FIRE RESPONSE PERFORMANCE. BEHAVIOURAL RESEARCH IN VIRTUAL REALITY

M. Kobes[1], N. Oberijé[1], N. Rosmuller[1], I. Helsloot[2] and B. de Vries[3]
[1] Netherlands Institute for Safety (NIFV), P.O. Box 7010, 6801 HA Arnhem, The Netherlands
[2] Vrije Universiteit Amsterdam, Faculty of Social Sciences, De Boelelaan 1081, 1081 HV Amsterdam, The Netherlands
[3] Eindhoven University of Technology, Faculty of Architecture, Building and Planning
P.O. Box 513, 5600 MB Eindhoven, The Netherlands

ABSTRACT

Fire response performance is the ability of an individual to perceive and validate clues of danger and to make decisions that are effective with regard to survive a fire situation with none or little health complications subsequently. In general, little information is known about human behaviour in fires yet. Human behaviour in fires is mainly studied by incident evaluations and real-life experiments, such as unannounced evacuation drills. Since in virtual environment test persons can be faced with the phenomenon of fire in a safe way, without being exposed to the extreme health risk of a real fire, the application of a behavioural assessment and research tool in virtual reality seems to be a valuable supplement on the existing research methods. The possibilities of a virtual environment for studying human behaviour in fires are so far hardly adopted by researchers. In this paper the development of an innovative virtual reality based research instrument will be discussed together with the methodology for the validation of the instrument.

KEYWORDS: Fire safety engineering, Evacuation, Way finding, Virtual reality, Simulation

INTRODUCTION

In the beginning of the 20th century the research on evacuation behaviour [1-3] started. The main focus was on the movement of people in corridors, on stairs and through doors. Several researchers, in particular Pauls, Fruin, Predtetschenski, Milinski, Habicht and Braaksma [4-6] have collected detailed information about occupant density and travel speed. This information has been of large influence on the approach of fire safety in building regulations worldwide.

For the fire safety in buildings, the required measures are technology based. According to the Dutch Building Regulation buildings should be designed in such a way that occupants can escape by themselves in case of fire. However, case studies show that occupants often are found to be incapable to escape in time. Moreover, incident evaluations indicate that the major fatalities occur in evacuations with a long pre-movement time, especially in hotels and apartment buildings [7]. The pre-movement time covers the processes of perceiving and validating clues of danger and the processes of decision making before and during the actual movement. These processes are supposed to be more decisive on survival [2,8] than the actual movement speed. It is also found that occupants behave frequently in contradiction to the assumptions in the regulations. Therefore, it is better to let the fire safety of buildings be based on actual human behaviour in fire, instead of to assume that human's behaviour will comply with technology based safety measures.

Human behaviour in fires is mainly studied by incident evaluations and real-life experiments, such as unannounced evacuation drills. Little of these studies are focused on the occupant decision-making process during evacuation. Therefore, else than travel speed and other reckonable aspects of evacuation, in general little information is known about human behaviour in fires. Besides that, the possibilities of a virtual environment for studying human behaviour in fires are so far hardly adopted by researchers. Since in virtual environments test persons can be faced with the phenomenon of fire in a safe manner, without being exposed to the extreme health risk of a real fire, the application of a behavioural assessment and research tool in Virtual Reality (VR) seems to be a valuable supplement on the existing research methods. Furthermore, it is comparatively easy to make design alterations in VR to investigate which building design corresponds best to actual human behaviour in case of fire.

From research in adjacent areas it becomes clear that results that are achieved with a VR research instrument, are comparable with the data from experiments in real environments. In particular, it is found [9] that a VR research instrument generates enhanced reliable information concerning the course behaviour of shopping public compared to the conventional method of an inquiry. Subsequently, as soon as a validated VR research instrument for the investigation of human behaviour in fires is available, a multiplicity of experiments can be conducted effortlessly.

The development of an innovative virtual reality based research instrument for fire safety engineering will be discussed in this paper, together with the methodology for the validation of the instrument. The innovative VR research instrument has to meet the already known information about human behaviour in fires. Therefore, the main conclusions of a literature review on human behaviour in fires will be discussed firstly. This literature review is the foundation for the scenarios and the assumptions in the validation methodology.

HUMAN BEHAVIOUR IN FIRES

This study is focussed on fire response performance. Fire response performance is the ability of an individual to perceive and validate clues of danger and to make decisions that are effective with regard to survive a fire situation with none or little health complications subsequently. The fire response performance of humans is influenced by [1, 10] (the behaviour of surrounding) people, (the design of) the building and (the effects of) the fire. The behaviour of people in fires contains the following dimensions:

- Social features (group behaviour)
- Individual features.

These five influencing factors on fire response performance are visualised in Fig. 1.

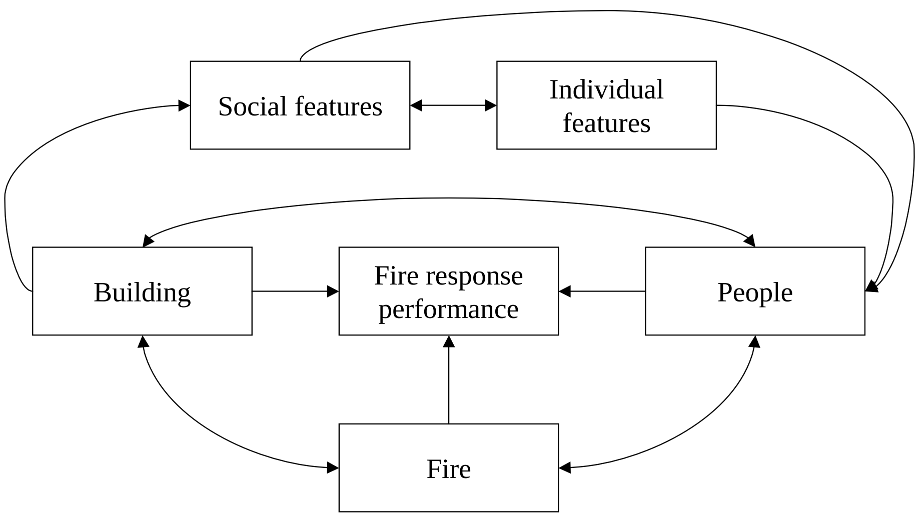

FIGURE 1. Factors that influence human's fire response performance

Fatal Fires

Like in other countries in The Netherlands most of the fire fatalities occur at night in residential buildings [11-13]. Besides in residential buildings, in the Netherlands fires with more than five fatalities have mostly occurred in public buildings [14]. Since 1970 twelve major fatal fires in the Netherlands have occurred at night in public buildings. In ten of these building the occupants present were asleep. Particularly, four fires, with in sum 63 deaths, occurred in hotel accommodations (8, 11, 11 and 33 deaths), three fires, with in sum 31 deaths, occurred in psychiatric institutions (6, 12 and 13 deaths) two fires, with in sum 14 deaths, occurred in homes for the elderly (7 and 7 deaths) and one fire occurred in a detention building (11 deaths). Besides being asleep, most of the occupants present in these buildings were dependent upon the help of others in the evacuation. The other two buildings were assembly buildings in which occupants present were awake, in particular a crowded pub (14 deaths) and an erotic night club (13 deaths).

In the Netherlands all the type of buildings mentioned above rarely have a sprinkler system present. Almost within all the major fatal fires an operational fire alarm system was not present. Hence most of these fires were noticed in a late stage. Consequently, survivors accounted a very rapid fire development as soon as they discovered the fire. Furthermore in most of the cases there was no trained Building Evacuation Team (BET) present. In all of the cases the main entrance was blocked by smoke and heat of the fire. Additionally, in half of the cases the fire exits were (or were assumed to be) locked and for that reason they could not be used. Therefore the occupants had to jump out of a window or had to wait for rescue by bystanders, personnel and the fire brigade.

In the USA most of the major fatal fires have occurred in assembly buildings with high occupant densities, specifically night clubs and theatres [15]. The determining factors for fatality in these fires are found to be the combustibility of interior finishing, the existence of blocked, closed or hidden (fire) exits, the limited capacity of the exits and the high number of occupants present in the building during the fire.

Evacuation

Aspects like clue validation and way finding performance during evacuation are found to have important effect on the probability of survival in case of fire. More interesting to know is which clues trigger the best fire response performance and how these clues effect way finding performance during evacuation.

Evacuation is the process in which the people present in a building notice a fire and whereupon they experience several mental processes and carry out several actions before and/or during the movement to a safe place in or outside the building [6]. The evacuation process is characterised by three certain basic activities, namely [1,4,7]:

- Awareness of danger by external stimuli (clue validation)
- Validation of and response to danger indicators (decision-making)
- Movement to / refuge in a safe place (movement / refuge).

Theoretically the basic activities can be converted into phases of the evacuation process, namely the clue validation period, the decision-making period and the movement / refuge period. The last mentioned period is also referred as the movement phase. The clue validation period and the decision-making period together is referred as the pre-movement phase.

Way finding covers the way how people orientate themselves within a building [16]. People need to have spatial knowledge and various cognitive abilities to succeed in way finding. Two aspects are crucial in the way finding performance, namely clues and choices. The way finding performance is determined by the perception and prior knowledge of persons who has to find their way within a building. Furthermore, there are four classes of environmental variables that influence way finding performance:

- Visual access
- The degree of architectural differentiation
- The use of signs and room numbers to provide identification or directional information
- Plan configuration.

Way finding starts in the pre-movement phase of the evacuation process. The ultimate goal of way finding in case of fire is to find the safest way from the endangered place to a safe place. The actions taken during evacuations are determined by the interaction between [1,10]:

- Building design, involving lay-out and interior design
- Environmental conditions, as a result of an incident
- Procedural aspects, covering the actions of staff, the level of occupant evacuation training and occupant prior knowledge
- Human behavioural aspects, including initial responses, mobility and affiliate behaviour.

The interactions between the four aspects take place during the clue validation period, the decision-making period as well as during the movement / refuge period. These four aspects are referred to in several performance-based regulations worldwide for fire safety engineering.

Clue Validation and Decision Making

Since decision-making during evacuation depends upon the clues that the occupants perceive and on the occupants' interpretation of these clues, clue validation is an important process in evacuation. The perception of danger determines the reaction on signs of danger [17].

A fire alarm bell or a 'slow whoop' signal is hardly recognized as a sign of danger and thus usually ignored by the occupants present in a building [18,19]. Furthermore sleeping children, elderly, people with a sleep delay, people under the influence of narcotics, alcohol or drugs and people in environments with significant background noise are unlikely to awake by a fire alarm [11]. A fire alarm using a spoken message, or a communication system by way of personnel directives, is taken most seriously by the occupants present in a building [20].

The sight and smell of fire and smoke are the clearest indications of a dangerous situation and the need of evacuation [8]. Nevertheless, even then people are found to continue their normal activities and wait for other people to respond first before they respond themselves [5,21]. Several accidents and experiments indicate that evacuation training of personnel has a positive influence on the reduction of the pre-movement time [5,7,22].

In case of fire, indications and clues which generally lead to an exploration of the situation are [3]:

- Hearing a strange sound
- Uncommon behaviour of other people in the surroundings
- Observing fire and smoke.

In many cases the degree of uncertainty concerning the danger situation delays the beginning of an evacuation. Therefore, eliminating the uncertainty is an important factor on improving human behaviour in fires.

Several incident evaluations have shown that people are confronted with smoke during evacuation. Moreover, people tend to evacuate through smoke filled areas, even though they are acquainted with the fact that smoke is hazardous [4, 23].

Way Finding Performance

The sight reduction and the breathing irritation as a result of smoke development both have a negative influence on occupants' way finding performance. Several interviewed evacuees who have tried to evacuate through smoke declared that they had to change direction or even had to return because of breathing problems, vision reduction, fear or other reasons [23].

Route choice depends upon the familiarity of the occupants with the building, the availability of exits, the accessibility of the route towards exits and upon the lay-out complexity [1,6]. Furthermore affiliative behaviour is considered to effect route choices during evacuation [21]. Occupants normally evacuate by using familiar routes, mostly the main exit which is normally the entrance of a building [12,17,22]. Not the actual length but the perception of the length determines the route choice [17,22,23]. For example, corridors with several bends and unfamiliar routes are experienced to be longer than straight and familiar routes [24].

Fire exits which are not regularly used tend to have a negative association [25]. Specifically, based upon evacuation experiments in a department store it is presumed that the fire exit will only be used if the door is open and additionally if the walking distance towards the main entrance is two times longer than the walking distance towards the fire exits. Furthermore, during a fire in an elderly care home 95% of the patients were evacuated by the main staircase and the other three available emergency staircases were not used at all. Therefore the total evacuation time was longer than calculated by the architect. Experiments and incident evaluations appear to show that personnel directives on route choice have a positive effect on the utilization of fire exits [17, 22, 25, 26].

Way finding is supposed to be more dependent on the lay-out of the building and seems to be barely dependent on (escape) route signs [16]. Incident evaluations indicate that evacuees are hardly aware of the presence of escape route signs at ceiling level or at least their route choice is not based upon it [26, 27]. Nevertheless, experiments show that photoluminescent low-level exit path markings are likely to be more effective during a fire evacuation compared to conventional escape route signs [27, 28]

BEHAVIOURAL ASSESMENT AND RESEARCH TOOL

Research Aim, Object and Subject

The primary aim of our behavioural research in virtual reality is the validation of a research instrument in VR. The additional aim of the research is (1) obtaining insight in human behaviour in fires, particularly in the intentions on which the route choice of evacuees are based upon; (2) appointing lay-out measures or design options which create optimum preconditions for people present in buildings so that they choose the safest escape route, and; (3) determining the effectiveness of the appointed measures and design options (the degree in which the behaviour of occupants is affected by the appointed measures and design options).

Evaluations of fatal fires reveal that (in The Netherlands) the major fatal fires have mostly occurred at night in residential buildings and in public buildings [14]. In public buildings a manager is responsible for the safety of the people present. Such buildings have the possibility for the simultaneous presence of dozens of persons and with that the potential to a fire with many casualties and subsequently high media and political attention. Moreover, incident evaluations have revealed that in most of the fatal fires a trained BET was not present.

Furthermore, it appears that particularly hotel accommodations have a high risk profile. In the Netherlands some thousands of this type of buildings are present and millions of individuals make use of hotel accommodations annually. Therefore a hotel building is selected as the object for closer research on human behaviour in fires. Nevertheless, it must be noticed that the other types of buildings mentioned in this paper are also interesting as a research object. But with regard to the scope of this research, that is the validation of a VR research instrument, a less complex building is preferred wherein persons are present who are mobile and capable of evacuating without the help from others.

The subjects who are examined are primarily related to way finding. There are three main reasons for the focus on way finding. First of all, the way in which persons find the safest escape route, and how this process can be supported with lay-out and design measures has been hardly examined [29, 30]. Thus, there is need for insight in the decision-making processes which evacuees pass through. Secondly, way finding itself can pre-eminently be studied in a virtual surrounding, since building modifications, for example design alterations of the escape route, are easily made within VR. Thirdly, building specifications are expected to influence evacuation behaviour.

Research Instrument

To obtain insight in the escape behaviour of people present and in the effect of the building design on that escape behaviour (way finding) a Behavioural Assessment and Research Tool (BART) has been developed. BART is based upon a well tried and tested simulation platform that is used by emergency training organisations all over the world for years now, that is the Advanced Disaster Management Simulator (ADMS™). ADMS™ is an interactive, real-time, physics-based virtual environment with realistic 3D visuals and audio. Primarily it is developed as a team training environment for incident command teams and emergency responders. It simulates emergency incidents such as fires, accidents, terrorist acts, hazardous spills, airfield incursions, and natural disasters for intra- and inter-agency coordination, training, planning, testing and validating emergency plans. The simulator is basically is a so called Serious Game, a realistic simulated environment. With BART the ADMS™ training platform can be used additionally for gaining research data on human behaviour in emergencies. Since the simulator uses multiple server-based networking processes to manage multi-user simulations, it is possible to do research on the behaviour of both individuals and groups. The movement of the virtual test person in BART is controlled by using a joystick. The projection takes place by means of a beamer on a 2 by 2 m sized flat projection screen.

For making the software of ADMS™ suitable for behavioural research, the software is extended with several functionalities. Primarily, a tracking and registration device is implemented which generates the required data for behaviour analysis. With this the test persons' movements within the virtual building is automatically stored. The tracking and registration device consist of a 3D real time movie, a time/event database and a run path diagram. An other important functionality is the additional object (a hotel) that has been visualised in the simulator. Therefore pictures are taken of the interior and exterior of a Dutch hotel. In Fig. 2 the degree of similarity between the real hotel and the virtual hotel is shown.

Photo of fire exit in real hotel

Photo of fire exit in ADMS™-BART

FIGURE 2. Degree of similarity between the real hotel and the virtual hotel

Also an option for making several design alterations in the lay out of the hotel is implemented. With the alteration option for instance the exit signs present at ceiling level can be replaced with exit signs at floor level. The width of a corridor can be changed too, as well as the design of the exit doors, the location of an exit door, the lighting intensity among other design alterations.

In the virtual hotel two standard fire and smoke situations are applied, namely:

Situation 0: no fire, no smoke.
Situation 1: small fire, light smoke with visibility limits.

The lower-side of the smoke layer is determined on 1.2 m altitude. When a test person walks in smoke he or she experiences limited sight. An expected action in this situation is to crawl instead of walk through the building. Therefore, the test person can modify the view altitude during the experiment. In the model two view altitudes are applied, namely:

Standard: view on 1.7 m altitude.
Crawling: view on 1.0 m altitude.

When the test person decides to crawl the maximum walking speed will decrease automatically.

Furthermore an injury indicator is implemented in the simulator. The injury indicator consists of changing breathing sounds related to the present situation. For example, when the test person walks in smoke (high injury level) he/she hears the sound of a hurrying breathing rate. The intentional function of the injury indicator is to simulate a stressing situation corresponding with the stress level in a real fire situation. By measuring the blood pressure and the heart beating rate of the test person before and after the experiment, and by comparing the two measuring results, the personal stress level is defined.

RESEARCH DESIGN

Exploring the Main Beliefs on Human Behaviour

Because of the aim of the validation of BART, six experiment scenarios are carried out in a real hotel as well as in a virtual hotel. Before the experiments are carried out an ethical commission has approved the research set-up. The experiments are unannounced fire drills. At night and one by one the participants are alarmed by means of a telephone message. In this message the hotel receptionist communicates to leave the building as soon as possible because of fire. In every separate experiment scenario, both in the real as in the virtual hotel, approximately 25 persons take part. These persons represent the average of the standard hotel occupancy (including gender, age, mobility, percentage of the Dutch-speaking occupancy). For the entire research in the real hotel 150 different hotel guests are involved. In the experiments in the virtual hotel another 150 different test persons are involved. Afterwards the 300 participants received a small gift and a leaflet in which the aim and the importance of the research have been reflected.

For the validation of ADMS™-BART the already known information in literature is implemented in the experiment scenarios. The concise formulated main beliefs on human behaviour and the connecting experiment principles are given in Fig. 3.

No	Main beliefs on human behaviour	Experiment principles
1.	Most fatal fires occur at night when occupants present are asleep	The test persons are at sleep and aroused by an emergency message
2.	Spoken emergency messages are taken most seriously by occupants	The emergency message is a spoken message by phone
3.	In most of the fatal fires a trained BET was not present	The test persons are tested individually and no BET official will assist the test person
4.	One of the four environmental variables that influence way finding performance is plan configuration	The corridors of the chosen hotel have several bends, side-halls and a dead end
5.	One of the four environmental variables that influence way finding performance is the degree of architectural differentiation	The lay out of the chosen hotel is classified as 'complex'
6a.	Occupants normally evacuate by using familiar routes, mostly the main exit which is normally the entrance of a building	The influence of smoke on route choice is monitored in scenarios 1 and 2. In scenario 2, 3, 4, 5 and 6 the main entrance is blocked by (simulated) smoke
6b.	In all of the fatal fires the main entrance was blocked by smoke and heat of the fire	
6c.	People tend to evacuate through smoke filled areas	
7.	Fire exits which are not regularly used tend to have a negative association	The influence of several design alterations on route choice, and thus the usage of fire exits, is monitored in scenarios 2, 4, 5 and 6
8.	Personnel directives on route choice appear to have a positive effect on the utilization of fire exits	The influence of personnel directives on route choice is monitored in scenarios 2 and 3
9a.	One of the four environmental variables that influence way finding performance is the use of signs	The influence of two types of signs is monitored in scenarios 2 and 5: green exit signs at ceiling level and green photoluminescent exit signs at floor level
9b.	Evacuees appear to be hardly aware of the presence of escape route signs at ceiling level	
9c.	Photoluminescent low-level exit path markings are likely to be more effective compared to conventional escape route signs	
10.	One of the four environmental variables that influence way finding performance is visual access	The functionality of changing the visual access is implemented in ADMS™-BART, for example, the location of doors and the transparency level of glass in doors and windows can be changed

FIGURE 3. Main beliefs on human behaviour and experiment principles

Experiment Scenarios

The main principles of the validation scenarios with their aim are appointed here. Every scenario is elaborated in a brief description, an observation focus and a proposition. The propositions are based on results out of a literature study (scenario 1, 2, 3), assumptions contradictory to fire regulations (scenario 1, 2, 4) or on a hypothesis (scenario 4, 5, 6).

Scenario 1: Standard Situation

Observation: Which escape route does the person use and which actions does he/she take?

Proposition: Over 70% (more than 18 persons) leaves the building through the main exit.

Scenario 2: Baseline Situation

Observations: Which escape route does the person use and which actions does he/she take? Does the person pass along the fire and through the smoke?

Proposition: Over 70% (more than 18 persons) pass along the fire / through the smoke and leaves the building through the main exit.

Scenario 3: Usage of Emergency Exit

Observations: Which escape route does the person use and which actions does he/she take? Does the person pass along the fire and through the smoke? Does the person follow the communicated assignment?

Proposition: Over 70% (more than 18 persons) follows the communicated assignment and leaves the building by using the nearest emergency exit. These test persons do not pass along the fire / through the smoke.

Scenario 4: Escape Route Signs

Observations: Which escape route does the person use and which actions does he/she take? Does the person pass along the fire and through the smoke? Does the person look at the escape route signs?

Proposition: Over 70% (more than 18 persons) looks at the escape route signs and leaves the building by using the nearest emergency exit. These test persons do not pass along the fire / through the smoke.

Scenario 5: Illumination Level

Observations: Which escape route does the person use and which actions does he/she take? Does the person pass along the fire and through the smoke? Does the person pass along emergency exits?

Proposition: Over 70% (more than 18 persons) leaves the building by using the nearest emergency exit in the first instance. These test persons do not pass along the fire / through the smoke.

Scenario 6: Escape Route Signs and Illumination Level

Observations: Which escape route does the person use and which actions does he/she take? Does the person pass along the fire and through the smoke? Does the person look at the escape route signs? Does the person pass along emergency exits?

Proposition: Over 70% (more than 18 persons) looks at the escape route signs and leaves the building by using the nearest emergency exit in the first instance. These test persons do not pass along the fire / through the smoke.

The experiment scenarios that are carried out in the virtual environment are in the first place the same as the experiments in the real environment. In five of the scenarios there is a perceptible fire present. In the real experiments the fire is simulated by means of a smoke generator, red randomly flickering light and crackling sounds. In the virtual experiments the fire is simulated by means of visual flickering flames and developing smoke and by means of audible crackling sounds.

Registration and Evaluation

In the real hotel the behaviour of the hotel guest (from the hotel room to the chosen emergency exit) is registered by means of cameras. Each vital action, such as changing view direction, changing movement direction, changing movement speed and opening doors, is registered related to time. Also the actions of the test person in the virtual hotel are recorded, related to time and position, and are automatically stored in a database. Furthermore the route choice is visualised in both a map and a movie in ADMS™-BART.

In an evaluating interview, directly following on the experiment, the hotel guest is asked to reveal the intention of his/her behaviour and to clarify his/her considerations. Therefore, after the recording of his/her escape is shown, the hotel guest is asked to answer some standard questions, such as:

- What was the extent of danger you perceived?
- Why did you choose that escape route and take those actions?
- Which information did you get out of the communication and the design of the escape route?
- How did you interpret that information?
- Was the route choice based upon the escape route signs?
- Which prior information and experience, both related to route choice and evacuation, did you have and did you use it during the experiment?

The results of the six validation experiments in both the real and virtual hotel are compared and considered to what extent the results concur. The result consist of a combination of certain vital actions, a certain exit choice (main exit A or B or fire exit C or D) and a certain route choice (number of turns, returns and total length of the chosen route) per scenario. These results are related both to time and to the intentions of the test person. After the validation assessment various additional experiments can be carried out in VR. Particularly experiments which intervene on the architectural situation of the hotel are qualified as additional experiments.

CONCLUDING REMARKS

Aspects like clue validation and way finding performance during evacuation are found to have important affect on the probability of survival in case of fire. More interesting to know is which clues trigger the best fire response performance and how these clues effect way finding performance during evacuation. In general little information is known about human behaviour in fires. Human behaviour in fires is mainly studied by incident evaluations and real-life experiments, such as unannounced evacuation drills. Little of these studies are focused on the occupant decision making process during evacuation. Furthermore, the way in which persons find the safest escape route, and how this process can be supported with lay-out and design measures has hardly been examined.

Since in virtual environment test persons can be faced with the phenomenon fire in a safe way, without being exposed to the extreme health risk of a real fire, the application of a behavioural assessment and research tool in VR is likely to be a valuable supplement on the existing research methods. A soon as ADMS™-BART is validated, a multitude of experiments can be carried out for deciding which building design fits best on actual human behaviour during fires. It is expected that BART generates the information for fire safety engineers and architects which is needed for the design of a fire safe building that corresponds to the actual human behaviour in fires.

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