriksen and Dederichs (2012) integrate reduced walking speed of children, assuming that other special needs of children can be compensated for by the presence of adults.

For safe evacuation and modeling it would be relevant to know the percentage of evacuees with certain needs, e.g. how many blind or deaf persons are part of a crowd, how many families with small children etc. But for most domains, there is a lack of data. Tubbs and Meacham (2007) report that for example in the US, approximately 20% of the population suffers from some disability or chronic disease relevant for evacuation. In a field study (Zinke et al. (2014)), we counted passengers in a subway station in Berlin. Including level changes inside the station, the overall number of moving passengers per hour in that station on a week day was 9,400. Out of these, 2.46% were (visibly for our observers) physically impaired.

3.2. Information processing: Perception, recognition, and appraisal of evacuation alarms

Human information processing is relevant during all stages of evacuation. Basic cognitive processes like perception are relevant, e.g. impaired sight in smoke, recognizing of signage. Evacuation research has focused on reasons for extended pre-movement times (see section 2). Some simulations use information-processing based models of pre-evacuation behavior (Viswanathan and Lees (2014)). The recognition of an alarm and the realization that there is a threat are crucial for fast evacuation. In order to overcome learned irrelevance (McClintock et al (2001)), perceived urgency has to be high. Künzer et al. (2014) showed that the perceived urgency varied between different signal words and also depended on the para-verbal aspect of the speaker's voice. The role of spoken warnings is given attention in warning design (e.g. Wogalter et al. (2002)), but rarely in evacuation planning. A lack of perceived urgency could be observed in the Tokyo underground assault 1995: Sarin, a non-smelling, invisible gas did not induce a sense of urgency as strong smell or smoke might have done. Murakami (2004) reports that many seated passengers did not leave the trains despite orders to do so: in Tokyo rush hour, occupying a seat was obviously more important than avoiding a possible danger.

In a field study, we observed an unannounced evacuation of a university building. Of 165 occupants that answered the post-hoc questionnaire, 23 % didn't recognize the evacuation alarm as such. They heard it, but thought it was the sound of a cell phone, a car alarm, an elevator sound etc. They reported never having heard the university's fire alarm before. So, lack of reaction in those cases was not due to motivation, but due to lack of knowledge. To our experience, in many public buildings, the sound of the respective evacuation alarm is not known. Due to a lack of standardization of alarms (at least in Germany), people would have to learn the relevant sound in every public building they visit (e.g. hospitals, schools). In that examples, the human factors "knowledge" and "expectation" interact with elements of the system, in that case standardization policies.

3.3. Cognitive needs: Certainty, feeling of control, curiosity

Humans have a strong need for certainty and an intact feeling of control (Dörner (2008)). Many psychologists agree that „being in control" is a basic motivation. Control can either be active (influence the situation) or passive (knowing, understanding, predicting). An emergency with physical danger threatens the feeling of control. To know what is going on can be a form of (re)gaining control in emergencies and evacuations. So, humans search for information instead of leaving immediately which has been shown in many case studies of disaster, like the fire in King's Cross 1987 (e.g. Sime (1995)). "Several studies of human behavior during emergency egress have shown that an evacuee's first reaction after realizing that there is an unusual situation is to investigate and gather more information about the situation." (Viswanathan and Lees (2014), p. 127). If people understand a situation, they can make decisions (e.g. to leave a building) and thereby feel in control instead of just obeying orders (Hofinger et al. (2013)). Therefore, giving adequate information about the danger (e.g. fire) and the necessary action (evacuation) is an important strategy in emergencies and disaster, especially in large crowds.

Humans not only search certainty but are also curious. Curiosity leads to new knowledge and so in the end to greater feeling of control. Thus, curiosity is related to reduction of uncertainty by the control motivation (e.g. Dörner (2008)). So, also curiosity and excitement lead to delayed evacuation, e.g. when evacuees take pictures or watch when fire fighters are working. In an incident at a subway station in Berlin in 2000, several passengers had to be lead out of the station by fire fighters because they wanted to watch instead of heading for safety (Hofinger et al (2013)). In the accident in the Moscow Metro mentioned in the introduction, several passengers took pictures instead of leaving. In these examples, the lack of knowledge about the dangers of smoke combines with natural curiosity. Evacuation research and planning has to take into account that people do not leave a site just because they are told to do so: Information about the danger is essential (cf. Wogalter et al. (2002)).

3.4. Group behavior: Affiliation and leadership in small groups in crowds

In evacuation research, phenomena of crowds and groups are important. It is important to mark the difference between crowd dynamics and group behavior. Crowd dynamics primarily describes movements with respect to velocity, density, paths of travel, consequences of obstacles etc. Moussaïd and Nelson (2014) list the following behaviors as relevant human factors in crowds: collision avoidance, physical interaction, social interaction, imitation, indirect interaction. Crowds are characterized considering the event, the general internal structure, the emotionality (Tubbs und Meacham (2007)). Relevant for the behavior of crowd – especially in emergencies – are also (Künzer and Hofinger (2014)) the degree of organization in the crowd, the existence of shared goals, the involvement in the event, tendencies for aggressive behavior, and also accepted cultural standards concerning e.g. the level of tolerable noise or physical proximity.

In contrast to general effects of crowd membership (e.g. Brudermann (2014)), the focus of (small) group behavior research is on psychological aspects of persons inside groups, e.g. affiliation, leadership, trust, helping behavior. Group behavior is relevant to evacuation, as a significant proportion of crowds usually is organized in small groups: „Social groups in size of up to 6 persons are frequently present during public events. Quite often such groups comprise the majority of visitors“ (Oberhagemann et al. (2014, p. 1251)).

Whether in crowds or small groups: Leadership is crucial in emergencies. Persons under stress are more likely to need and to accept leadership than in normal circumstances. Thus communication in evacuation should include clear instructions for action along with information concerning the danger (Wogalter et al. (2002)). With clear display of leadership and distinct information, almost all evacuees can be influenced. Schneider and Kirchberger (2007) identified three different basic reactions: about 10 to 15% of the evacuees show controlled and rational behavior. They can take the role of (informal) leaders. The majority of 70% will be scared but remain calm and act as instructed, while the remaining 10-15% will behave unpredictably or helpless. In experiments, even those could be controlled by explicitly addressing selected individuals among them (Sugiman (1988)).

In small groups, a high level of affiliation is experienced among the members (cf. Sime (1995)). When stress is experienced by a group, affiliation could lead to an urge to maintain social bonds by gathering and moving together (Sime (1985)). The effect is highlighted by Köster et al. (2014, p. 1051): „the need to associate with family and friends may dominate over flight instincts.” By seeking closer proximity with group members, people also seek for orientation and support (Schadschneider et al. (2008)). In our field experiments, this behavior could also be found, in the unannounced evacuation as well as in informed groups of participants. Participants formed groups and stayed in groups in order to find the escape route and to support one another. This behavior was expressed most often in small groups of max. four persons. As a positive effect of affiliation among group members we found supportive behavior in order to evacuate smoothly and unharmed. On the other hand, groups of people partly slowed down the crowd by waiting for each other (Hofinger et al. (2013)). This corresponds with other findings (Reuter et al. (2014)): small groups within crowd can both hinder and speed up the movement of the crowd.

4. Human Factors classifications for evacuation research

The examples given in section 3 demonstrate the broad range of human factors relevant for evacuation. They encompassed individual and group factors. Most of the cited studies include one or several human factors, but we haven’t found much theoretical foundation for the choice of factors considered. It seems that theory development is often lead by empirical evidence – delayed evacuation from sites with adequate escape routes leads to research on the reasons for delay. We feel that the time has come for a more systematic approach to human factors in evacuation: As simulation models grow more complex with increasing computer capacity, there is a chance to model also more complex human behavior within its ecological context. For that, models of human factors are needed that give an orientation which variables and their relations could be relevant.

A human factors approach is more than considering psychological variables. In human factors science, the interaction of the person with the system they work in and their physical and technical environment is in the focus. Human factors deals with designing systems so that they adapt to human physical, cognitive and emotional, and social characteristics with their strengths and limitations (Badke-Schaub et al. (2012)). The following levels of human factors have to be regarded in their interrelations:

- The individual level: general human characteristics and the individual person's traits and states
- Group level: teams or groups and their interactions, e.g. leadership, communication
- Organizational level: management, processes, rules etc.
- Technological level – tasks, tools, and technologies
- The system's environment: Physical, societal, financial environment for the system in focus

Each of those levels consists of many factors. In groups (cf. section 3), leadership, affiliation, helping behavior, communication and shared emotion are relevant for evacuations. For individuals, the following factors seem most relevant (cf. Hofinger et al. (2013); Jungermann (2000)):

- General human characteristics: Information processing, stress reaction, emotion
- Individual characteristics of the evacuees
  - Physical characteristics, e.g. size, strength, impairments age
  - The momentary physical and mental state (e.g. drunk, euphoric, tired)
  - Knowledge: experience with emergency situations, local knowledge
  - Personality traits (e.g. anxiety, risk taking)
  - Motivation (e.g. control, curiosity, affiliation)

Psychological or human factors models specifically for evacuation are rare (Jungermann (2000)). Looking into human factors research in general, we found that classifications either focus on errors or unsafe acts, or they are formulated for the special tasks and circumstances of one domain. These models are not meant for evacuation but for the interaction of a person or a team, usually operators, with a (technical) system.

The most prominent error classification by Reason (1990) classifies unsafe acts as slips and lapses, mistakes or violations: Slips and lapses occur, an action is not performed as intended. Causes lie in information processing, mainly attention and memory failures. In contrast, mistakes are made: An action is performed a planned, but does not lead to the intended result. Mistakes can be knowledge-based or rule-based. Violations on the other hand are committed: an intention other than safety guides action. This can happen routinely or in exceptional circumstances.

Reason (1990) also shows that unsafe acts only lead to accidents when they meet latent conditions on different levels off the system. An "error chain" has several elements on all levels of a system, including organizational factors, unsafe acts or errors, and failure of technical barriers. Based on Reason's (1990) classification of unsafe acts and the idea of the error chain, the Human Factors Classification System was developed for aviation (HFACS, Shapell and Wiegmann (2001)). In the error chain, a focus is on preconditions (of unsafe acts) into which category they include several environmental factors and personal factors of the operators. In the classification of unsafe acts, they add perception errors to "slips and lapses", include decision-making errors in "mistakes", and illustrate every category with examples from aviation. This approach to classification could be useful for evacuation research: On the basis of a general human factors model, those variables that are most relevant for safe evacuation are elaborated. An example for application could be understanding the reasons for a delayed evacuation: A person who does not leave a building might not have heard the alarm (perception error), interpret it wrongly (knowledge mistake), judge the alarm as irrelevant (routine violation), take a wrong route (decision-making error) etc. The underlying action model could help to improve agent-based simulations by more complex agents. Knowledge about sources of error and unsafe acts (here: failure to evacuate) can help to find solutions in evacuation planning and guidance.

In conclusion, from a human factors point of view, evacuation research and planning can be stimulated by theories and classifications described in this paper. Future theoretical work, case studies, modelling, and empirical testing will show how useful a systematic approach to human factors in evacuation is.

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