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# A virtual reality study of behavioral sequences in residential fires

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ABSTRACT

Decision-making in residential fires can be difficult to study in an experimental setup. Virtual reality could be a way to expose participants to a residential fire scenario and collect data on their behavior. However, the validity of the data obtained needs to be assessed. To explore that, the data collected in two virtual reality residential fire scenarios in form of sequences of behavior was compared to the general model developed by Canter, Breaux and Sime. Two scenarios were developed, one with and one without a smoke alarm. Two samples of 20 participants each were exposed to a fire in a virtual house. The participants were residents of houses with the same layout as the virtual one, making them familiar with the building. The sequence of actions they performed were recorded and decomposition diagrams were drafted based on them, to then be compared to the general model. The results show that the participants' sequences of behavior did not only fit those predicted by the general model, but also that the participants followed many different sequences, covering most of the possible patterns indicated in the general model, as it is expected in a real world fire.

## 1. Introduction

A clear trend in Sweden, as well as many other developed countries, is that the majority of fire-related fatalities occurs in residential buildings [1–3]. The proportion varies among those countries, although it is usually between 70 and 90% of fire related fatalities occurs at home [4]. Kobes et al. [5] identified some behaviors (smoking, cooking, use of candles, use of electrical appliances, use of heating appliances, and playing with fire) as the most prevalent causes of fires in residential buildings. The nature of residential buildings allows their occupants to engage in these behaviors without any safety routine or supervision. Moreover, certain expected behaviors in this type of buildings (such as all occupants being asleep at the same time) can reduce the chances of early detection, suppression and evacuation attempts. In fact, some studies have shown that, while only approx. 20% of the fires in residential buildings occur during the sleeping hours, they account for around half the total number of fatalities in this type of buildings [5,6].

Data from the Swedish Civil Contingencies Agency shows that in many residential fires in Sweden, people became aware of the fire early enough to evacuate safely, although, for some reason, they did not [1]. To improve fire safety designs, a deeper understanding of this behavior is therefore needed. Data from the fire investigations performed by the firefighters and the police were used to determine what actions people performed that delayed their evacuation. Those actions seemed to be not only appropriate but in many cases also necessary to tackle the situation. Examples of actions were efforts to extinguish the fire, alerting other occupants, or calling the rescue service before leaving the building [1]. While those actions are in no way irrational or out of place, they take valuable time that may not be fully taken into account in the design of the fire safety strategy of residential buildings. With that in mind, the question of what people do when they become aware of a fire in their own homes becomes relevant. However, obtaining such data has proven to be a challenge.

For example, the cost of replicating a house with a high level of detail in a laboratory can be a major obstacle for research even if that might provide a good environment for investigating behavior actions after a fire. Additionally, due to the inherent high risks, exposing people to fire and smoke is not ethically viable. These limitations are valid for any method used in human behavior in fire research. In recent years, however, virtual reality (VR) has become a suitable method for overcoming such limitations [7,8]. Kinateder et al. [9] have argued that VR experiments can be compared to laboratory experiments, with analogous advantages and disadvantages. Thus, it is possible that VR could be used to render valid results. Replicating a house with a high level of detail in VR is relatively simple, and virtual fire and smoke present no more risks than those related to the use of VR in general. These risks are associated

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with those from motion-sickness (e.g. nausea, losing balance, etc.), which do not necessarily affect all VR users, and do not have a lasting effect. Nevertheless, a VR scenario that feels too real could also lead to high stress in participants that may not be intended or necessary. This could be especially damaging for fire victims, and precautions need to be taken to avoid peaks of stress.

While VR has been used for human behavior in fire experiments before [10–14], questions about its ecological validity (i.e. how well the VR method replicates a real world scenario [9]) are constantly raised in the wider human behavior in fire community. Therefore, validation of the VR method is crucial to develop it further. One way of checking validity of data is to compare it to existing models. Hence, the aim of this paper is to compare the outcomes of a VR experiment based on a residential fire to the general and fundamental model developed by Canter, Breaux and Sime [15].

The general model (see Fig. 1) was derived from data collected by interviewing survivors of several fires in the late 1970s [15]. The selected sample of fires covered three kinds of buildings: domestic, multiple occupancy and hospitals. The interviewees gave their accounts of the events they experienced, and a sequence of their actions was drawn. This information was presented in decomposition diagrams for better understanding, from which the general model was developed. This model gained acceptance and is widely used by the human behavior in fire community [16–18], as it depicts sequences of behaviors and the possible outcomes. While there are other models of behavioral sequences also widely accepted in the community (i.e. PADM [19]), the general model was chosen not only for its simplicity but also for the agreement between the data used to develop the model and the data that could be collected in the VR scenario. Canter Breaux and Sime [15] aimed to reduce the patterns of behavior from the decomposition diagrams into a general model, in such way that any fire would represent a variation of that model.

It could be argued that a set of behavior sequences obtained in a VR experiment should not only be contained within the general model, but it should also cover most if not all the expected outcomes in it. The sequences of behavior obtained should hence not be reduced to a handful of sequences repeating the same pattern, but instead present many different ones. The objective of this paper is to study if the observed sequences of behavior of participants in a VR experiment cover most of the possible sequences of behavior predicted by the general model. To accomplish this, decomposition diagrams of the sequence of actions performed by participants exposed to a residential fire in VR are made. The decomposition diagrams obtained are then compared to the general model.

## 2. Method

To investigate if behavior in VR experiments follow different patterns, an experiment was designed in which participants were exposed to a virtual fire in a 3D computer modelled house that looked very similar to their own. Behavioral sequences were then drafted and compared to the general model. In addition, a qualitative evaluation of the benefits and the limitations of the use of VR in this experiment was made.

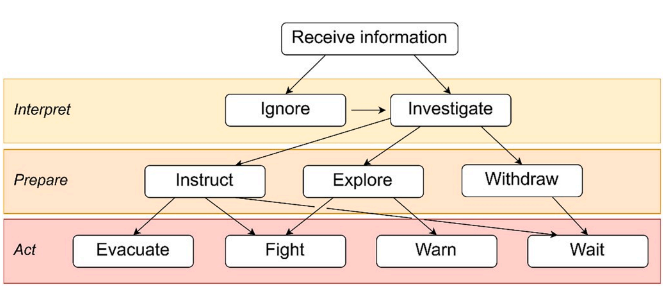


**Fig. 1.** Reproduction of the summary of the general model developed by Canter, Breaux and Sime [15].

A house located in Stångby, Sweden, was replicated in a 3D model. The house is part of a tract housing development, with around 80 identical houses. This allowed getting many participants who would see a high similarity between the 3D model and their own house. The façade and layout of the house were a replica of the real house. The virtual house was modelled on a street with other identical houses, which was similar to the participants' neighborhood. Section 2.3 gives further details on the layout of the house.

### 2.1. Participants

Residents of Stångby living in the modelled house or the mirrored version of it were recruited for this experiment. Recruitment was done by going door-to-door to peoples' homes and asking them to take part in the study. Participants were divided in two groups, each group corresponding to a scenario. The scenarios are described in detail in section 2.4. Table 1 shows the characteristics of the participants for each scenario. Each participant received two cinema tickets (valued around SEK 250 or €25) as a form of compensation for their participation.

### 2.2. Equipment

The equipment consisted of a high-end gaming computer, a VR head-mounted display (HTC Vive™, dual AMOLED 3.6" diagonal screen, $1080 \times 1200$ pixels per eye, 90 Hz refresh rate and $110^\circ$ of field of view, and $6^\circ$ of freedom of movement) with their hand controllers, headphones, and an omnidirectional treadmill (Cyberith Virtualizer). The high-end gaming computers met the performance requirements of the head-mounted display, and it included an Intel i7-7700k CPU, Nvidia GeForce GTX 1080 8 GB GPU and 32 GB of ram. The computer was capable of keeping a locked framerate of 90 frames per second throughout the experiment, in order to avoid inconsistencies between the participants' movements and the rendered images. The virtual environment was generated using SketchUp™ version 2015, and the game engine used was Unity 3D™ (version 5.6.2f1).

The omnidirectional treadmill allowed the user to move in any direction and "walk" in the virtual environment without changing their physical location. It consists of a low-friction surface on which the user can move almost as if they were walking. The user moves in the virtual environment at their preferred walking speed on the treadmill. Walking on the treadmill is not like natural human walking. It requires the user to tilt slightly forward to displace their center of mass causing the feet to slide backwards due to the low friction of the surface. A ring and a sturdy harness prevent the user from falling. The harness still allows the user to turn $360^\circ$. The ring and the harness can also move vertically with the user, allowing the user to bend down and duck while walking. It was considered that the treadmill would help the immersion for the participant, since it would allow a more natural movement in the scenario compared to navigation by use of hand controllers.

During the experiment, a computer screen showed the researchers what the participants were seeing in the head-mounted display. The images on the computer screen were recorded. No recording was made of the participants themselves.

After the experiment, participants filled out a questionnaire, providing demographical data, as well as a description of their experience during the experiment. The questionnaire also asked for ratings of realism of the scenario, sensations of fear, stress, and discomfort.

### 2.3. The house

The real house has two floors and a garden. On the ground floor, there is an access hall, a storage room, a laundry room, a bathroom, a kitchen and a living room. In the upper floor there was a second living room, a second bathroom, the master bedroom, two smaller bedrooms,

**Table 1**
Description of the two samples of participants by age and gender.

| scenario | gender | | age | | | | | |
|---|---|---|---|---|---|---|---|---|
| | female | male | min | max | average | st.dev. | median | mode |
| 1 | 9 | 11 | 35 | 51 | 42 | 4.16 | 41.5 | 42 |
| 2 | 7 | 13 | 34 | 47 | 39.4 | 4.12 | 39 | 39 |

and a small storage room. The garden is all around the house, including two decks and a parking spot for a car. Fig. 2 shows the layout of the ground floor and the upper floor and the facades. A wooden fence and an array of bushes separate the garden from the neighboring ones. The house is on a street with other identical houses. The 3D model of the house had the same features, including the street and the neighboring houses. Fig. 3 shows a view of the kitchen from the living room, for both the real and the modelled house.

### 2.4. Scenarios

The experiment required a scenario that would represent a residential fire, in which it was possible for the participant to call the rescue service, try to extinguish the fire, alert or rescue another person in the house, and allow the participant to evacuate the building. To prompt the participants to evacuate, the scenario was designed in such way that the fire could not be extinguished, and staying inside the house would be unsafe. Additionally, the entrance used by participant to enter the house was blocked in order to force them to look for an alternative route.

There were two scenarios: Scenario 1 (S1) and Scenario 2 (S2). The scenarios were identical with the sole exception of the sound of a smoke alarm in S2, which was needed to represent the cases in which there is a smoke alarm alerting occupants about the fire. In both, the fire was located at the front door (see point 1 on Fig. 2). The fuel was a pine tree, similar to a Christmas tree without ornaments, which was visible next to the main entrance since the beginning of the experiment. A fire extinguisher was visible on the corner of the kitchen counter (point 2), to give the participants the possibility of fighting the fire, although they were not instructed to do so. When in operation, the extinguisher sprayed dust, resembling a powder extinguisher. However, it was designed to run out without extinguishing the flames, so that participants would need to leave the house to be safe. A computer generated sleeping adult (non-player character) was placed on the couch in the living room (point 3), to give the participant the opportunity to rescue or alert another occupant. Their presence was also not pointed out, but participants could easily see them. No animations were included, and the non-player character just laid on the couch in a sleeping position with their eyes closed. The fire only started when the participants reached point 4 in the upper floor. A ringing cellphone guided the participants to that point, and it could be used to call the rescue service. The smoke reached the upper floor by the stairs, which were next to the front door. Other than the main entrance (which was blocked by the fire), there were three exits to the outside: in the laundry room, in the kitchen, and in the living room. All exit doors had windows in them, and participants could clearly see they led to the outside.

Pilot tests were conducted to test the scenarios. They showed some issues in the design of the scenarios that were corrected before running the experiments. During these tests, it became clear that some participants would try to close the door in any bedroom to stay inside, and/or try to open the windows to vent the smoke. Since it was fundamental that the participant tried to evacuate the house, it was not possible to either close doors or open any windows.

### 2.5. Experimental procedure

The experiment ran between June and August 2017, and each run took approx. 30 min per participant. Upon arrival to the experimental room, participants were asked to sign an informed consent form they received in advance. They were then fitted with the equipment and were instructed how to use it, and a training scenario was launched. The training scenario had no resemblance to the house, and had some features for the participants to get used to the equipment and its use. A series of arrows guided the participants through the training scenario, in order to get them acquainted with the use of the omnidirectional treadmill. Some objects were placed on shelves so participants could learn to hold them or carry them.

After the training, the experiment started with the participant standing outside the VR house looking at the house façade and the neighborhood. While standing there, they were told that they were seeing a replica of their own house. They were told to walk into it and evaluate how realistic the house felt. They were asked to start at the ground floor, then continue with the upper floor, and after that, the

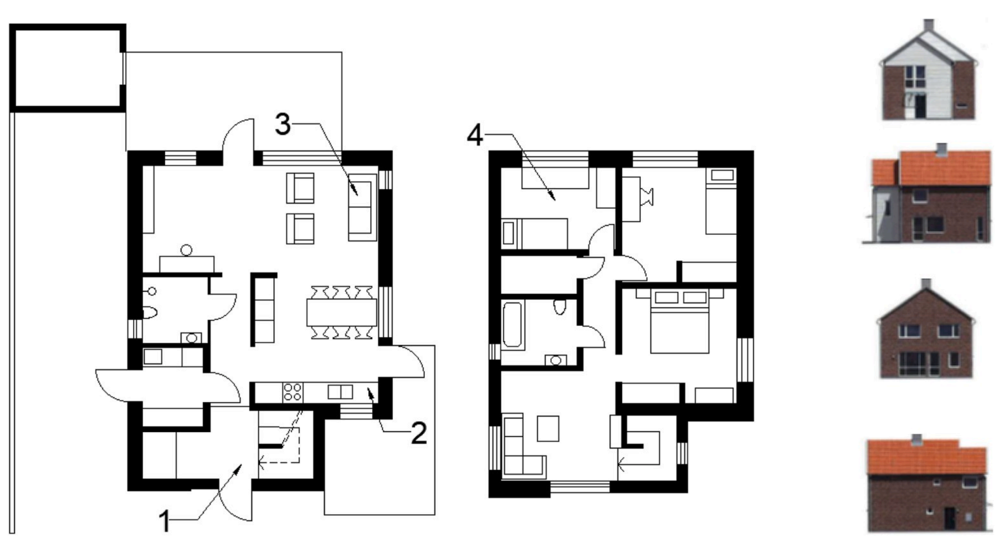


**Fig. 2.** Floor plans and facades of the selected house.

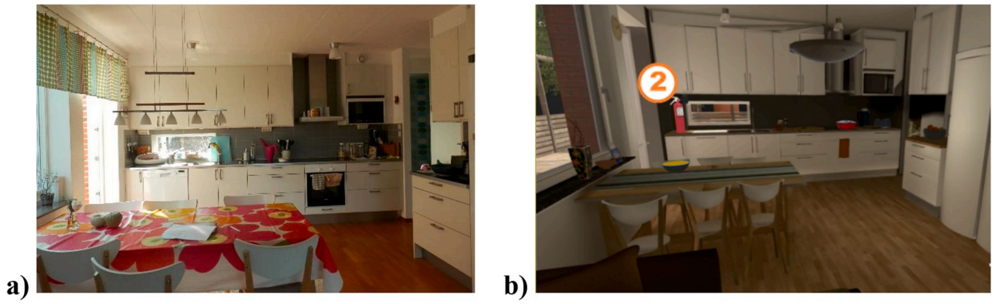


**Fig. 3.** The kitchen of the real house (a) and the VR house (b). Notice extinguisher indicated at point 2.

garden and down the street. It should be noted that there was no reference to a fire or any sort of emergency. The participants were told they were not going to be given any more instructions and the experiment started.

The participant entered the house and started to explore it. When the participant approached the non-player character (1 m or less), a message showed up above the non-player character reading “Shhhh” indicating the person was asleep. The participant had to climb the stairs to get to the upper floor. The stairs looked like regular stairs, but for the omnidirectional treadmill, it consisted of a series of ramps, which were invisible to the participant. Therefore, the movement for the participant to climb the stairs was not different than the movement to walk in any other part of the house. When the participant reached the middle of the hallway on the upper floor, a cellphone started ringing. The sound of the phone guided the participant to the farthest room from the stairs (see point 4 in Fig. 2), and it would not stop until the participant reached for the phone. At this time, the smoke instantly filled the entrance, the stairs and the hallway in the upper floor, but the participant, facing the opposite direction, could not see the smoke until they turned around. In S2 the alarm was activated with the smoke.

Once the participant turned around and saw the smoke, whether there was an alarm or not, they had to act according to what they saw fit. As mentioned before, trying to open windows or closing doors was not possible, but some participants attempted to do so in order to avoid going down the stairs. These attempts were recorded. Once they realized there was no other option, they went downstairs and saw the fire.

It was possible to use the phone at any point to dial 112 (the number of the emergency dispatch center in Sweden), and if done so a message appeared on the cellphone screen stating that the firefighters were on their way. They could use the extinguisher also at any point to try to extinguish the fire, and try to rescue the non-player character. Waking up the non-player character consisted of the participant approaching it and getting close enough (about 1 m), in which case a message showed up indicating that they could wake up the non-player character by touching their shoulder. When the participant did so, the non-player character instantly disappeared and a message showed up telling the participant that the person had evacuated the house and was safe. The experiment ended once the participant exited the house by any other door than the main one (which was blocked by the fire).

During the experiment, notes on the sequence of the actions performed by the participants were taken by hand. Participants were able to interact with most of the objects in the house during the entire experience, but only the actions relevant to the fire emergency were taken into consideration in this study. The experiment was individual, and each participant did it only once. After the experiment they were asked to fill in a questionnaire.

### 2.6. Analysis

A posterior analysis of the video recordings allowed determination not only of the order in which the different actions were performed by the participants, but also how many times that action was attempted. That sequence of events was then translated to a “transition matrix”, similarly to what was done by Canter, Breaux and Sime [15]. The actions used in both the rows and the columns of the transition matrix are described as follows:

- *Smoke starts*: this marked the beginning of the emergency in S1. The smoke starting means it was visible, but it did not mean that the participant saw it yet.
- *See smoke*: this marked the moment the participants in S1 saw the smoke and understood something was going on. Seeing the smoke meant that the smoke was not only visible in the participants' field of view but also there was a reaction from the participants' side to it. This reaction consisted of stopping doing other actions, paying attention to the smoke and/or a verbal expression of surprise or curiosity, followed by exploration.
- *Smoke and alarm starts* (S2 only): the beginning of emergency, the fire being detected.
- *React to alarm, see smoke* (only S2): refers to participants who interrupted what they were doing at the moment the alarm went off, and looked around to see what was going on.
- *Misinterpret smoke (S1 only):* as mentioned before, the smoke was designed to give little room for misinterpretation. It is clear that misinterpretations could occur, but it was not possible to tell if the participant misinterpreted the smoke or did not notice it. Therefore, only reaction to the smoke was recorded, and the misinterpretation was not measured.
- *Misinterpret alarm* (only scenario 2): refers to participants who did not interrupt what they were doing the moment the alarm went off, and carried on with their activity at the time. Contrarily to the misinterpretation of the smoke in S1, in S2 it was easy to tell if the participant stopped what they were doing to look around and try to identify what that sound was.
- *Smoke control*: this category refers to participants who attempted to control the smoke spread by trying to open a window upstairs or trying to close a door behind them in the bedrooms.
- *Call 112*: this action refers to the participants using the cellphone to call the rescue services.
- *Reach ground floor*: the action refers to the moment the participants went down the stairs and walked past the fire.
- *Try to extinguish*: attempts to fight the fire by any means. The fire extinguisher was the expected tool for this task, but other objects or techniques such as reaching for a carpet, towels or filling a bowl with water were also recorded.
- *Awake person*: the attempts of rescuing the sleeping person were classified in this category.
- *Exit house*: refers to the successful evacuation of the house.

Decomposition diagrams were generated using transition matrices. The reduced sample size (20 participants in each sample) did not allow for statistical tests to compare the strength of association as done by Canter, Breaux and Sime [15]. To generate the decomposition diagrams, the actions detailed above needed to be analyzed in order to assess how they fit in the general model. The assessment referred to whether the action could be considered part of one of the three nodes identified by Canter, Breaux and Sime: “interpret”, “prepare”, and “act”.

## 3. Results

The different actions were classified as follows:

- “Smoke starts” and “smoke and alarm start”: these actions are triggers of the event, and can be compared to the “receive information” category in the general model.
- “See smoke” and “react to alarm, see smoke”: these actions fall in line with the interpret node. They refer to the right interpretation of the cues received, which lead to tackle the emergency.
- “Misinterpret smoke” and “misinterpret alarm”: these actions also fall in the interpret node, and they are a wrong interpretation of the cues received.
- “Reach ground floor”: this action cannot be included in the interpret node, as in both scenarios to reach the ground floor participants must have seen the smoke in the hallway and in the stairs. In the prepare node, this action can lead to different outcomes such as exiting the building, fighting the fire and awake the sleeping person.
- “Smoke control”: this action refers to ways of limiting the spread of the smoke (by closing doors) or ventilating the affected rooms (by opening windows). It can be included in the prepare node as it can be considered an action that would be followed by waiting to be rescued or, alternatively, improving the conditions of the escape route to attempt an evacuation.
- “Call 112”: this action proved to be ambiguous, as it can be considered part of “prepare” or “act” nodes, or even none of them. It could be included in the prepare node if the action is to be considered part of the strategy of waiting to be rescued. It could be included in the act node if it is seen as a part of the act of fighting the fire. Canter, Breaux and Sime included it in the act node, classifying it as “warn”. It is unclear how it can be interpreted as a warning, since calling the fire fighters can hardly be considered a warning but instead a call for action. Alternatively, calling the firefighters does not accomplish any extinguishing or any evacuation. In this paper it was included in the prepare node as the initial statement of considering it part of the strategy of waiting to be rescued, which is consistent with the “withdraw” category in the general model.
- “Awake person”: this action also can be ambiguous and fit both nodes. It should be considered that in this scenario, the sleeping person was an adult. As such, waking them up and informing them about the fire could be considered a warning (act node). Alternatively, it could be argued that the action refers to instructing them to evacuate or help out with the extinguishing attempt. In that case, the action would be classified into the node “prepare”, as it resembles the “instruct” category. It could also be considered as an act of rescuing the person, in which case is still unclear in which node the action can be classified. In this paper, the “awake person” action is classified as part of act, comparable to “warn” in the general model.
- “Exit house”: this action is clearly part of the act node.
- “Try to extinguish”: this action is also easy to classify as part of the act node.

Tables 2 and 3 present the transition matrices for S1 and S2 respectively. Each cell shows the number of participants that, having performed the action described in each row, moved on to perform the action described in each column. Since no action can precede the one in the first column, and no action can succeed the one in the last row, the first column and the last row are empty in both tables.

It should be noticed that the total number of participants in each row does not add up to 20, because some participants decided to stop the experiment at different stages.

Fig. 4 shows the decomposition diagram for each scenario. The labels on the arrows do not show the strength of association as can be seen in Canter, Breaux and Sime’s analysis [15], but rather the proportion of participants in the scenario performing an action based on their previous one (as shown in the transition matrix). The three sections (interpret, prepare and act) are also indicated to facilitate the comparison to the general model. Arrows returning to the same action indicate a new attempt to perform the same action by different means (e.g. first trying to extinguish the fire with the extinguisher, and then trying to do the same using water). It should be noticed that an action was only considered as “repeated” if it was performed by different means. Repetition by the same mean was not included, as it became clear that some participants struggled more with the equipment than others, and their repetition may be due lack of dexterity rather than a different attempt.

In the case of S1, the “misinterpret smoke” action is given without any frequency of its occurrence. This was due to the fact that by design of the scenario, the smoke was made as unambiguous as possible. It was presented in a thick, pitch black layer at the ceiling level. It was designed in that manner to compensate for the lack of olfactory and thermal cues, aiming to avoid cases in which the participant would be uncertain of what it was.

Some participants ran during the evacuation, but most of them only walked faster than before they saw the fire. Ducking due to the smoke layer was observed for 16 participants. One participant refused to walk through the smoke. Even though others expressed reluctance to do it, all of them went down the stairs through the smoke (one of those participants even mentioned they will be holding their breath, took a deep breath, and went down). The participant who refused to go down interrupted the experiment because they “ran out of ideas of what to do next”. Furthermore, they explained they would have just waited indefinitely until the firefighters arrived to the scene. As it was a single occurrence, this action (corresponding to “wait” in the general model), was not included in the decomposition diagrams.

Only about 50% of the participants in S2 reacted to the alarm. That means that roughly only half of the participants responded to the audible cue, while the rest ignored the sound and carried on with whatever activities they were into at the time.

Eight participants out of 40 chose to interrupt the experiment before exiting the house. Seven were females and 1 was male. While the male participant interrupted because he was determined not to go through the smoke and ran out of ideas on what to do next other than just waiting, the 7 female participants interrupted because of motion-sickness related symptoms.

Five participants, three in S1 and two in S2, attempted to extinguish the fire by other means than the use of the fire extinguisher. All of these attempts were included in the category “try to extinguish”. Some

**Table 2**
Transition matrix for scenario 1, showing the number of participants performing each action in the columns after having performed the action in each row.

| Scenario 1 | see smoke | smoke control | reach ground floor | try to extinguish | call 112 | awake person | exit house | total |
|---|---|---|---|---|---|---|---|---|
| see smoke | | 5 | 9 | | 3 | | | 17 |
| smoke control | | 1 | 5 | | 2 | | | 8 |
| reach ground floor | | | | 11 | | 3 | 2 | 16 |
| try to extinguish | | | | 2 | | 3 | 10 | 15 |
| call 112 | | 3 | 2 | | | | | 5 |
| awake person | | | | 2 | | | 4 | 6 |
| exit house | | | | | | | | |

**Table 3**
Transition matrix for scenario 2, showing the number of participants performing each action in the columns after having performed the action in each row.

| **Scenario 2** | alarm starts | react to alarm | misinterpret alarm | smoke control | reach ground floor | try to extinguish | call 112 | awake person | exit house | total |
|---|---|---|---|---|---|---|---|---|---|---|
| alarm starts | | 10 | 9 | | | | | | | 19 |
| react to alarm | | | | 6 | 11 | | 2 | | | 19 |
| misinterpret alarm | | 9 | | | | | | | | 9 |
| smoke control | | | | 2 | 4 | | 2 | | | 8 |
| reach ground floor | | | | | | 13 | | 1 | 3 | 17 |
| try to extinguish | | | | 1 | | 3 | | 9 | 2 | 15 |
| call 112 | | | | 1 | 2 | | | | | 3 |
| awake person | | | | | | | | | 10 | 10 |
| exit house | | | | | | | | | | |

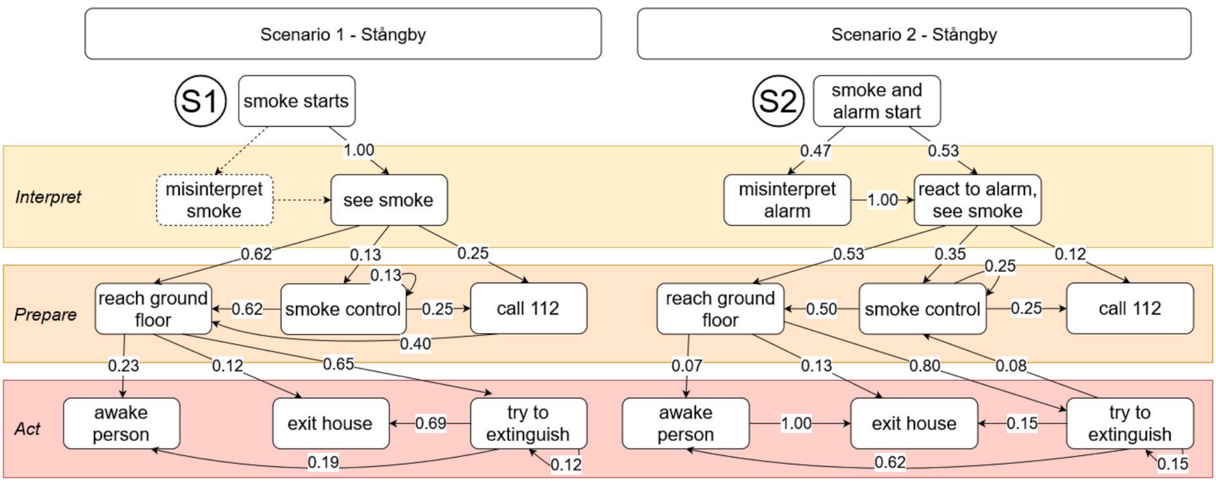


**Fig. 4.** Decomposition diagram for each scenario, showing the proportion of participants choosing among the subsequent actions. Returning arrows show a repeated attempt to perform the same action by other means.

attempted to remove the burning tree by pulling it, which was not possible. One attempted to use a nearby carpet or the towels hanging in the bathroom to cover the flames. Another participant tried to fill a bowl from the kitchen with water to dump it at the fire. Four out of these five participants also attempted to use the extinguisher, two of them trying the other means after emptying the extinguisher. The other participant did not try to use the extinguisher at all but instead went for another mean.

In the questionnaire, participants were asked to rate the perceived realism of the scenario, from 1 (low) to 7 (high). Fig. 5 shows the frequency of each rating. All categories received medium to high ratings for their realism, being the averages for each category between 4.64 and 5.89. The fire and the non-player character got the lowest averages, while the smoke and the sound of the alarm got the highest ones.

Participants were also asked to rate from 1 (low) to 7 (high) some sensations of unease they felt during the experiment. Fig. 6 shows their frequency given to each response. The average rating for insecurity and stress were 4.03 and 4.19 respectively. For fear and physical discomfort they were 2.97 and 2.70.

Many participants seem to be unaware of the sounds they were exposed to in a VR environment. In many cases, the researcher in the room could hear the sound of the alarm leaking out of the headphones, and still see no reaction from the participant. In some cases in S2, participants later reported thinking the sound was unrelated to the

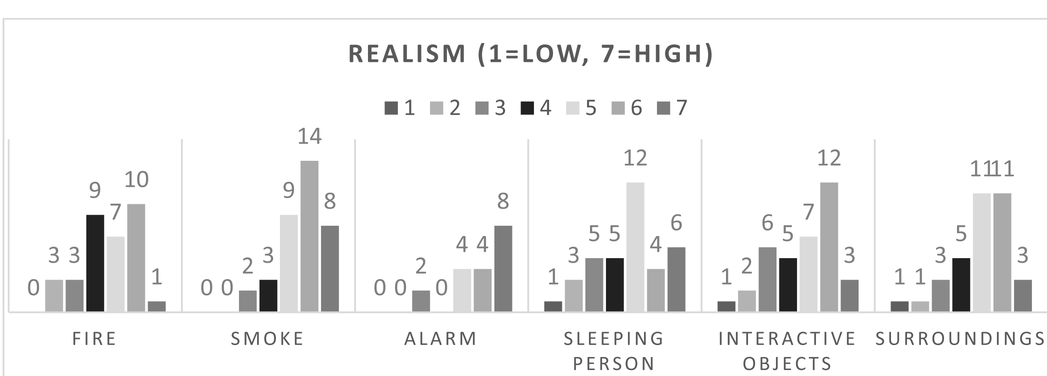


**Fig. 5.** Number of participants giving a certain rating of realism of different components of the VE.

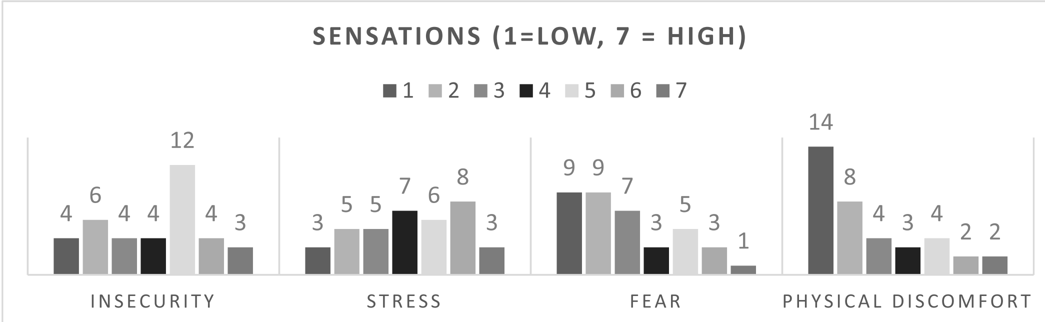


**Fig. 6.** Number of participant giving a certain rating to sensations felt during the VR experience.

experience, attributing it to the real world environment. Among their interpretations of the sound were "a microwave in the next room", "a truck", and the researcher's cellphone.

## 4. Discussion

By comparing the decomposition diagrams presented on Fig. 4 to the general model shown on Fig. 1, it becomes clear that there are strong similarities between the two. The three nodes are present in each of the diagrams, and the actions performed seem to follow the same patterns, even if the classification of the most ambiguous actions is done in another way. Both the correct interpretation of the cues and the wrong one are included in the interpret node for the two scenarios. As mentioned before, S1 was designed to avoid misinterpretation of the visual cue of the smoke. Even though it was possible to follow on the computer screen what the participant was seeing, it was not possible to tell if they were fixating their eyes on the smoke layer or something else, even if the smoke layer was in their field of view. Therefore, the "see the smoke" action could only be considered as such if the participant reacted to it in any way. Any misinterpretation was not possible to define clearly. A possible solution to this issue is to use eye-tracking devices to pinpoint the fixation of the sight.

Although the similarities between the decomposition diagrams shown on Fig. 4 and the general model are clear, it is worth to discuss how the decomposition diagrams would have looked like if they failed to fit the general model. One reasonable failed outcome would be the decomposition diagrams not covering all possible actions. An example of this would be the vast majority of the participants not doing anything else but leaving the house immediately. No participants attempting to control the smoke, extinguish the fire or call the rescue services would be considered non-realistic behavior. The overrepresentation of a single action or the complete absence of another would indicate that the VR scenario failed to replicate reality to such an extent that the participants' behavior was severely skewed towards a given outcome. Instead, the data obtained showed a spread of different sequences of actions, as it was the case in the real-world data set. Another sign of failure would have been participants not attempting to perform an action they failed at more than once. Repeated attempts to perform some actions by trying alternative methods of controlling the smoke or extinguishing the fire were observed in the VR scenario. No participant trying a different solution to the problem would have been at the very least suspicious, since the original decomposition diagrams by Canter, Breaux and Sime [15] show repetition of attempts in several cases. Moreover, while it is unclear what constituted a repeated action in the case of Canter, Breaux and Sime's analysis, in this experiment a repeated action was only taken into account if it was performed by a second method, as it was mentioned before, to avoid mistaking lack of dexterity in VR for repeated attempts. These possible benchmarks for failure in this experiment add robustness to the results.

The frequency of performance of the different actions shows that there was no single preference for a given sequence of behavior in the VR scenario. This means that the scenarios did not prompt participants to act in a specific, uniform way, but that they made their own choices and those choices represented many of the possible outcomes indicated in the general model. This result indicates that the sequences of behavior obtained in this experiment were not only within the predictions of the general model, but also that many different sequences were represented. This matches what would be expected in a real fire, that is, different people showing different behavior.

It should be noted that the classification of the actions in the different nodes is not universal and can be subjective to certain degree. Sime [20] indicated that too, mentioning that, for example, the act of opening a door can be classified as part of evacuation, rescue, or even fighting the fire. Similarly, in this study, the classification of certain actions (like awaking the person, or calling the rescue service) could have fallen in a different node if more context is given to the action. However, this different classification does not change the fact that the sequences of actions obtained still reflect behaviors expected in the general model.

The fact that the decomposition diagrams presented in this paper cover most of the possible actions indicated in the general model shows that participants in this experiment behaved in a comparable way to that of the survivors of the real-world fires. This outcome can be considered a positive answer to whether or not VR can be used as a method for human behavior in fire research, but it may be more of a hint than a full answer. The obtained diagrams do not show unexpected behaviors or repetitive patterns. The results failed to disprove that VR can produce realistic data, but the lack of more detailed data does not allow for closer comparisons. A more robust answer could be achieved by running the same experiment both in VR and in the real world. Such an experiment would give access not only to the whole picture of the scenario the participants in the real world emergency are subjected to, but it will also allow to uniform the classification of the possible actions.

Ducking was expected as it was also observed during the pilot tests. However, participants holding their breath while walking down the stairs was unexpected. It is likely that these participants wanted to indicate to the researcher in the room that they knew going through the smoke was dangerous. It is also likely that there were some participants less prone to share their thoughts, and could have hold their breath or at least thought they should do it in a real event. Even considering only those who communicated the idea, it is remarkable that the scenario prompted them to behave in that way, even though they were not instructed to do so.

In S2, about half of the participants did not react to the alarm even though it sounded loud and clear, and the sound leaking from the headphones could be heard by the researcher in the experimental room. It should be noticed that ignoring the fire alarm in this case is not the same as ignoring or misinterpreting other audible cues (e.g. crackling of the fire) that may also be easily misinterpreted in real life and ignoring them is not uncommon [15]. It can be argued that the sound of a domestic smoke alarm is not necessarily unambiguous, but that the volume of its sound can help to recognize it as such. However, the loudness of the sound could play a role. It has been observed in other scenarios that participants in VR experiments can decide to remove one of the headphones in order to reduce the volume they are hearing. Subjecting them to loud noises may not be necessary, but further research is needed to look not only into why participants tend to neglect sounds but also into how to compensate for this effect.

The participants rated the realism of the different visual features in the experiment between medium and high. This is a positive result, because of the experiment relying on the perception of realism to tackle the situation, although it can be improved with more advanced skills in the design of the 3D model. It should be noted that likely most participants have never seen real life smoke conditions similar to that in the experiment, and they may have assessed the realism of the smoke compared to less heavy and more benign sightings of smoke. The ratings for the sensations show medium levels of insecurity and stress, and low levels of fear and physical discomfort. This indicates that the VR experience made the participants feel some levels of negative sensations, but they were not extreme.

The participants who interrupted the experiment did so at different stages of it, including the very beginning (while walking on the ground floor) and after extinguishing efforts (when they could easily just exit the house). In every case, the experiment was interrupted immediately. The large number of participants interrupting the experiment because of motion sickness may be related to a misalignment in the calibration of the head-mounted display and the calibration of the omnidirectional treadmill. Other participants also expressed some minor levels of sickness, but they considered the feeling was not too unsettling to continue with the experiment. It should be noted that the misalignment in the calibration may be due to human error rather than the devices. Both devices rely on calibrations custom made for the user (such as the distance between the eyes and the position of the head with respect to the center of the omnidirectional treadmill), which were not possible to implement for each participant. It is therefore likely that those participants who interrupted the experiment had physiological features that made the misalignment too hard to ignore.

The sudden disappearance of the non-player character after being woken up was not a realistic feature but it was deemed necessary. While the non-player character standing up and walking out of the house would have been more realistic, it was thought that it could influence the participant to do the same [7]. To avoid that, the instant disappearance and the message were chosen.

An interesting outcome, although of limited occurrence, was the attempt by some participants to extinguish the fire by other means than the fire extinguisher. While their attempts were fruitless especially because the scenario did not allow other objects to be used (e.g. it was not possible to pick up the carpet on the floor or the towels in the bathroom, or there was no water in any faucet in the house that could be used to fill a container), those attempts were registered as extinguishing attempts. If the scenario was designed for those actions to be feasible (e.g. if it was possible to pick up the carpet or the towels, if it was possible to fill a container with water and use it later to extinguish the flames), the outcome would still be same, since the fire in this scenario was not possible to extinguish. However, the realization that participants may come up with other ideas of how to tackle the situation than those expected is a valuable lesson, and future VR scenarios should take this into consideration.

## 5. Conclusion

The behavior of the participants replicated qualitatively the expected behavior of people in residential fires according to the general model. The sequences of behavior obtained were contained by the general model, and at the same time, they covered most of the possible outcomes of that model. A quantitative comparison was not possible to perform due to the reduced size of the VR sample. The results show a strong similarity between the two obtained models, but subjectivity in the classification and lack of full clarity from the original study allow for questions on how strong the similarity is. However, the results did not disprove the suitability of the VR method as a tool for its use in human behavior in fire research, and therefore can be considered a contribution to the validation process of the VR method. The experiment pointed out some limitations of VR as a research method, such as participants feeling sick, and lack of reaction to the sound of the alarm. The experiment also showed that some participants were willing to try other means to extinguish the fire once the fire extinguisher ran out, which shows that the VR scenario can prompt some people to try and tackle VR problems in more than one way, as it is common in the real world.

## 6. Ethical considerations

According to the Swedish ethics act [21] all research involving procedures that may be psychologically invasive to the participants must be subject to a review by a regional ethics board. An application for ethical approval was submitted prior to the experiments, considering the possible risks: tripping and falling, and feeling extremely nauseated. Participants were covered by insurance in case of an accident during the experiments, and medical costs related to any injuries were covered. Participants were reminded about their right to interrupt the experiment at any time and for any reason. Only adults were allowed to take part, and they were made aware that they should not sign up if they suffered from epilepsy. The study was reviewed and the ethical board decided that it did not require an ethical approval [22]. Nevertheless, the recommendations included in the decision of the ethical board were included in the experimental design.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.


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