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Geographical Information Management and Applications

MSc Thesis

Combining Agent-Based Models with Virtual Reality to collect micro-level behavioural data in a smoke evacuation situation

Student: Myran Warmerdam, 5541352

Supervisor: Dr. Ir. P.W.M. Augustijn (Ellen-Wien) and Dr. P. Raposo (Paulo)

Professor: Prof. Dr. M.J. Kraak (Menno-Jan)

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Universiteit Utrecht
TU Delft
University of Twente.
Wageningen UR

Preface

My name is Myran Warmerdam, and before you lies the final report of my Master's thesis for the GIMA master's programme. It is the result of a research into combining Virtual Reality and Agent-Based Modelling. In this thesis I used the knowledge and skills that I have learned in my years of being a student.

It has been a very interesting and educational process, but I would lie if I said it was easy. I have never been the best at modelling or programming and the past one and a half year of Covid-19, have not made it any better. However, with the support and feedback of my supervisors Ellen-Wien Augustijn and Paulo Raposo I was able to bring this thesis to an end.

Furthermore, I would like to thank Roel Bossink for giving me access to the VR laboratory at the ITC building and putting effort in helping me get enough participants for the experiments. I would also like to thank Lucia Rabagomayer for her help with Unity and I would like to thank everyone who participated in my experiments.

Finally, I would like to thank my responsible professor, Menno-Jan Kraak, for the time to read my thesis.

Abstract

The main research objective of this thesis was to fill the gap in micro-level behavioural data, that is missing to improve agent-based models. Furthermore, it aimed to enhance an evacuation model with a dynamic smoke environment. The dynamic smoke model was implemented to a static evacuation model, and the behaviour of the agents was adapted. New variables were introduced to the agents, so that they could perceive risk and cope with these risks. The micro-level behaviour data was collected by performing experiments in Virtual Reality. The experiments focussed on three elements: general behaviour when encountering smoke, smoke density and the location of the smoke. In the experiments, a mixed 5x2 design was used. Each participant went through five VR simulations, which were built in Unity3D, with either a low density or a high density. By conducting experiments with the evacuation model, the results of the VR experiments were compared to the model. Results were similar on average, however, differences in the environments made it difficult to compare. Future research should be focussed on a more realistic smoke model, a more realistic VR environment that matches the evacuation model better and a larger sample size in the experiments.

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1. Introduction

Over the last decade, the use of agent-based modelling to simulate the dynamics of geographical systems has seen a considerable increase (Crooks & Heppenstall, 2012). Agent Based Models (ABMs) can be very useful, as they provide the opportunity to disaggregate a system into individual components, where each component can have its own set of rules and characteristics (Crooks & Heppenstall, 2012).

ABMs represent systems at a high level of detail and variety. They are much more detailed than their predecessors. ABMs consist of agents to represent entities in these systems. Agents have a set of attributes and interact with each other and their environment. This means that, as the number of agents increases, the level of representation also increases (Heppenstall, Crooks, See, & Batty, 2012). The behaviour of the agents is based on a set of rules. These rules can be based on interviews, questionnaires, map exercises and, in the case of an evacuation model, on analysis of emergencies in the past (Rüppel & Schatz, 2011).

It is impossible to test an evacuation, for example, in case of fire, in an actual burning building (Rüppel & Schatz, 2011). This means that the behavioural data on how agents react in an evacuation when encountering fire or smoke can never be completely right. Data can be based on test evacuations, but under the influence of stress of an actual fire or smoke situation, people can act differently. In the past, the focus of data collection was, for example, on mobility parameters such as movement speed. Nowadays, these parameters are not sufficient "to describe the complex process of decision making of people during an evacuation" (Rüppel & Schatz, 2011). That the input behavioural data in a model has to be accurate, is quite important. According to (CBS, 2018), there were 76020 reports at the fire department in the Netherlands. In the same year, 1050 people were hospitalized and 52 persons died because of a fire or inhalation of smoke (CBS, 2018). These statistics show the importance of evacuation planning.

The question of whether the data is accurate enough or not is brought up in other researches. Santos & Aguirre (2004) claim that the ability to simulate human behaviour in an evacuation accurately is missing from evacuation models. Kuligowski & Gwynne (2008) identified several behavioural facts of people in an evacuation and suggest developing a complete and comprehensive model, to understand why these behaviours occur.

Lately, new types of data collection for the development of ABMs have been introduced. These include serious gaming and Virtual Reality (VR). Serious gaming and VR immerse the user in a computer-simulated environment with real-time interaction (Javan et al., 2020). According to Fleming et al. (2016), serious games are: "interventions that are games, or that utilize elements of gaming, as an integral and primary method for achieving a serious purpose, such as a health or educational goal." According to Bishop & Gimblett (2000), VR is a virtual environment where the user feels present, while still being in the real world. Rüppel & Schatz (2011) claim that both VR and serious gaming could offer new possibilities in data collection.

As stated before, it is impossible to test run a real evacuation without having to put humans at risk. Thus, to get accurate data on evacuation behaviour, a simulation in which people can be present could be useful. When using an immersive VR, the user feels present in a simulated emergency evacuation, making the person act like he would in an actual emergency. This way, micro-level behavioural data can be collected. As Shendarkar, Vasudevan, Lee, & Son (2008) state: “As VR is the next best thing to reality, the perceived values derived from these experiments are the closest approximations that can be obtained without actually emulating a real emergency.” Shendarkar et al. (2008) combined ABMs and VR to extract crowd behaviour data. They created a simulation in VR of an evacuation of an intersection after an explosion.

These new types of data collection are especially suitable when we are not trying to collect behavioural data on past or present situations, but, when we are dealing with non-existing or future situations. For example, in a building that has never been on fire, a fire or smoke situation would be a future situation. In cases like this, micro-level behavioural data could be very useful. This thesis focussed on collecting micro-level behavioural data for a smoke situation. Smoke is not static; it moves through an environment instead of being located in the same space. Therefore, it could be considered a dynamic environment. Not many ABMs consist of a dynamic environment. In this thesis a static evacuation model is enhanced with a dynamic smoke environment.

2. Research objectives

The main research objective of this thesis is to fill the gap in micro-level behavioural data, that is missing to improve agent-based models. Furthermore, it aims to enhance an evacuation model with a dynamic smoke environment. This leads to the following main objective:

How can Virtual Reality be used to collect behavioural data to enhance agent-based models?

This objective is to be fulfilled by dividing it into three sub-objectives.

- The first sub-objective is to add a smoke model to the ABM, by creating a dynamic environment.
  - *How can the environment, the agents and the processes of the current evacuation model be described? (1)*
  - *How can a dynamic environment (fire – smoke) be integrated into the ABM? (2)*
- The second sub-objective is to let test persons walk through the VR environment to gather behavioural data in an evacuation situation. To conduct these experiments, it is important to know which data needs to be collected. For example, how do agents react when encountering smoke, will they go through it, or walk away and find another exit? Furthermore, the objective is to create a realistic VR environment for the experiments.
  - *Which data is needed to implement agent – environment interactions and how can a realistic VR environment for the experiments be created that matches the available ABM? (3)*
- The third objective is to see how the data of the VR experiments can be integrated into the ABM and how the data from the VR experiments differ from experiments with the ABM.
  - *How can the agent-based model be improved by adding micro-level behavioural data and how do the VR and ABM experiments compare to each other? (4)*

2.1. Scope

In this thesis, the focus is on using VR experiments to collect micro-level behavioural data to be used in an evacuation ABM. Important here is that this research does not try to collect all the data that is relevant to evacuation models. The focus is on gaining experience in the creation of the VR environment and in using VR in combination with ABM. It is necessary to make choices to collect the most important data.

Additionally, this research is an exploration into collecting micro-level behavioural data. Behavioural data can be used directly to steer agent behaviour, via Machine Learning (ML) algorithms. However, implementing such an algorithm is not part of this thesis.

3. Theoretical framework

3.1. Agent-based modelling

In the late 1940s, digital computers appeared. The scientific applications of digital computers involved, from the beginning, spatial and temporal problems. The field of digital computation advanced rapidly, and by the mid-1950s, this led to computable problems involving spatial systems, such as cities and transportation (Batty, 2012). Digital computers lighted the spark for mathematical theories on spatial systems, leading to the first traffic flow models in 1955. In these models, the traffic flow was implemented in a digital environment in the Chicago Area Transportation Study (Plummer, 2007).

Since then, models changed from being aggregate, cross-sectional, comparative, and static to dynamic and disaggregate models. Agent-based modelling (ABM) is one of the types of modelling that came onto the horizon (Batty, 2012). The progression has mainly been possible because of the rise of automata approaches. An automaton is a processing mechanism with, over time, changing characteristics based on its internal characteristics, rules and external input (Crooks & Heppenstall, 2012).

According to Macal & North (2007), agent-based modelling (ABM) is: “a new approach to modelling systems comprised of autonomous, interacting agents". Macal & North (2007) also state that ABM promises to have far-reaching effects on businesses. Models could change the way businesses and researchers respectively use computers to support decision-making and electronic laboratories to support their research. Some researchers even claim ABM “is a third way of doing science”, next to deductive and inductive reasoning (Axelrod, 1997). Marshall (2017) argued that ABM has two advantages over mathematical techniques: first, because of the nature of the time change in the model, the behaviour becomes miscellaneous, adjusting and intricate; second, the communication of agents results in “dynamic networks” and modelling such connections allows the investigation of the outcomes that are hard to represent using other models employing mathematical representation.

3.1.1. Agents

An ABM consists of agents that interact with each other and with an environment. Agents are part of a program, and they represent social actors, for example, persons, political parties or even nations. Based on a set of rules, they are programmed to react to an environment in which they are located. This environment is a model of the real environment in which the social actors operate (Abdou, Hamill, & Gilbert, 2012).

In Figure 1, a simple model of two agents interacting with each other and the environment can be seen. Agents derive information from the environment. This information determines the perception that they have about the state of the environment. Based on the set of rules that are programmed, agents decide on which actions to perform, and these actions affect the environment. The agents can interact indirectly, for example, by affecting a common resource or directly by communication. This communication can be used to exchange information about possible strategies, knowledge about the resource and agreements on how to solve collective action problems (Janssen, 2005). In the case of a fire or smoke model, the arrow that goes from the agent to the environment is not always in place. For example, when an agent encounters a smoke field, and the agent chooses to turn back, the smoke is, and thus the environment, not affected.

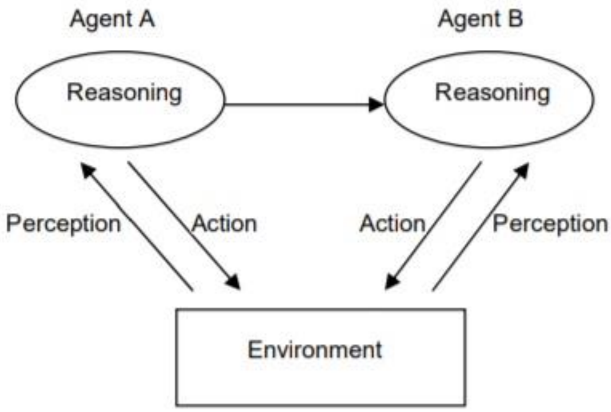


Figure 1: a model of two agents interacting with an environment (Janssen, 2005).

As stated before, agents act based on a set of rules. These rules affect the behaviour and the interactions, and relationships of agents with other agents or the environment in which they operate (Chen & Zhan, 2008). Rules are usually based on literature, expert knowledge or data analysis (Crooks & Heppenstall, 2012). More detailed information on how data can be collected, can be found in the 'behavioural data' section.

3.1.2. Evacuation modelling

As this thesis uses an evacuation model, this section explores the world of evacuation modelling. According to Kasereka et al. (2018), evacuating people from a building that is on fire is quite difficult. The main reason for it being difficult is that an evacuation scenario influences the behaviour of humans. Other reasons are different types of people; everyone responds differently and the configuration of the place that is to be evacuated (Kasereka et al., 2018). Joo et al. (2013) also stress the difficulty in evacuation situations. They claim that "predicting human behaviour in complex and uncertain environments like emergency evacuation is considered almost impossible" (Joo et al., 2013). Thus, it is essential to research the process behind evacuations further. Over the years, several evacuation models have been proposed. Joo et al. (2013) proposed a model based on affordance. Gibson (1986) defined affordance as: “a property of the environment that provides an action opportunity offered to an animal (human), either for its good or ill.” The objective of Joo et al. (2013) was to develop and verify an ABM that is based on affordance, to model human behaviour in emergency evacuation situations. In their research, human behaviour is limited to individual based decision-making. More complex behaviour involving interactions and communication with other agents was left out.

More recently, Kasereka et al. (2018) proposed an intelligent ABM that focuses on a better way of evaluation. Where most models focus on defining the number of survivors as a key parameter for evaluation, this model proposes four parameters. The four parameters are the number of people alive after the evacuation, the number of deaths, the average potency (potency starts between 50 and 100, then decreases when affected by fire or smoke, when it reaches 0, the person is dead) and the average time it takes to reach an exit. Their model is based on a set of eleven hypotheses and the movement of the agents is based on a Dijkstra algorithm to determine the shortest path. However, Kasereka et al. (2018) do not take several behavioural factors, like emotion and stress, into account. Furthermore, the model uses both a simulation for fire and smoke, which are both modelled as agents, with their own set of rules (Kasereka et al., 2018). Based on these rules, the smoke and fire spread through the environment, affecting the evacuees. As one of the objectives of this current research is to implement a fire or smoke situation into the evacuation model, the fire and smoke models used by Kasereka et al. (2018) could prove useful.

Corrêa, Bicho, & Adamatti (2019) also propose a new model that simulates the dispersion of smoke in a nightclub. The smoke is simulated using the concept of potential fields in combination with cellular automata. Potential fields are usually for models that describe agent movement. To model the dispersion of smoke in a closed environment, the authors made some changes to the equations that calculated the potential field. The modifications enabled the model to have a single obstacle, the fire, and several possible targets, the doors. The obstacle generates a repulsive force, and each target generates an attraction force. Thus, the model's potential field is defined by its attractive points, which are the exit doors, and a repulsive point, which is where the fire originates. The smoke is generated from the repulsive point, then moving according to the vectors generated by the potential fields (Corrêa et al., 2019). In Figure 11, in section 5.2, the steps according to which the smoke disperses can be seen.

As Corrêa et al. (2019) state, the results of the experiments showed that their smoke dispersion model represents a good approximation of what would happen in a real-life smoke evacuation situation. This model could be used to implement a dynamic environment for the evacuation ABM.

To use an ABM for an evacuation, the agents need to behave like real human beings. What seems to be missing in the current evacuation models is micro-level behavioural data. Collecting micro-level behavioural data is hard, as it is impossible to test-run a fire or smoke situation. In the next section, an overview of the literature on behavioural data is given.

3.2. Behavioural data

As stated earlier, several models on evacuation already exist. However, there is a lack of micro-level behavioural data to base the behaviour of the individual agents on. Conventional crowd simulations are often based on the assumption that behaviour should be modelled through homogeneous parameters and is assigned to each individual beforehand (Shendarkar et al., 2008). Simulating a flock of birds or fish is quite simple, but modelling a human being requires the interaction of more heterogeneous features of psychological and physical attributes (Hamagami & Hirata, 2003). Thus, Shendarkar et al. (2008) use bottom-up modelling to define the behaviour of an active entity at the individual level.

Other research also states that differences between recommended, modelled behaviour and real-life actions exist and these differences increase the chances of casualties in evacuation situations (Bernardini, Lovreglio, & Quagliarini, 2019).

A lack of micro-level, bottom-up evacuation behavioural data does not mean there is no behavioural data at all. Kuligowski & Gwynne (2008) have come up with a list of behavioural ‘facts’, on which most models base their simulation. These ‘facts’ are obtained from a variety of incidents:

1. The first instinct of people is to feel safe in their environment
2. People will engage in actions that lead to information
3. People act rationally and altruistically
4. People will most likely engage in preparation activities before beginning to evacuate
5. People will move to their familiar exit, even though it is not the closest exit

More recent research also provides insight into behavioural data in an evacuation situation. Bernardini et al. (2019) studied the behaviour of people during the evacuation in case of an earthquake. Of course, this thesis focusses on a fire or smoke situation, but some behaviours are general evacuation dynamics (Helbing & Johansson, 2010). That people show herding behaviour is one of the findings in the research of Bernardini et al. (2019). Herding behaviour is defined as individuals aligning their thoughts in a group (a herd) by interacting in this group (Raafat, Chater, & Frith, 2009). In the case of Bernardini et al. (2019) this was shown by people joining each other in the evacuation to exchange information. People also activate their information-seeking behaviour both before the evacuation and during their motion towards an evacuation target (Bernardini et al., 2019). Another type of behaviour is attachment to personal things. This behaviour is also stated by Bañgate, Dugdale, Adam, & Beck (2017), who studied the influence of social attachment on mobility during a crisis. In about 30% of the cases, people mainly collect electronic devices, such as smartphones and laptops, before starting to evacuate (Bernardini et al., 2019).

In the case of the ABM that is used in this thesis, it is important to know what people would do in a fire or smoke situation. Familiarity is an important factor in the progress of an evacuation. Familiarity means that a person understands the structure of the building. This could be a good thing, so occupants know where to go in a fire or smoke situation, but it can also be a bad thing. People who are familiar with the structure of a building do not always go to the nearest exit. Instead, they go to an exit with which they have had previous experience, which is not always the nearest exit (Gwynne, Galea, Lawrence, & Filippidis, 2001).

In his experiments involving volunteers moving through smoke-filled corridors, Jin (1997) finds several behavioural characteristics when people encounter a smoke situation. Firstly, the travel speeds were reduced as a response to the conditions. Secondly, participants tended to stagger around their ideal path rather than moving directly to their target. This was because of the difficulty to determine the present direction caused by the visual conditions. Thirdly, participants were seen moving towards the walls to obtain guidance in their way to their target (Jin, 1997).

When facing a smoke barrier, the strategic options people choose from can be categorized as follows (Gwynne et al., 2001):

- People maintain the current course and pass through the smoke.
- People redirect their course away from the smoke barrier and head towards another exit.

Proulx (1998) found in his research, based on a fire in a high-rise building, that: “the response when encountering smoke … was to 'keep going down' for 34%, another 31% 'reversed direction and went upstairs', 11% indicated 'sought refuge' and 10% 'changed stairs, and reached outside by alternate exit stair'.” Gwynne et al. (2001) provide insight into the percentage of people that retreat from smoke and choose a different direction, stated against the visibility distance. This can be seen in table 1.

Visibility distance (feet)	The percentage of people that retreat from smoke
0-2	29.0
3-6	37.0
7-12	25.0
13-30	6.0
31-36	0.5
37-45	1.0
46-50	0.5
>60	1.0
Number of occupants	570

Table 1: the percentage of people that retreat from smoke stated against the visibility distance (Gwynne et al., 2001).

Research (Zheng, Jia, Li, & Zhu, 2011) about fire density and fire spread rate shows that the larger the fire and the larger the fire spread rate, the more difficult the evacuation and the longer it takes. Also, the location of the fire matters, in combination with the structure of the room. A designer of a room or building should take into account the configuration of the room. In Figure 2, three examples of the configuration of a room are given. The open spaces in the walls represent doors, through which occupants may escape. It is easier for occupants of the room to escape from configuration 2 (top right in Figure 2) than 3 (bottom in Figure 2) (Zheng et al., 2011).

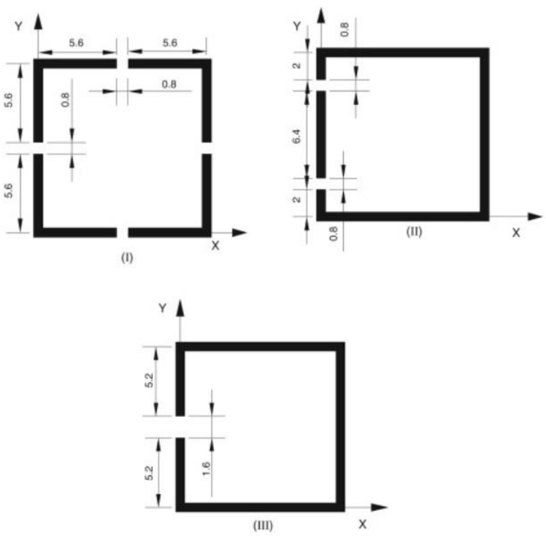


Figure 2: room configuration of three rooms (Zheng et al., 2011).

3.3. Risk Assessment

The previous part is about what people do in an evacuation situation. This phenomenon can also be explained from a more general perspective. This section is about risk assessment and coping with these risks. When facing risks, people go through a complex process of collecting information, deciding what actions to take and communicating with others to determine the effectiveness of their actions (Abdulkareem, Augustijn, Filatova, Musial, & Mustafa, 2020).

Abdulkareem, Augustijn, Mustafa, & Filatova (2018) and Abdulkareem et al. (2020) developed a theoretical model for risk perception and coping with these risks based on the Protection Motivation Theory (PMT). PMT is one of the dominating approaches in the domain of explaining, measuring and assessing risk perception. PMT has been applied to study health-protective behaviour (Bassett & Ginis, 2011) and was originally proposed by Rogers (1983). According to the PMT, a person goes through two steps when facing a risk:

- Threat appraisal; during the threat appraisal the perceptions of risk are formed. In this stage, an agent assesses the probability and the consequences of a risky event occurring. The purpose of this stage is to determine whether a risk is at an acceptable level or not.
- Coping appraisal; when the risk perception is high, the agent goes through the coping appraisal phase. In this stage, the agent considers several protective behaviours. The stage consists of two main parts: adaptation-efficacy and self-efficacy. Adaptation-efficacy is about the belief of a person that the recommended behaviour will protect them. Self-efficacy measures the ability of the agent to perform the recommended behaviour.

The model consists of two Bayesian Networks (BN). The goal of BN1 is to answer the question: "is there a risk?". If the risk is present and at an unacceptable level, agents continue to BN2. This stage answers the question: "what to do?" (Abdulkareem et al., 2018). In Figure 3, the cognitive process of an agent encountering a disease can be seen.

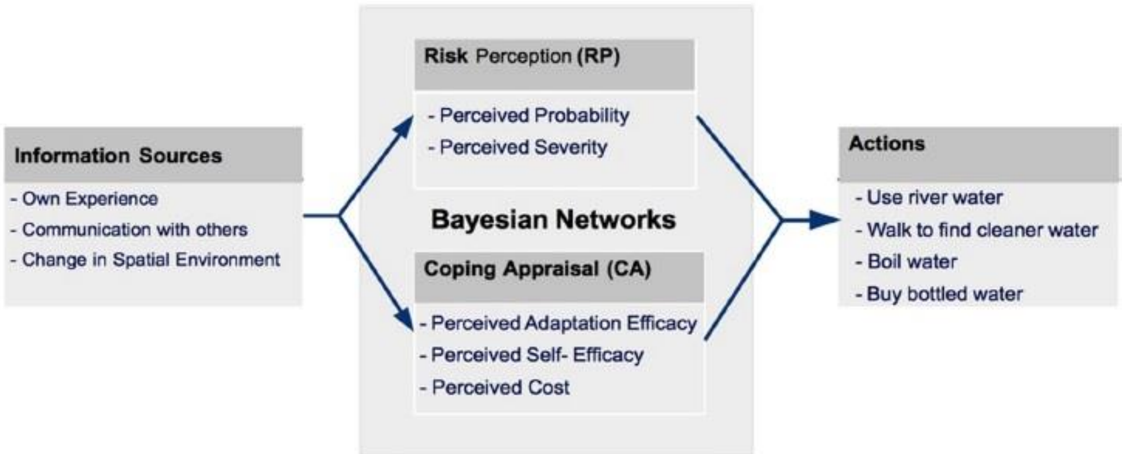


Figure 3: the cognitive process of an agent when encountering a disease (Abdulkareem et al., 2018).

In the case of the evacuation model of this thesis, this risk assessment model would be initiated when encountering smoke. Upon encountering, the agent would need to determine whether the risk is acceptable or not. This assessment can be based on the visibility distance, as is suggested by Gwynne et al. (2001), see table 1. When finding the visibility distance unacceptable, the agent can decide to continue to BN2, where he decides what to do. In the case of the smoke situation, the agent will redirect their course and look for another exit (Gwynne et al., 2001).

3.4. Virtual Reality

Virtual reality (VR) could be a possible way of collecting micro-level behavioural data. VR has three characteristics: response to human interaction, real-time 3D graphics and immersion. The first two characteristics are quite clear, but immersion needs some clarification. Immersion means that either the point of view of the user or some part of the body of the user is contained within the simulated environment (Earnshaw & Vince, 1995). Shendarkar et al. (2008) define immersive VR as follows: "the use of various computer graphic systems in combination with various display and interface devices to provide the effect of immersion in an interactive 3D computer-generated environment in which the 3D objects have a spatial presence." By using an immersive VR it is possible to simulate an evacuation situation, without putting anyone to risk.

Shendarkar, Vasudevan, Lee, & Son (2008) already experimented with VR to extract micro-level behavioural data. Their experiment focused on an intersection, while in the current study, the experiment area is a closed environment. Nevertheless, their research could be useful in setting up the experiment and processing the collected data to improve the ABM. For their experiment, they used the Cave Automatics Virtual Environment (CAVE). The immersive effect is created by using stereoscopic glasses to create the illusion of 3D. To model the graphics in the VR environment, OpenGL Performer was used, while the programming was done with Visual ++. Essential modules of the VR scene are the crowd that is generated from replicated 3D models of humans, the smoke and fire, which was modelled by using multiple translucent planes that move continuously, re-orienting themselves based on the user's view, to create the smog effect and the intersection, including policemen and exit signs.

The combination of modelling agents in an environment and virtual reality (VR) has been researched before. As done by Shendarkar, Vasudevan, Lee & Son (2008), the VR experience was used to gather data to create a model. In the current study, the purpose is to let a test person walk through a VR environment to gather data to enhance an existing model. Even in earlier studies, the VR possibilities were explored, but the aim was to develop a model, not improve it (Bishop & Gimblett, 2000). However, the way these studies built the virtual environment could be useful for this study.

Rüppel & Schatz (2011) provide new insights into the combination of VR and evacuation modelling. Their research focused on having a test person play a game that simulates an evacuation, instead of following the movements and actions of an agent, as is proposed in the current study. Their study makes use of serious gaming. Rüppel & Schatz (2011) define serious gaming as follows: "[serious gaming] combines fun methods and concepts as well as game technology with other information and communication technologies (e.g., sensors, computer graphics, multimedia, artificial technology) and sciences (e.g., computer science, design, psychology, pedagogy) in "serious fields of applications", beyond the pure entertainment use". In their research, Rüppel & Schatz (2011) introduce a new serious game, based on the

Building Information Model (BIM). However, currently, the BIM, in combination with the serious game approach, lacks some vital information for generating realistic game scenarios. BIM tools provide the possibility to exchange data between content creation tools for creating game objects. But, as Rüppel & Schatz (2011) state: "the definition of dynamic game objects for a realistic and immersive real-time simulation of building-related game scenarios is still associated with a major effort." Serious gaming is based on scoring points. The goal of this study is to collect behavioural data; people could react differently when making it a 'race', instead of having the main focus on surviving. This makes going through the major effort of creating dynamic game objects not worth the time. However, aspects of the BIM could provide useful information for creating a virtual environment for this study.

3.5. User Study

3.5.1. Experimental design

To collect data via a VR simulation, experiments need to be set up. A classical experimental design is often referred to as a randomized experiment (Bryman, 2012). In such an experiment, two groups are established. The group that receives the experimental treatment is the experimental group. The group that does not get the experimental treatment is the control group. An important aspect of an experimental design is the use of random assignment of the sample to the experimental and control groups. Because of this, experiments tend to be very strong in terms of internal validity (Bryman, 2012).

Nazemi et al. (2021) used a mixed 5x2 experiment in their study. They researched the perceived safety of bicyclists using a bicycle simulator combined with immersive virtual reality. In their study, five different environments are used as within-subject factor, and the different conditions, in their case the level of traffic, was used as between-subject factor. The environments were presented to the participants in two sequences to account for ordering and learning effects. Another VR experiment is performed by Wang, Chardonnet, & Merienne (2021). In their study they tested a speed protector to optimize user experience in virtual environments. In their experiments, the participants had to go through a selection of three environments with different conditions in a random order.

As is done by several other studies (Wu, Cai, Luo, Liu, & Zhang, 2021);(Jennett et al., 2008), the participants are divided into two groups. One group performed a non-immersive test, while the other group performed the test in an immersive VR environment. After the experiments, participants of both groups filled in a questionnaire, to measure the level of immersion. Jennett et al. (2008) created a questionnaire and refined this questionnaire based on three different experiments.

3.5.2. User experience

When researching user experience, a wide range of methods exists. In order to decide which method to use best, a three-dimensional framework was made (Nielsen Norman group, 2014). The three axes of this framework are:

- Attitudinal versus behavioural
- Qualitative versus quantitative
- Context of use

The context of use is not applicable for this thesis, as it focusses on how a product is used, and this thesis is not about a product.

3.5.3. Attitudinal versus behavioural

The distinction between attitudinal and behavioural is mainly based on what people say versus what people do. Usability studies often lie in the middle of these two sides. These studies use a mixture of self-reported and behavioural data. A usability study leaning more towards the behavioural side is often recommended. This means that it focuses more on the actions of people, rather than on what participants say. According to the Nielsen Norman group (2014), usability mainly focusses on assessing how easy a product is to use. This in itself seems not interesting to this thesis, as this thesis does not aim to produce a product. However, to improve usability, user testing is a useful method that is also used in the VR experiments. User testing consists of three components: gathering representative users, letting them perform representative tasks, and observing what they do, where they succeed and where difficulties lie.

3.5.4. Qualitative versus quantitative

When doing usability studies, qualitative ways of researching involve directly observing how people use technology. This allows the researcher to ask questions during or after the study. Asking questions about why the user chooses to do certain things, helps to answer the "what people say" (Nielsen Norman group, 2014).

In contrast, quantitative ways of researching involve deriving insights from mathematical analysis. The instrument of data collection, for example a web-server tool, captures large amounts of data, making mathematical analysis possible. The quantitative data is used to determine the behavioural data.

The differences between the qualitative and quantitative ways of doing a usability study are shown in figure 4.

Figure 4: questions that are answered by research methods across the landscape (Nielsen Norman group, 2014).

3.5.5. Sampling

When gathering representative users, the question arises whether to work with samples or to include the whole population. The population is the universe of units from which the sample is to be selected (Bryman, 2012). When this set is too large, the choice can be made to go for a sample. This sample is a subset of participants drawn from the entire population (Martínez-Mesa, Alejandro González-Chica, Pereira Duquia, Rangel Bonamigo, & Luiz Bastos, 2016).

Deciding on the sample size is not always easy. When the sample does not reach the required size but representativeness is preserved, statistical interference may be compromised. However, samples without representativeness may not be reliable enough to say something about the population, even if the sample is large enough (Martínez-Mesa et al., 2016). Samples in studies related to VR experiments differ in size. Some studies have samples as large as 150 (Nazemi et al., 2021), while another study only works with a sample of twelve (Zhang, Ban, Kim, Byun, & Kim, 2021). A study regarding VR stimuli performed by Bulagang, Mountstephens, & Teo (2021) consists of a sample of twenty participants.

3.6. Summary

All in all, when modelling an emergency evacuation, it is necessary to think about both the behaviour of the agents and the environment. Several evacuation models already exist; Joo et al. (2013) propose a model based on affordance, and Kasereka et al. (2018) propose an intelligent ABM that focusses on a better way of evaluation. More recently, Corrêa, Bicho, & Adamatti (2019) propose a model that simulates the dispersion of smoke in a nightclub. This model provides a good way to implement a fire and smoke model in an ABM.

Studies about the behaviour of agents show that people show herding behaviour and attachment to personal belongings during evacuations (Bernardini et al., 2019). Abdulkareem et al. (2018) developed a model to assess risk, based on the PMT. This model uses both risk appraisal and coping appraisal, to guide the agents' decision making process. In a smoke situation, evacuees must determine the risk, and then cope with the risk. Translated to behaviour this gives people two strategic options: maintaining the current course and passing through the smoke (in case of finding the risk acceptable) and retreating from the smoke and choosing another exit (in case the risk is unacceptable) (Gwynne et al., 2001). Other important behaviour is that people base their strategy on the visibility distance through the smoke (Gwynne et al., 2001). This can be translated to smoke density: the higher the density, the more people retreat and the lower the density, the more people go through.

Furthermore, the location of the smoke atter, in combination with the structure of the building or room (Zheng et al., 2011).

Regarding VR and experiments, Shendarkar et al. (2008) experimented with the combination between VR and ABMs. This study provides good information to set up a VR experiment.

The most important behavioural elements are collected and shown in table 2.

Risk perception		Coping Appraisal	
No Risk	Risk	General	Smoke
Feeling Safe in the Environment			
People will engage in actions that lead to information	People will engage in actions that lead to information		
People act rationally and altruistically			

		Engage in preparation activities	
		Herding behavior	
		Collecting of personal belongings	
			Move through smoke: Reduce speed
			Move through smoke: stagger around their ideal path
			Move through smoke: move towards walls
			Head towards another exit, based on visibility/density

Table 2: the most important elements from the theoretical framework.

4. Methodology

This section discusses the methodology that is applied in this thesis. By describing each step of this research in detail, the study remains transparent, making it replicable (Bryman, 2012).

4.1. Research approach

Based on the previous sections, the following conceptual model is created.

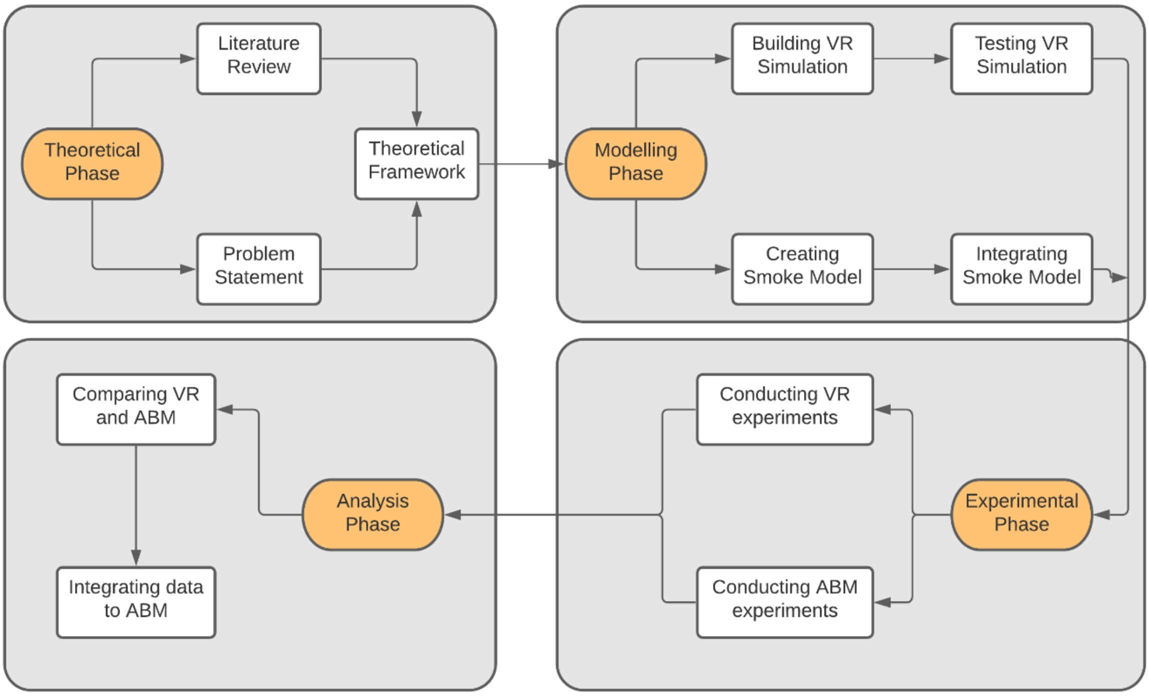


Figure 5: Phases of the research

In Figure 5, all the steps of this research are visualized. As can be seen, the research consists of four phases. The first phase is the theoretical phase. In this phase, the problem is stated based on a review of the literature on the topic. The problem statement leads to the theoretical framework, in which the important literature on the topic is discussed. Based on information from the literature, the modelling phase starts. The modelling phase is split in two parts: the ABM and VR modelling. In the first part, an evacuation ABM is improved by creating and implementing a smoke model. The way the agents interact with this dynamic environment is also programmed into the model by adding behavioural data. In this phase, sub-questions 1 and 2 are answered. In the second part, a VR simulation is built. In this part, sub-question 3 is answered. After the VR simulation is build, the simulation is tested. With a tested simulation, the experimental phase starts. In this phase, sub-question 4 is answered and the VR experiments are conducted. Then the analysis phase starts, where the data from the VR experiments is integrated into the ABM. After integrating the data, the second part of the experimental phase starts, with the ABM experiments. After the experiments, the research switches back to the analysis phase, and the results from both experiments are compared. After this, sub-question 5 is answered.

Now that the structure of this research is presented, the methods applied for each sub-objective, as established in chapter 2, are explained.

4.1.1. Sub-objective a

The current evacuation model is static; the environment is the same every run. This kind of model could provide useful information when simulating a test-evacuation. However, fire and smoke spread through the environment, thus creating different situations during an evacuation. In case there is smoke in a building, the environment could be considered dynamic. The agents need to adapt to changing situation. For example, an exit could be blocked off during one run, while in another run the exit can still be accessible. Thus, the first sub-objective is to find out how the agent-based model can be adjusted to integrate a dynamic environment. This way, a fire or smoke situation could be implemented. To fulfil this objective, an overview of the evacuation model prior to the implementation is given, as formulated in the following sub-question:

How can the environment, the agents and the processes of the current evacuation model be described? (1)

The agent-based model that is used in this thesis is an evacuation model of the ITC building in Enschede. This model was built in Netlogo to test the influence of variation in pre-evacuation time and exit choice on evacuation time (Augustijn-Beckers, Flacke, & Retsios, 2010). The environment that is used in the model, can be seen in Figure 6. The three exit that are available to the agents, are visible as well (marked in yellow). The one on the bottom is the main exit, while the two on top are the emergency exits. The agents in the model are students and staff members.

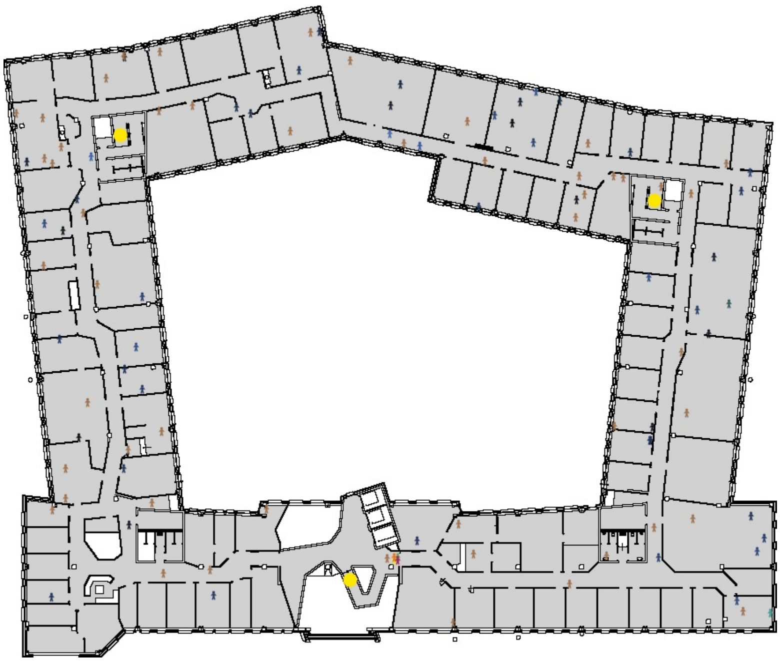


Figure 6: floorplan of the ITC-building with its three exits, which is used in the ABM.

To answer this first question, the model needs to be described. ABMs can be hard to understand and replicate, as there is no standard protocol for describing them (Grimm et al., 2006). Furthermore, ABMs are harder to analyse and communicate than analytical models, as they are more complex in structure (Grimm, Wyszomirski, Aikman, & Uchmański, 1999). To make the understanding and analysis of ABMs easier, Grimm et al. (2006) proposed a standard protocol, the ODD-protocol.

The idea of the protocol is to always structure the information about an ABM in the same way. To do this, it consists of seven elements, split into three blocks: overview, design concepts, and details, as can be seen in figure 10. For this thesis, only the overview is discussed. After completing the overview, readers should be able to describe the models' objects (classes), the entities (the agents and the environments) and the scheduling of the models' processes (Grimm et al., 2006).

When it is clear how the evacuation model works, it can be enhanced by adding a smoke model. As stated before, the current model is static. In order to add the smoke model, changes to the model need to be made. This leads to the following sub-question:

How can a dynamic environment (smoke) be integrated into the ABM? (2)

To answer this question, a model that simulates fire or smoke can either be created or integrated. Corrêa, Bicho, & Adamatti (2019) introduce a new model that simulates the dispersion of smoke in a closed environment and tested this model in a night club. The model uses cellular automata associated with the concept of potential fields and modelling an evacuation situation using agent-based simulation. An adaptation of this model is used in this thesis to integrate smoke into the ABM. The conceptual model in Figure 7 shows how the smoke model is build.

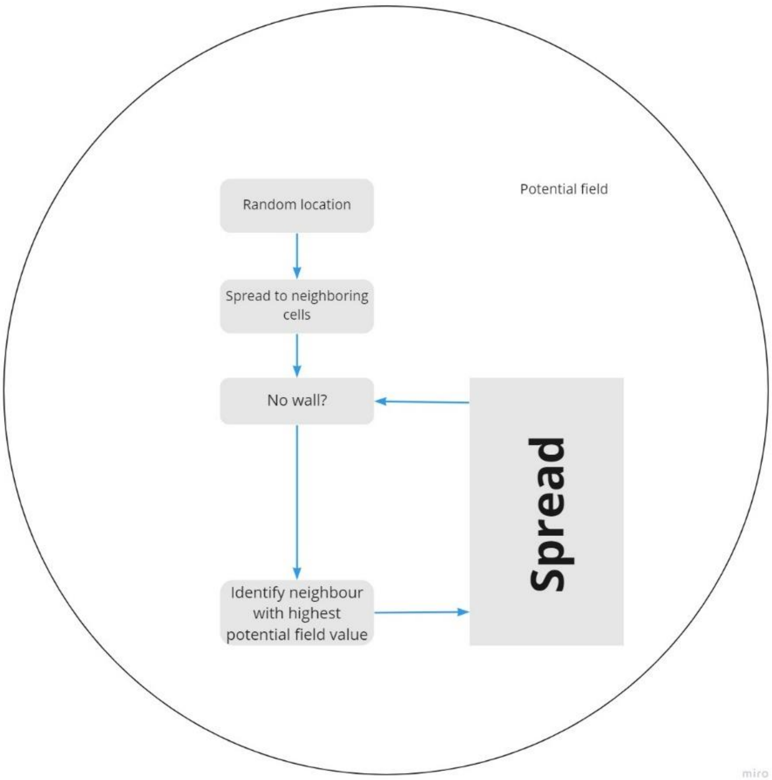


Figure 7: the conceptual model of the smoke model.

In short, the smoke is generated in a random location and a potential field is calculated. From the starting point the smoke spreads to its eight neighbouring patches (Moore's Neighbourhood). Then the regular spreading starts. The diffusion is based on the potential field: each smoke patch identifies his neighbouring patch with the highest potential field value, to which the smoke spreads. This process is repeated, until the smoke reaches 20000 patches. The smoke density can also differ, which is regulated by a global variable.

After a dynamic environment is added to the model, the behaviour of the agents also needs to change. The way they interact with both the other agents and the environment differs from when the model is static. The way the agents react to encountering smoke needs to be programmed in, as well as what they do after. This not only matters for the students and the staff in the building, but also the evacuation officers. It is important to know what they will do when they encounter smoke. The behaviour of the agents is changed in such a way, so that they can perceive risk and make a decision on what to do. A conceptual model that shows these choices can be seen in Figure 8.

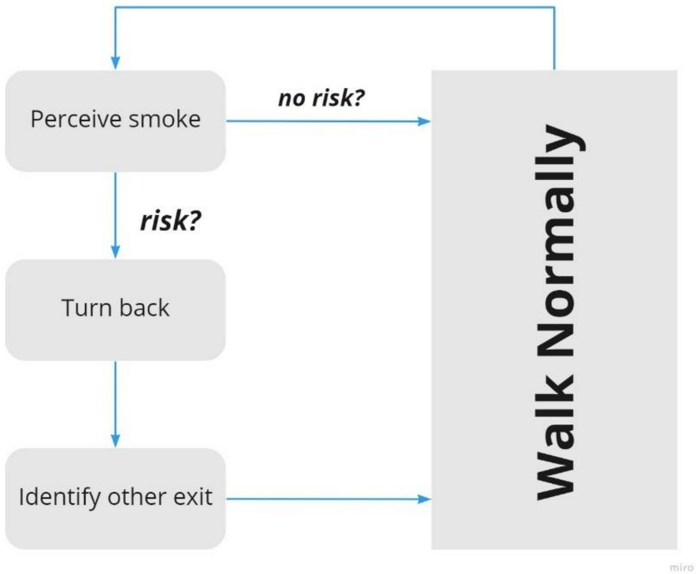


Figure 8: conceptual model of the Risk Perception and Coping Behaviour

The risk perception is based on the smoke density. The smoke density is modelled by a global variable that determines the density of the smoke. According to Gwynne et al. (2001), when the smoke is more dense, the visibility distance is lower, and more people turn around. In the model this is done by introducing an acceptable smoke level. For each agent the acceptable smoke density differs. If the smoke density is higher than the acceptance level of the agent, he will turn around. If it is lower, the agent chooses to walk through.

4.1.2. Sub-objective b

The second sub-objective is to find out how behavioural data can be collected using virtual reality based on a simulated environment.

The fourth sub-question is as follows:

Which data is needed to implement agent – environment interactions and how can a realistic VR environment for the experiments be created that matches the available ABM? (3)

After the ABM is enhanced with a smoke model, it is important to gather behavioural data. In this thesis, data is collected by performing VR experiments. Based on the theoretical framework, the experiments are focussed on the coping appraisal when encountering smoke. Gwynne et al. (2001) showed the percentage of people moving away from smoke based on different visibility levels. In this research the smoke density can either be high or low, and the exit can be visible or not visible (indicated by the exit signs). Furthermore, Zheng et al. (2011) show that the location of the smoke matters. Thus, the following elements are checked in these experiments:

- General smoke behaviour
    - How many people will turn around and how many will go through?
- Smoke density
    - Do people go through smoke when the density is low and do people not go through smoke when the density is high?
- Location of the smoke
    - Does the location of the smoke matter when choosing to go through or not?

VR and serious gaming are upcoming ways of collecting behavioural data. As stated before in section 3.5, a serious game is not the way to go for this research. In this thesis a simulation was built. The simulation can be built in several ways. This part of the study focusses on building this simulation. One of the possibilities is to use a game engine. According to Huang et al. (2018) the most predominant software in the market is Unity3D, Unreal Engine4 and Autodesk Stingray. Unity3D might be less powerful regarding the visualization authenticity and suitability to specific software, but is, according to Huang et al. (2018): "overall more suitable for testing early-stage architectural and urban design scenarios due to the accessible workflow, better correlation with ABM and the wider user communities."

With the Unity3D software, five simulations are build. Each simulation has a different layout and the location of the smoke differs. An alarm and a voice over the speaker tell the participants to start evacuating. The participant encounters smoke inside a building and has to find a way out. This can either be by going through the smoke, or by looking for another exit. Exits are indicated by exit signs, which are visible with low density, but invisible with high density. The simulation takes place indoors, as the agent-based model is indoors as well.

Now that it is clear which elements from the theoretical framework are important and how a VR simulation can be build, VR experiments can be set up.

4.1.2.1. Experimental design

In this thesis, a mixed 5x2 design is used, as was done by Nazemi et al. (2021). Five different environments are used, where the length and the look of the hallway where the smoke is varies. Each participant goes through all five simulations, with either low smoke intensity or high smoke intensity. There are environments with multiple exits, but also environments where all exits are blocked off by smoke to test the impact of the location of the smoke. The within-subject factor is in this thesis the environment; each participant tests all the different environments. The between-subject factor is in this thesis the smoke intensity; each intensity is tested by different participants. In other words, one participant goes through five runs, where each run is in a different environment, with either low or high smoke intensity. The sample is randomly divided into two groups. One group does the experiment in a non-immersive setting, while the other group performs the experiment in an immersive VR environment. Within both groups, the smoke density is randomly assigned to either high or low. The results of the experiments in VR are used as input data for the evacuation model. The experiments in the non-VR settings are used to determine the level of immersion of the VR experiments.

4.1.2.2. Subjects

For the experiments, twenty participants, 13 male and 7 female, were selected. The sample consisted of a random selection of people, who could either be students or staff. The people who could be students were randomly selected through social media. The staff were selected through email and social media. The age of the participants varied between 20 and 63 (Mean = 38,2, SD = 15,8), the age distribution of the participants can be seen in Figure 9.

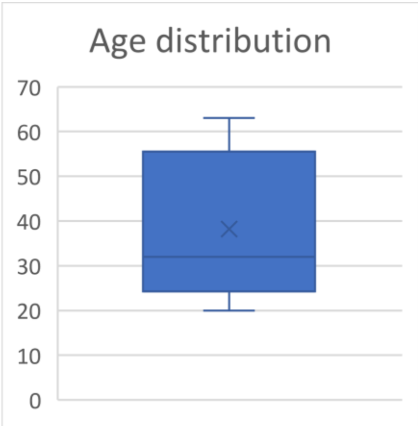


Figure 9: the age distribution of all the participants.

Some of the participants had previous experience with VR, and some had none. The division into two groups was not based on this previous experience. The participants were of different backgrounds, such as physiotherapy, assistant professor, GIS researcher, sustainable energy technology, ICT and coastal management.

4.1.2.3. Experimental equipment

The experiments took place in a virtual reality laboratory. Group 1 performed the experiment on the computer, with a mouse and keyboard. The computer was equipped with a 2.5 GHz Intel Core i5 CPU, 8 GB memory and a GeForce GTX 1050 video card.

For the experiment of group 2, a head-mounted display (HMD) was used in combination with two controllers, which are rendered as hands in the simulation. The HMD that was used is the HTC Vive. In order to render the VR simulation, a PC with the following hardware was used: 4.0 GHz Intel Core i7 CPU, 16 GB memory and a GeForce GTX 1080.

4.1.2.4. Test procedure

As is done by Wu, Cai, Luo, Liu, & Zhang (2021), a preliminary test was run prior to the actual experiments. For this test, three professors were asked to participate. The goal of this test was to get feedback on the immersion and the VR equipment, the procedure of the experiments and the layout of the environments. Based on this input, the test procedure was revised to ensure success and effectiveness of the actual experiments. The received feedback during these sessions mainly focussed on the visibility. The exit signs were too bright, meaning that they could be seen as light through the smoke even if the density was high. This resulted in test persons going through the dense smoke, because they could see where the exit was. This was edited before the final experiments took place. Furthermore, the immersion questionnaire was slightly revised, to make some questions more clear.

For the experiment, 20 participants were invited, and they were divided into two groups of ten. Before the testing started, they were introduced to the background and the procedure of the experiments. The participants in group 2 also got to get familiar with the VR experience by using a test scene. In this test scene, they were able to move around by using the controllers and to throw balls, shoot with a bow, to get the hang of the equipment. Lastly, they were asked to read and sign an informed consent form.

After the experiments were concluded, the participants of the VR group were asked to fill in two questionnaires. The non-VR group only filled in one questionnaire. The first questionnaire contained questions regarding the immersion and the realism of the simulation and was filled in by both groups. The questions on immersion were adopted from the immersion scale of Jennett et al. (2008). These questions can be found in Appendix 1.1. The questionnaire consists of 32 questions and leads to an immersion score of 1 for strongly disagree to a score of 5 for strongly agree. This score is appropriately adjusted for positive and negative questions, which is added to avoid wording effects (Jennett et al., 2008). The highest possible score is 75, however, the results of the scores are relative, to compare between both groups. The purpose of the questionnaire is to see if the VR experiment is significantly more immersive than the non-VR experiment.

The second questionnaire contained questions about the choices made during the simulation and was only filled in by the VR group. It focused on the actions when encountering the smoke. The movement of the participants is stored in a video-output file, but the *why* behind these movements is also important. This questionnaire can help in understanding the process of the risk perception of the evacuees. The questionnaire can be found in Appendix 1.2.

Analysing the behaviour of the participants when encountering smoke, is done by video recording each simulation in the Unity3D editor. The editor provides a built-in recorder, which allows the user to record a play run. When starting a simulation, the *play* button is pressed. The recorder then captures the screen during the run. This recording results in a video file, which was used to watch each session back and analyse each choice made by the participants. Different choices that can be made are turning back from the smoke or going through the smoke.

4.1.2.5. Analysis

The results from the immersion score questionnaires from both groups are analysed using the SPSS software by IBM. This is done by performing an independent samples test. This test results in a t-value, which is useful when comparing the means of two groups, which was done in this case. The result from this test tells if the immersion scores from the VR experiments are significantly higher than the scores from the computer experiments or not. The relationship between the scores and age of the participants is also tested. This is done by performing a Pearson correlation test, which is a suitable test when measuring two quantitative variables.

Another test is run to see if the choice to go through the smoke or to turn back is influenced by the density of the smoke. To test this, a chi-square test is performed. This is a useful test to determine statistical independence or association between two or more categorical variables ("SPSS tutorials: chi-square test of independence," n.d.).

The second questionnaire, regarding the explanation behind the choices made in the simulations, is analysed by using a frequency analysis. This is possible after quantifying the answers from the participants. A coding system is created, in order to be able to get standardized results. For this, the QDA Miner software is used.

The VR experiments will lead to a number of observations:

- How many people will turn around to reach an alternative exit and how many people will continue to reach their original exit.
    - This is measured by analysing the video output from the Unity3D editor
- The influence of the smoke density on the risk perception and coping appraisal
    - If the smoke density is high, does this lead to a higher risk perception?
    - If the smoke density is high, do more people turn around, thus change their behaviour?
- The influence of the location of the smoke on the behaviour
    - Does the percentage of participants that go through or turn back differ per simulation?

4.1.3. Sub-question c

The third objective is to find out how to use the data from the experiments to improve the ABM. The last sub-question is as follows:

> *How do the VR and ABM compare to each other and how can the agent-based model be improved by adding micro-level behavioural data? (4)*

Before implementing the data from the VR experiments into the ABM, experiments with the ABM are conducted. The goal of these experiments is to compare the data from the VR to the ABM. There are three important aspects that are tested in the VR experiments and can be linked to the ABM by conducting experiments. These are general smoke behaviour, smoke density and the location of the smoke. Each of the experiments are discussed below.

4.1.3.1. General smoke behaviour

In these experiments it is checked how many agents walk through the smoke and how many agents turn around. The model is run ten times, with a different location of the smoke and a smoke density of 50. The sum of leavers that encounter smoke is counted as well as the amount of leavers that walk through and the amount that turn back. Simulated values are compared to the VR experiment data.

4.1.3.2. Smoke density

In this experiment, a number of test runs are done, to see how many agents walk through the smoke when the density of the smoke differs. Two sets of tests are done:

- Low density: smoke density is set to 25
- High density: smoke density is set to 75

Each set is run five times and the amount of leavers that walk through and that turn around are counted. The simulated values are again compared to the results of the VR experiment.

4.1.3.3. Location of the smoke

As the environments used in the VR simulation are different than the environment in the ABM, this is difficult. However, in the VR experiments the smoke was located on the emergency exit each time. To compare the percentage of evacuees that go through the smoke and the percentage of evacuees that turn back from the smoke when the smoke is located on or around the emergency exit, the following experiment is set up:

- The smoke is generated on one of the emergency exit, instead of on a random location.
- Two sets of 5 runs are done:
    - In one set the smoke is on the left emergency exit, in the other set the smoke is on the right emergency exit.
- The percentage of leavers that go through the smoke is calculated, as well as the percentage that turns back.

Result from these experiments are compared to the results of the VR experiments.

4.1.3.4. Data integration

Data from the VR experiments can be integrated in different ways:

- By directly driving agent-behaviour from data via Machine Learning
- By statistical analysis of the results of the VR tests leading to an adjustment in agent behaviour

Steering agent behaviour directly from data is not possible in this case as the dataset derived from the VR experiments is too small for machine learning. This is why the statistical approach is taken. After comparing the results of the aforementioned ABM experiments to the data from the VR experiments, the data can be integrated. In case the results are similar, there is no need to change anything. However, if the results differ from each other, the ABM needs to be adapted.

5. Results

5.1. Sub-objective a

How can the environment, the agents and the processes of the current evacuation model be described? (1)

As stated before, describing an ABM can be difficult, however, Grimm et al., (2006) created a standard protocol to make understanding and analysing easier. This protocol is called the ODD-protocol, as can be seen in Figure 10. In this thesis, only the overview is discussed to enable readers to describe the models' classes, the agents and environments and the scheduling of the models' processes.

Overview	**Purpose**
	State variables and scales
	Process overview and scheduling
Design concepts	**Design concepts**
Details	**Initialization**
	Input
	Submodels

Figure 10: the ODD-protocol (Grimm et al., 2006).

The first element is to describe the purpose of the model. The ABM model used in this thesis is an evacuation model, built with Netlogo, of the ITC building in Enschede. The model was used to simulate evacuation behaviour. The goal of the study was to test the influence of variation in pre-evacuation time and exit choice on evacuation time.

This model contains three different types of agents (leavers, followers and officers). Each of these have their own behaviour. The model also contains five different types of environments: a network following the centrelines of the corridor, the walls and walkable space (indicating where agents can /cannot move), emergency exits, and a set of raster cost distance layers that will guide the leavers and officers to the emergency exits. The individuals are characterized by the state variables: student or staff, pre-evacuation time, walking speed, person size, interaction time and exit choice.

In the evacuation model, there are three kinds of agents: leavers, followers and officers. **The leavers**, representing students and staff members, will evacuate on their own. Important behavioural variables to the leavers are pre-evacuation time and exit choice. The leavers wait until their pre-evacuation time is over, they select an exit, and then follow the raster environment corresponding to this exit to bring them to the emergency exit. They do this by checking the raster value of their current location, comparing it to the neighbouring values, and moving to the lowest value. As emergency exits have the value zero, they automatically move to the exit. The movement model used for the agents differs for each agent type. The movement of the leavers is based on a free-space model. The leavers avoid collision with obstacles and other agents. They will move towards their destination, this can either be the nearest exit or another exit as indicated in their exit preference, based on a cost-distance input file. The exits have a value of 0, while the other patches have a value that is gradually getting higher the further away from an exit. By seeking out the patch with the lowest value each tick, the leavers move towards one of the exits. This exit is based on their preference, which can either be the main exit or the nearest exit. The nearest exit can be any of the three exits and is dependent on the leavers' location.

Followers represent the staff or students that are not able to evacuate on their own. The followers can only evacuate by following a leaver or an officer, if that leaver or officer is in the direct vicinity, or when they are close to an exit. Followers do not have a preferred exit or pre-evacuation time. The movement of the followers is dependent on the distance to the nearest exit. If the follower is within eye distance of an exit, it will act as a leaver and evacuates itself. If a follower is not within eye distance of an exit, it shows random movement until it is picked up by an officer or a leaver. The follower then follows the officer or leaver until they reached an exit.

The officers are staff members who had a professional evacuation training and are responsible for the evacuation. Their main behaviour is to clear the building, by going through each room. The movement for the officers is steered by two aspects: the centre line network model of the corridors and rooms and the location of other officers in the building. The officers work in pairs, so each officer takes either the left or the right side of the network. The movement of the officers is interrupted upon encountering a follower, then the officer stops moving. The officer enters every room as far as needed to fully view each wall and corner. The movement of the officer continues until the whole floor is secured, then the officer will evacuate himself. The evacuation is the same as the way the leavers move but the officers only move towards the nearest exit. There are four officers in the evacuation and they start clearing the floor and the central staircase. They split into two groups of two officers, one group going left and the other going to the right. Officers navigate via the network. This network leads them into rooms when the network was a line to the side. One officer will check the rooms on the right side of the network, the other will check the rooms at the left hand side. When an officer encounters a leaver or follower that has not yet started evacuating, they will prompt them to evacuate. This is represented by the interaction time.

Third, the scales should be discussed. The pre-evacuation time is taken from literature. According to Gwynne, Galea, Parke, & Hickson (2003) the pre-evacuation time for staff varies between 0 and 246 seconds, with a mean of 70.8 seconds. For students it varies between 8 and 200 seconds, with a mean of 73.7 seconds (Gwynne et al., 2003). The walking speed for all agents is between 1.2 m/s and 1.8 m/s. The person size is set to 0.3 by 0.3 meters. The agents cannot occupy the same space at the same time. The interaction time is 10 seconds. The exit choice can either be the nearest exit or the main exit.

The third element is to describe the spatial and temporal extent of the model. In the model, 20 ticks equal one second. The total temporal duration of one run is equal to one evacuation and will be around 6 minutes or 7000 ticks. The simulation automatically stops after the last officer has evacuated. Spatially, the model represents the ITC building, visible in Figure 6. The raster layers have a resolution of 879 by 740 pixels.

Now that it is clear how the original evacuation model works, a smoke model can be added to it. This is done by answering the next sub-question.

How can a dynamic environment (fire – smoke) be integrated into the ABM? (2)

The existing evacuation model focusses on the behaviour of the agents upon hearing that they need to evacuate. On their way to the exits, they do not encounter anything that can make change their behaviour. In this section of this thesis, a smoke model was added to the evacuation model. As stated in the theoretical framework, Corrêa et al. (2019) propose a smoke dispersion model, based on the potential field approach. Figure 11 shows the steps their model takes to disperse the smoke. The first step is to let the model randomly select a starting point, from which the smoke will disperse. In the second step, the smoke spreads 1/8th of its intensity to its neighbours, according to Moore's Neighbourhood. In the third step, the smoke spreads half of its intensity to the patch to which the potential field vector points.

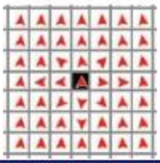
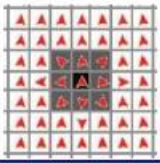
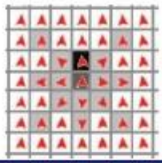
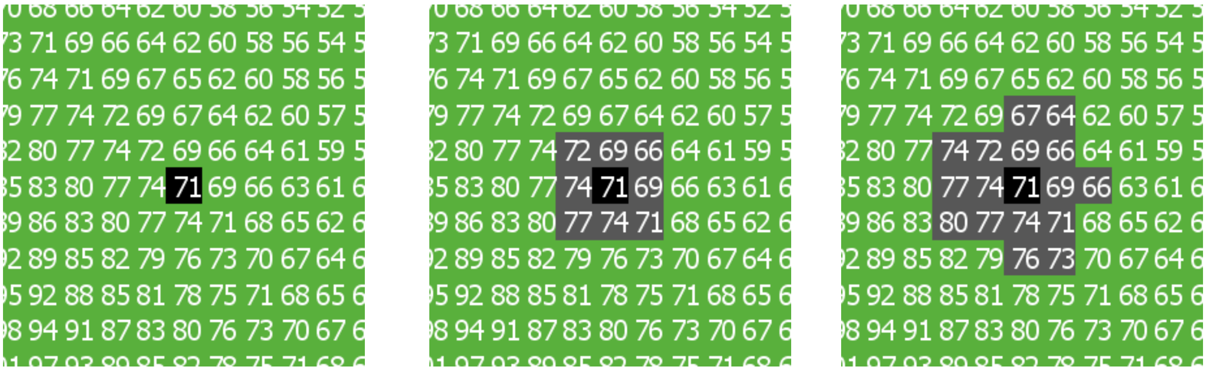
1st step	2nd step	3rd step
Each tick generates the smoke at the starting point of the fire (black patch), which is defined by the user.	Smoke spreads 1/8 of its intensity to its neighbors (Moore's Neighborhood).	Smoke disperses half (1/2) of its intensity to the patch that its potential field vector is pointing to.
		

Figure 11: steps of how the smoke disperses (Corrêa et al., 2019)

In this thesis, the smoke is placed in a random patch on the map, with the colour black, as is illustrated in figure 12. In the second step, the smoke is spread by turning the neighbouring (Moore's Neighbourhood) patches grey, see Figure 13. The third step is modelled differently in this thesis. The smoke spreads based on the value of the potential field, instead of on the direction of the vector. This potential field is calculated based on the following equation:

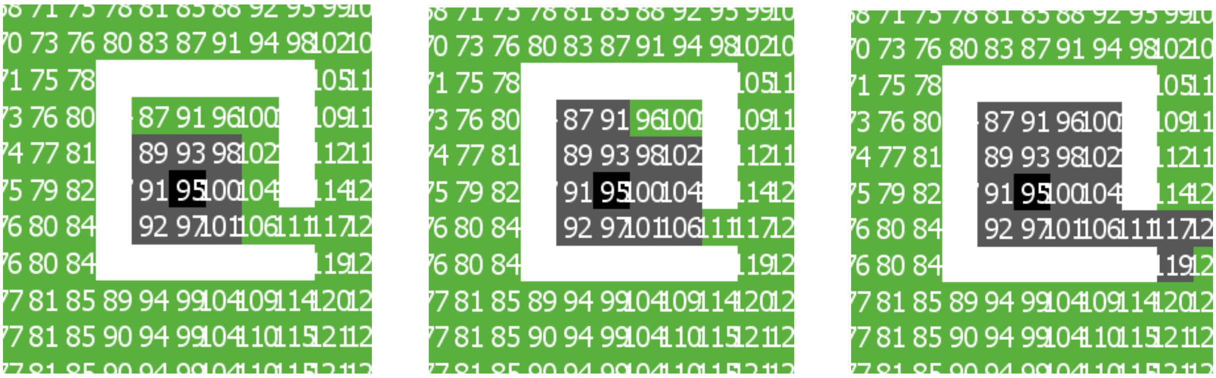
$$V = Vg * \exp{(-lambda * Xg)} \quad (1)$$

In this equation Vg is the potential field at the location of the target, from where the potential is generated. The distance from the target is expressed in Xg. In Netlogo this is done by using the "distancexy"-command. The x and y coordinates that are used in this command, are the coordinates of the location of the exits in the evacuation model. Netlogo then calculates for each patch the potential field value, based on how many patches away it is from the target. The smoke spreads to its neighbour patches with the highest field values and a certain colour (in the example below green). Thus, it moves away from the starting point in the direction of the doors. This step is visualized in Figure 14.



Figures 12, 13 and 14: screenshots of the three steps of the spreading of the smoke (source: Netlogo).

To implement the smoke model into the evacuation mode, the smoke needs to be aware of its surroundings. The ITC building consists of rooms and corridors, separated by walls. The smoke cannot go through the walls, but can only spread through the open doors. In the example above, the smoke could only spread to a neighbouring patch that is green. An example of how the smoke reacts to a wall, can be seen in Figures 15, 16 and 17.



Figures 15, 16 and 17: screenshots of the smoke spreading around a wall (source: Netlogo).

This mechanism is also used in the evacuation model. The smoke spreads only to those patches that are light grey (pcolor = 8). As the walls are visualized as black (pcolor = 0), the smoke does not recognize these patches as neighbouring patch.

The end result of the smoke model implemented in the evacuation model can be seen in figures 18 and 19. The smoke is located respectively on the bottom of the model and in the upper right corner.

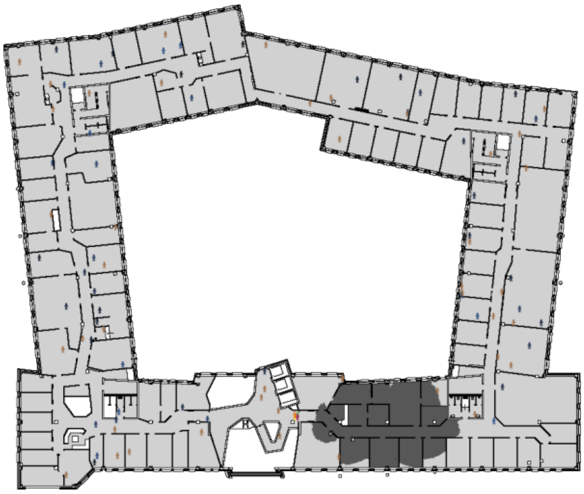
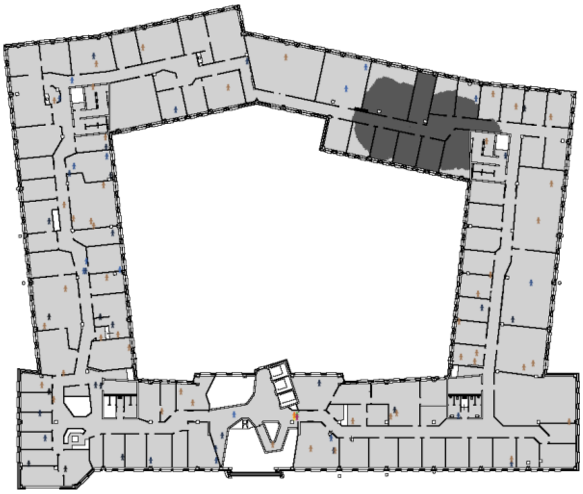
 

Figure 18 (on the left side) and figure 19 (on the right side): the smoke model implemented in the evacuation model; with the smoke on the bottom of figure 18 and on the top right side of figure 19.

For the smoke model to work in combination with the evacuation model, both models are run separately. First, the smoke model is run until it covers 20000 patches. Second, the evacuation model starts.

In the model, agents move patch by patch, based on cost-distance values. These values are calculated by creating a cost-distance raster in the ArcMap software, using a raster of the walls of the ITC-building and point-files of the exits. The cost-distance rasters can be seen in figure 20 and 21.

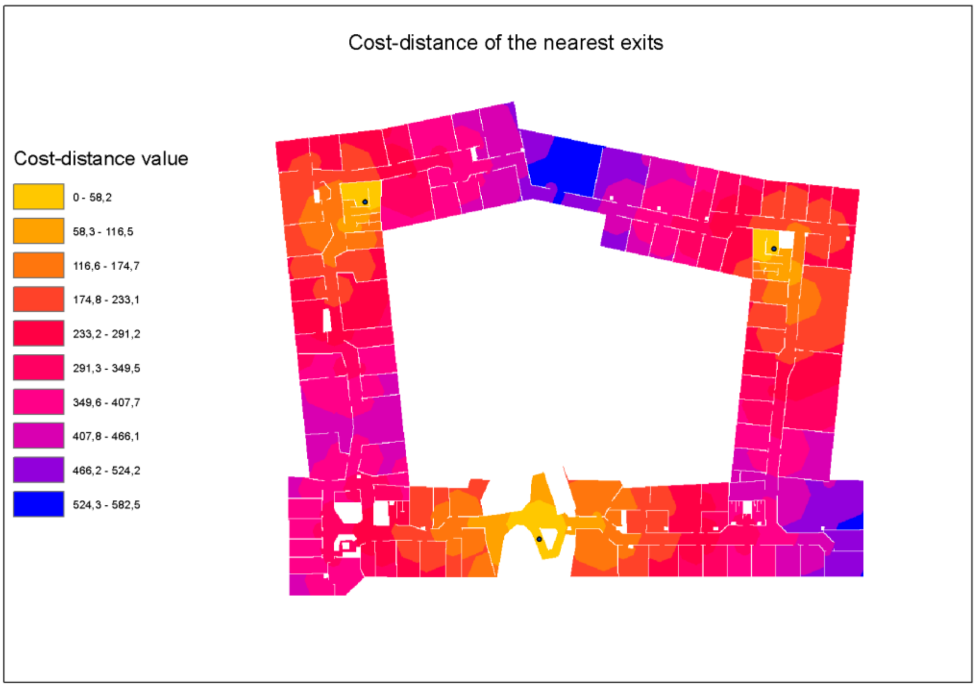


Figure 20: cost-distance map raster with the nearest exits as input, indicated with dots.

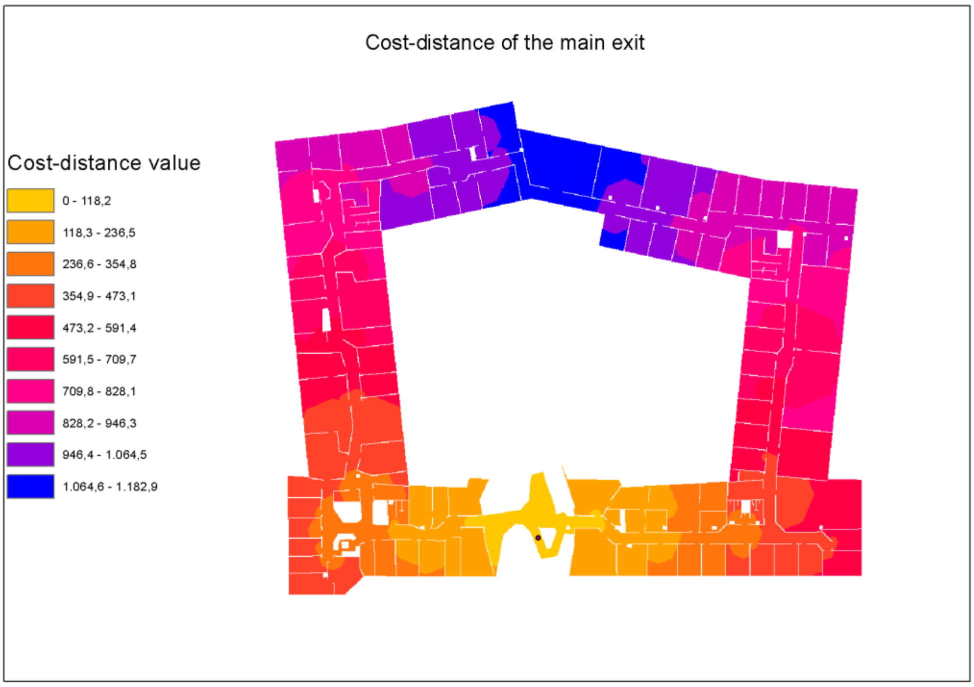


Figure 21: cost-distance raster with the main exit as input, indicated with a dot.

For *exitchoice = 0*, all three exits are used as input. The cost-distance raster is converted to an ASCII-file, which is loaded into Netlogo. The values for the patches are stored in a variable called *distance_nearest_exit*, which results in a cost-distance value for each patch. The farther away from an exit, the higher the value. The exit, which was used as input point, has the value "0". For *exitchoice = 1*, the same procedure is done, but only the main exit is used as input and the values are stored in the variable *distance_main_exit*.

When the model starts, the agents move towards their preferred exit, by following the variable *minpatch*. This variable calls the values of the patches around the agent (Moore's Neighbourhood) in either *distance_nearest_exit* or *distance_main_exit* and chooses the lowest value. This results in agents moving towards the patch with the lowest value each time, leading them to an exit.

The density of the smoke is not modelled explicitly (the raster layer is binary smoke -non smoke) and does not include a density value, but a global variable is introduced that will indicate the smoke density. This density is homogenous (all smoke has the same density). By running the model several times with different density values, the impact of density on the evacuation behaviour can be modelled. The density value is expressed in percentages (1-100).

Besides the introduction of the smoke, the behaviour of agents needs to change to respond to this smoke. This has to be done for both leavers and officers. Adjustment of the behaviour of followers is not needed because they will follow leavers/officers. The change in behaviour is split into two aspects: sensing the smoke and deciding what to do (walk through the smoke or turn around and find an alternative exit). This is where the risk assessment, see section 3.4, comes in. The leavers and officers start to evacuate and constantly assess the risk. It works slightly different for the leavers and the officers.

First, **the risk assessment of the leavers** is discussed. A diagram of their behaviour can be seen in Figure 22. The leaver starts by walking according to their normal regular behaviour, which was described in sub-question 1. Each step, they check if they reached an exit (then their *minpathc = 0)*. If this is the case, they have evacuated and die (which is a way to write an agent out of the simulation).

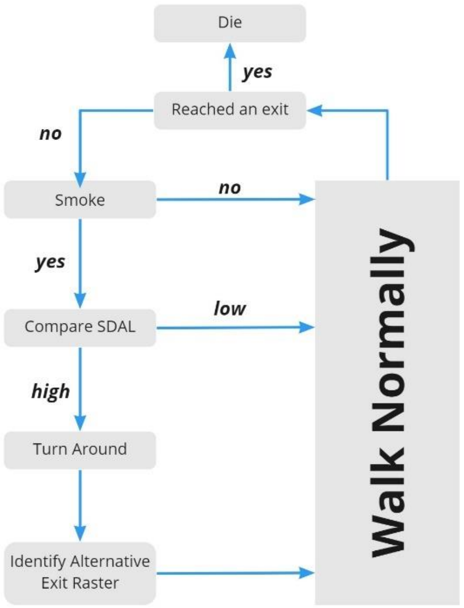


Figure 22: UML diagram of the behavioural process of the leavers.

They also check each step if they encountered smoke. This is done by checking the colour of their *minpatch.* If the *minpatch* of a leaver is white, there is no risk and they continue according to their normal behaviour. However, if their *minpatch* is grey (meaning a smoke filled patch), they assess the risk to check whether it is acceptable or unacceptable. This is done by introducing the **smoke density acceptance level (SDAL)**. This variable is a random value on a scale 0-100. The value indicates when an agent will walk through the smoke, and when this agent will turn around. For example, when a leaver has an *SDAL* of 60, and the global smoke density value is set to 80, the density of the smoke is greater than the acceptance level of the leaver, and he will turn around. When the agent has an *SDAL* of 82, the agent will walk through the smoke. In case the *SDAL* is higher than the smoke density value, nothing changes in the behaviour of the leaver. If the *SDAL* is lower than the smoke density, the agent turns around and looks for another exit. To turn around and be able to look for another exit, these leavers must change their *exitchoice* variable and the input for their *minpatch*-variable. To do this, the agents have three options:

- Set *exitchoice* to “1” and *minpatch* to the main exit based on the already existing *distance_main_exit.*
- Set *exitchoice* to “2” and *minpatch* to the emergency exit in the upper right corner based on *distance_upperright_exit*
- Set *exitchoice* to “3” and *minpatch* to the emergency exit in the upper left corner based on *distance_upperleft_exit*

After changing their *exitchoice* and *minpatch* input, they check if their new *minpatch* is white. If this is not the case, they continue to the next option and check again.

For the second and third option, two new cost-distance rasters were generated. A cost-distance analysis calculates a value for each cell based on how much it costs to get from that cell to a certain point. In this case, that point was either the upper left exit or the upper right exit. A raster of the walls of the ITC-building was created, where the walls had the value *NoData* and the space between the walls had the value *1.* This raster was used as cost input for the cost-distance, so the farther away from the exit, the higher the cost to reach it.

For the first raster, the exit in the upper right corner was used and for the second raster, the exit in the upper left corner was used. This resulted in the cost-distance rasters as can be seen in figures 23 and 24.

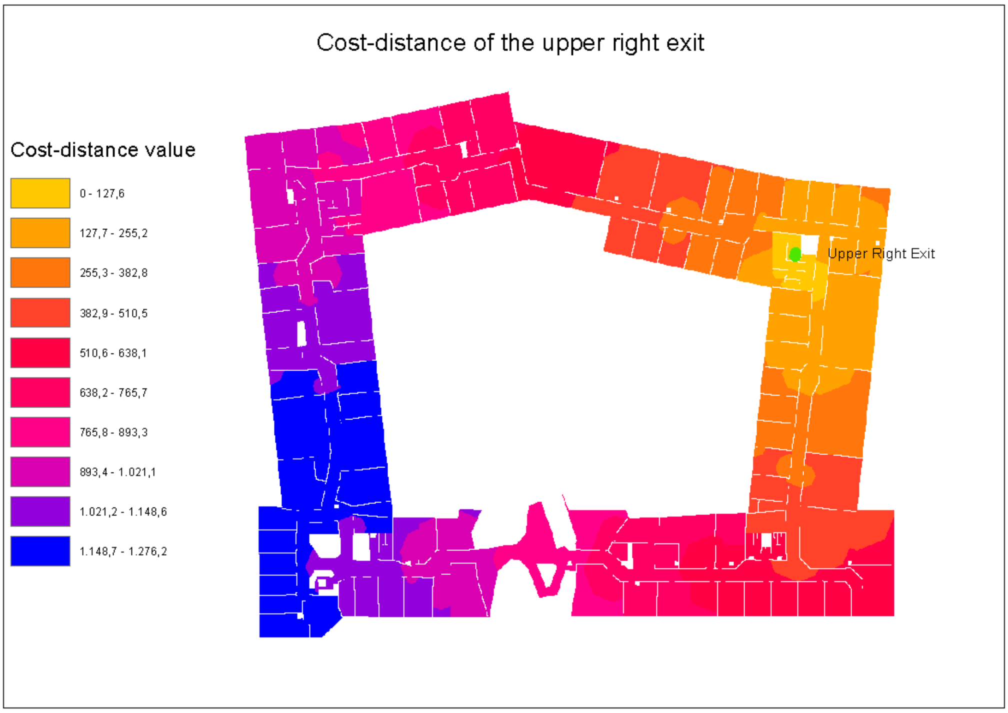


Figure 23: cost-distance raster of the upper right emergency exit.

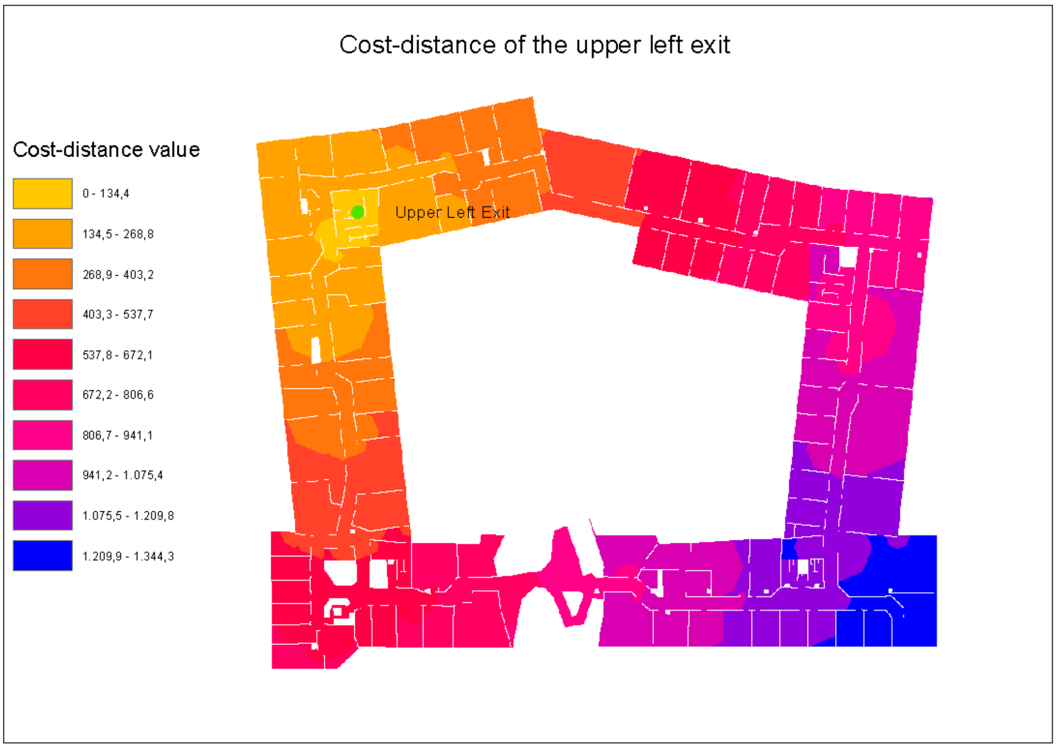


Figure 24: cost-distance of the upper left emergency exit.

The *NoData* values were later reclassified into a value that was higher than the highest value of the cost-distance. This was done to correct for a slight overlay discrepancy in Netlogo.

Second, **the risk assessment of the officers** is discussed. A diagram of the behaviour of the officers can be seen in Figure 25.

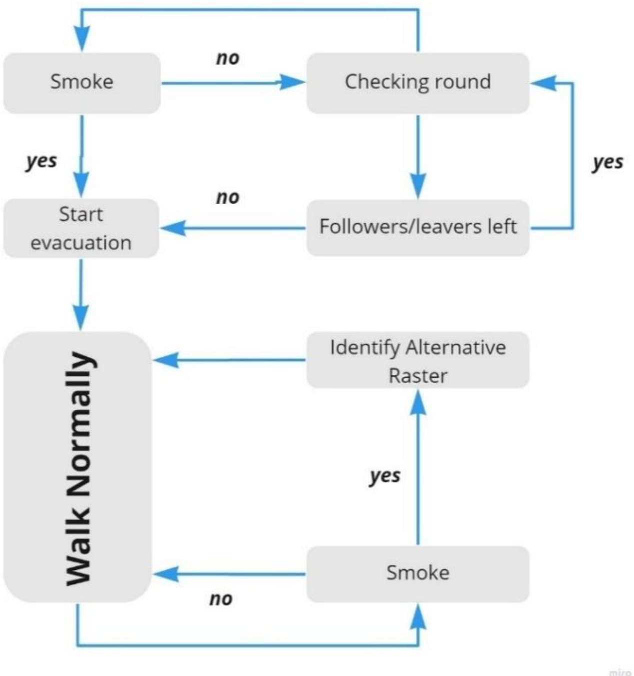


Figure 25: UML diagram of the behaviour of the officers.

The behaviour of the officers can be split into two processes. **The first process** consists of checking the building, to see if there are any leavers or followers left. This movement is based on a network. An officer can either walk left or right of this network. An officer that walks left of the network, checks if the patch ahead of him has a network-value. If this is the case, this means that the officer has to go to the left to check a room or make a turn. He then checks again if the patch ahead has a network-value. If this is not the case, the officer checks if the patch right of him has a network-value. Here the risk assessment of the officer comes in. In case there is no risk and the patch ahead of the officer is light grey (no smoke), the officer walks forward. In case the patch ahead is grey (smoke), the officer has to decide whether to continue his round or not. As the officers are trained to avoid danger, thus they will assess the sight of smoke as an unacceptable level of risk. This means that, in case the patch ahead is grey (meaning smoke) the risk is unacceptable and the officer will start to evacuate, which is **the second process**. In some cases, the officer gets stuck when starting to evacuate. This happened because the *minpatch* was a smoke patch. To solve this, a new variable was introduced: the *walk_back_time.* This variable is a countdown from “100” to “0”, and is activated when the officer encounters smoke. At the same time, the officer switches his *walk_preference* to the opposite direction. This results in the officer walking back over the network for some time. After the *walk_back_time* has reached “0”, the variable *round-finished?* is set to true, thus activating the evacuation mode. In this process the officers stop clearing the building of leavers and followers, and head towards the nearest exit. From here, the officers move based on *minpatch*, following the same procedure as the leavers do. All four officers start with *exitchoice* = “0” and they check each step if their *minpatch* is light grey (no smoke) or grey (smoke). In case of smoke, they switch to another input file for their *minpatch*, just like the leavers. This way they always find a way out, in case the route to the nearest exit is blocked off by smoke.

5.1.1. Verification

Some new functionality is introduced into the model and a couple of checks are performed to see if everything works properly.

A check on the behaviour change of the agents when encountering smoke was therefore conducted to check if the agents respond to the smoke. Figure x shows the *exitchoice* of a leaver before encountering smoke. As it is “0”, it indicates that the leaver chooses the nearest exit. In this case, this is the upper right exit (see Figure 6 in section 4.2.1). Figures 26 and 27 show a leaver that encounters smoke, changes his *exitchoice* to “1”, turns around and heads towards the main exit.

Figures 26 and 27: a leaver and his exitchoice that encounters smoke, changes his exitchoice and walks away towards the main exit (source: Netlogo).

The check shows a leaver encountering smoke, changing his *exitchoice* and heading towards another exit. Thus, it is confirmed that the encountering of smoke changes the behaviour of a leaver.

A second check is conducted to verify that the agents respond to the SDAL. In the figure below we see two agents with their *SDAL*. In figure 28 the variables of leaver 94 are shown. The GDAL of this agent is 98. Figures 29 and 30 show the leaver encountering smoke and deciding to go through.

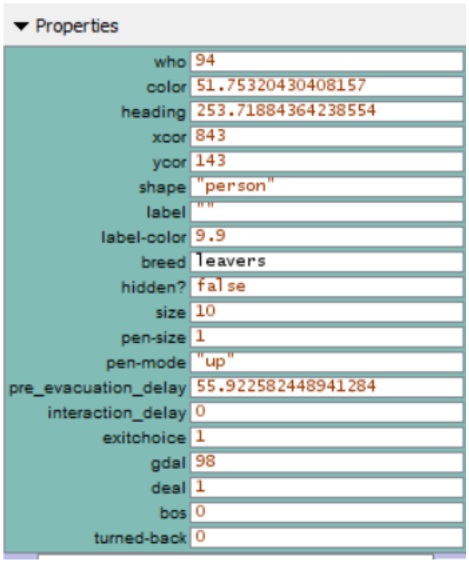
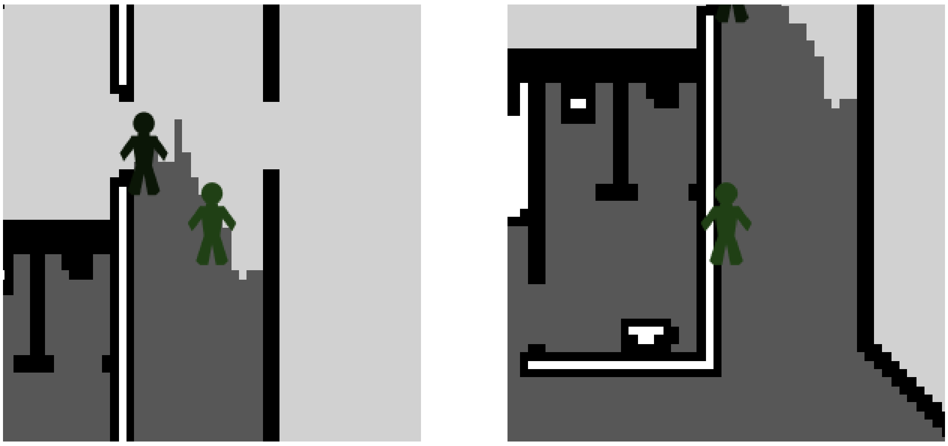
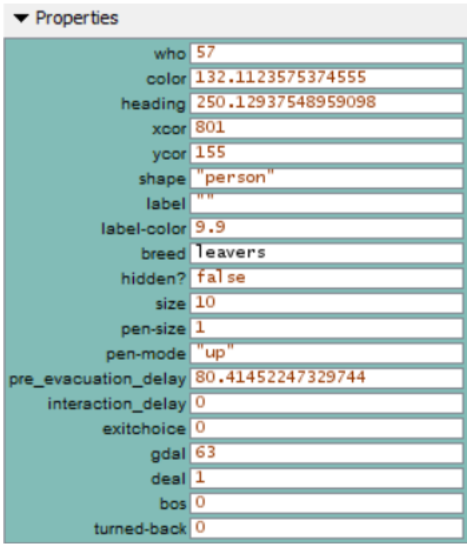


Figure 28: the settings of leaver 94 who is followed to check the response to smoke(source: Netlogo).



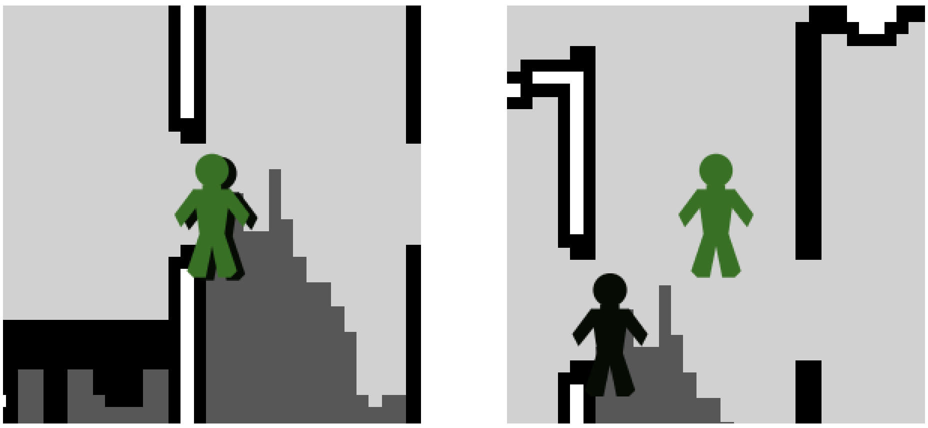
Figures 29 and 30: the moment the leaver encounters smoke and the leaver going through the smoke (source: Netlogo).

In Figure 31 the variables of leaver 57 are shown. The GDAL of this leaver is 63. Figures 32 and 33 show the leaver encountering smoke and moving away from it.



▼ Properties

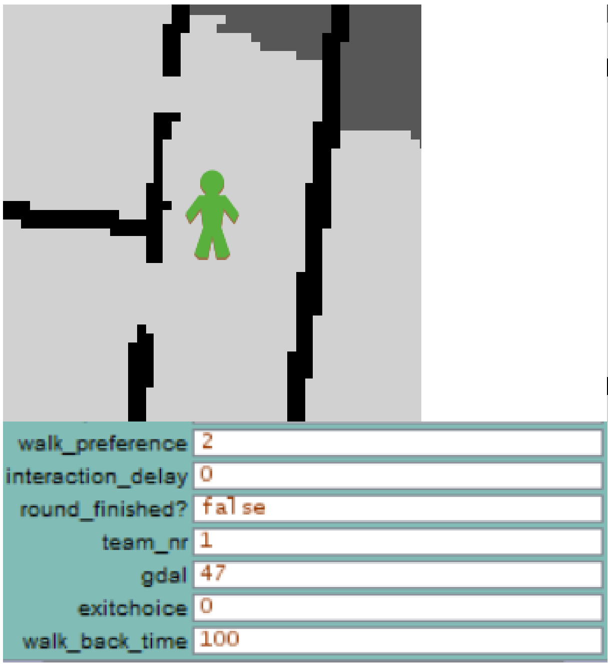
who	57
color	132.1123575374555
heading	250.12937548959098
xcor	801
ycor	155
shape	"person"
label	""
label-color	9.9
breed	leavers
hidden?	false
size	10
pen-size	1
pen-mode	"up"
pre_evacuation_delay	80.41452247329744
interaction_delay	0
exitchoice	0
gdal	63
deal	1
bos	0
turned-back	0

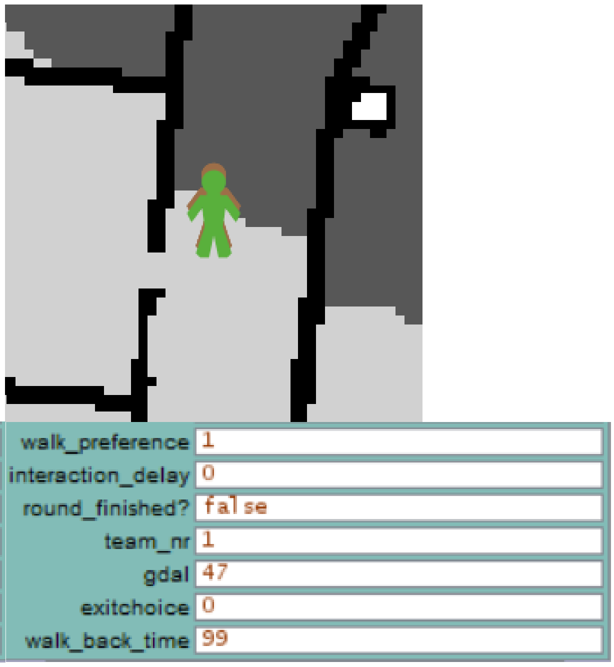


Figures 31, 32 and 33: the settings of leaver 94 who is followed to check the response to smoke, the moment the leaver encounters smoke and the leaver going through the smoke (source: Netlogo).

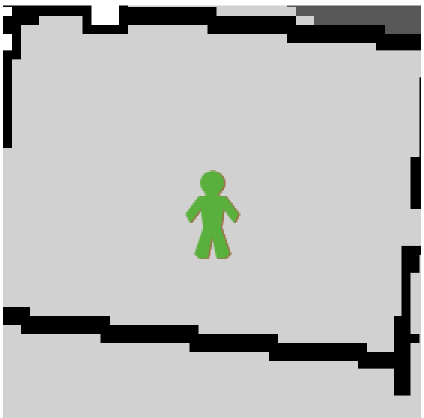
Based on these results, it is confirmed that the *GDAL*-variable, in combination with the *smoke_density* global variable, works as intended.

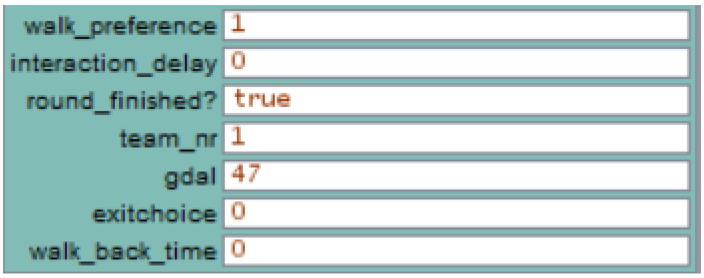
A third check is conducted to see if the behaviour of the officers is indeed changed when encountering smoke. Figure x shows the variables of an officer before encountering smoke. As his *walk_preference* is “2”, the officer walks on the left side of the network. His variable *round_finished?* is “false”, thus he is still checking for evacuees in the rooms. Furthermore, his *walk_back_time* is still “100”, meaning he did not yet encounter smoke. Figure 34 shows the officer in a corridor of the building, heading towards the smoke. Figure 35 shows the same officer after encountering smoke. The *walk_preference* has switched to “1”, meaning he will walk back over the network in the opposite direction. Additionally, his *walk_back_time* is set to “99”. This value will now start counting down to “0”. Once it has hit zero, the officer sets *round_finished?* to “true”, and he starts evacuating himself. This can be seen in Figures 36 and 37.





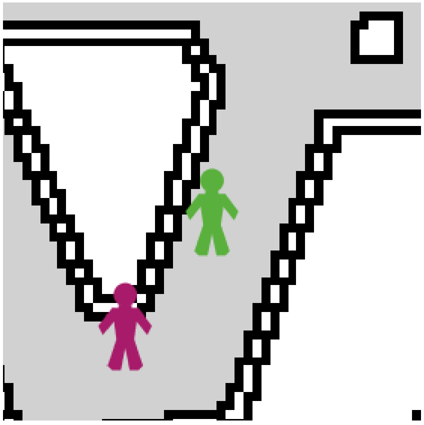
Figures 34 and 35: officer with his variables before (left) and after (right) encountering smoke (source: Netlogo).

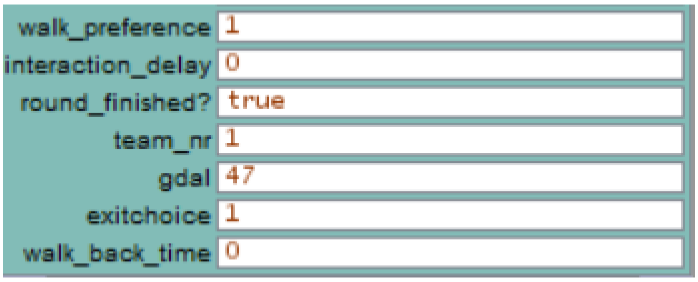




Figures 36 and 37: the officer walking back across the network and his variables (source: Netlogo).

At last, Figure 38 shows the officer heading towards the main exit, as he is evacuating himself. Additionally, Figure 39 shows the variables of the officer, with *exitchoice = 1*. These results show that the change in behaviour of the officers works as intended.





Figures 38 and 39: the officer heading towards the main exit and his variables (source: Netlogo).

5.2. Sub-objective b

Which data is needed to implement agent – environment interactions and how can a realistic VR environment for the experiments be created that matches the available ABM? (3)

As stated in section 4.2.2, the following elements are checked in the VR experiments:

- General smoke behaviour
  - How many people will turn around and how many will go through?
- Smoke density
  - Do people go through smoke when the density is low and do people not go through smoke when the density is high?
- Location of the smoke
  - Does the location of the smoke matter when choosing to go through or not?

VR experiments are set up by building a simulation in Unity3D. The experiment consists of letting test persons walk through different VR environments. The University of Twente owns a VR laboratory with an HTC VIVE VR headset used in the experiments.

Testing the simulation in the VR laboratory was vital for the process of this thesis. After the first environment was built, a testing session took place in the lab. The Unity3D software was connected to the HMD by using both the Steam software package and the SteamVR plugin in Unity3D. As the author does not own an HMD, this could only be done at the lab. Several testing sessions were needed to get the connection working properly. After succeeding in connecting the HMD to the simulations, a pre-experiment was conducted. As stated before in the methodology, the aim of this session was to make sure everything worked as expected before conducting the actual experiments. The feedback of these testing sessions was mainly focussed on the exit signs being visible through the smoke, even when the smoke had a high intensity. This issue was fixed before conducting the final experiments.

The experiment consisted of five different environments. Figures 40, 41 and 42 aim to give an impression of what the environments looked like from the inside.

Figure 40: an impression of how the simulations looked on the inside.

Figure 41: an impression of how the simulations looked on the inside.

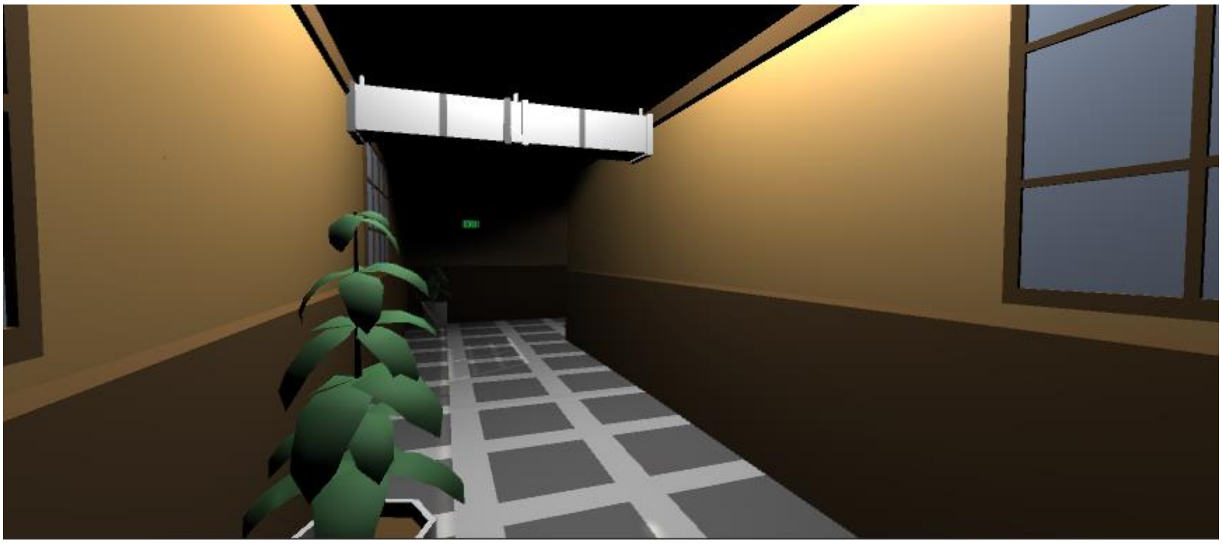


Figure 42: an impression of how the simulations looked on the inside.

The experiments tested the behaviour of people when encountering smoke. Additionally, it tested whether people follow the exit signs present in a building, or if they choose to find another way. Each environment simulates a situation inside a building, but with a different layout. These layouts can be seen in Figures 43, 44, 45, 46 and 47. As stated before, the environment is the within-subject factor, so each participant goes through all the environments. *The first environment,* as seen in Figure 43, starts in an office. Behind a door is a corridor, going both left and right. The exit signs in this environment point to the left side of the corridor. Following this exit sign leads to a corner, after which a corridor filled with smoke lies. Behind the smoke the exit can be found. If the participant chooses not to follow the exit sign, or decides to turn back when encountering the smoke, there is another exit on the other side of the corridor.

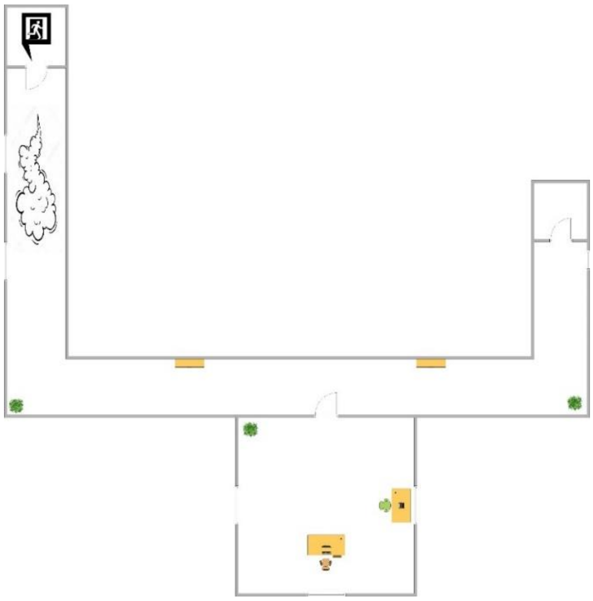


Figure 43: floorplan of the environment of simulation 1 where the smoke is located in the left corridor, with the emergency exit indicated on the left side.

The second environment starts off in a corridor and can be seen in Figure 44. The exit signs lead around a corner. Halfway across this corridor the exit sign leads to a staircase, which is filled with smoke. To get to the emergency exit, the participant must go down the stairs. If the participant chooses not to follow the emergency exit signs, another exit can be found by following the corridor. After another corner then lies the non-emergency exit.

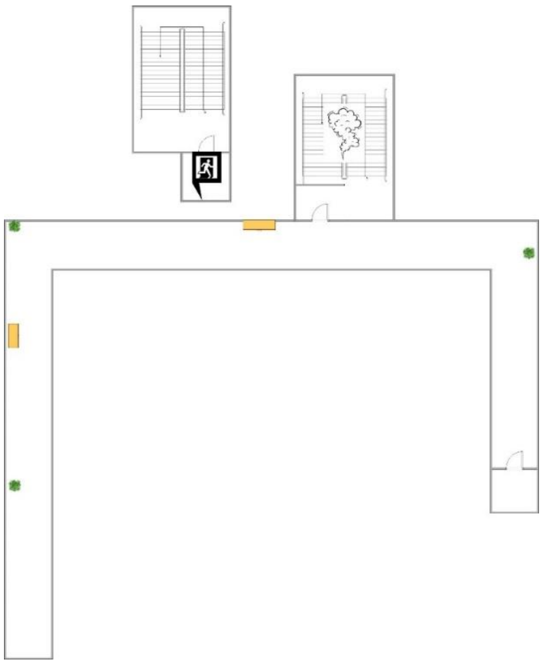


Figure 44: floorplan of the environment of simulation 2 where the smoke is located in the staircase, with the emergency exit indicated downstairs.

The third environment has the shape of the letter *Y*, as visualized in Figure 45, and it starts off at the bottom part of the letter, then offering the participant the choice to go either left or right. The emergency exit is on the left side, while the non-emergency exit is on the right side. The left corridor is filled with smoke, while the right corridor offers a safe path.

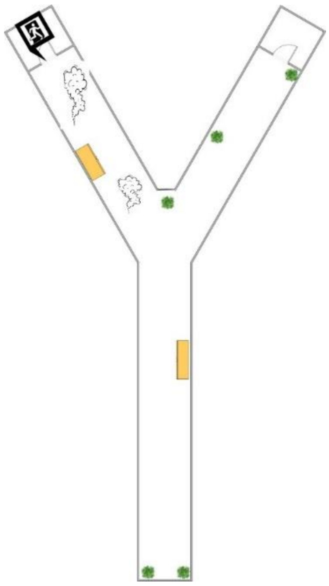


Figure 45: floorplan of the environment of simulation 3 where the smoke and the emergency exit are located in the left upper corridor.

The fourth environment, as seen in Figure 46, starts in a classroom, with exits both in the front and the back of the room. The emergency exit sign leads to the front of the classroom. Behind a door lies a corridor, filled with smoke. The non-emergency exit is in the back of the classroom, also leading to a corridor, at the end of which the exit can be found.

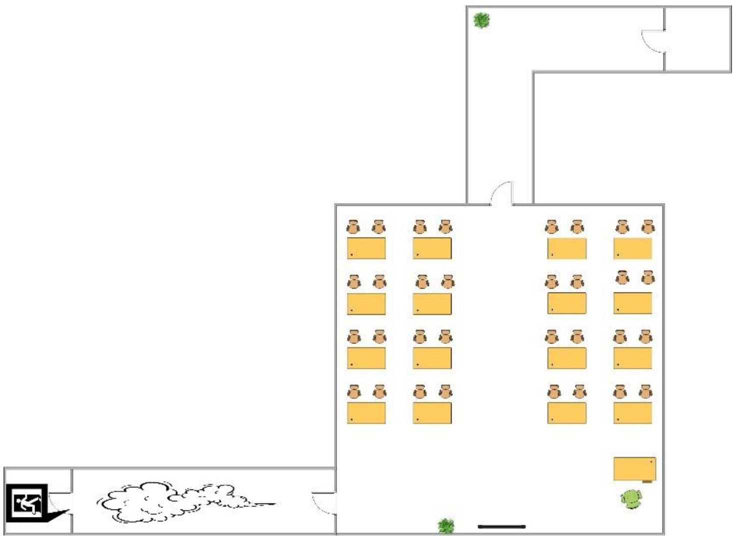


Figure 46: floorplan of the environment of simulation 4 where the smoke and the emergency exit are located in the left lower corner.

The fifth environment consists of an office room with exits on two sides of the room and can be seen in Figure 47. The emergency exit leads again to a corridor filled with smoke, while the non-emergency exit leads to a wider hallway. This wider hallway leads to a T-intersection, with smoke in both corridors. When the participant in this environments decides to not take the emergency exit, or to turn back after encountering the smoke, they will still find smoke on their way out. Here they must decide between going back again to the smoke filled emergency exit, or to take other exits which are also filled with smoke.

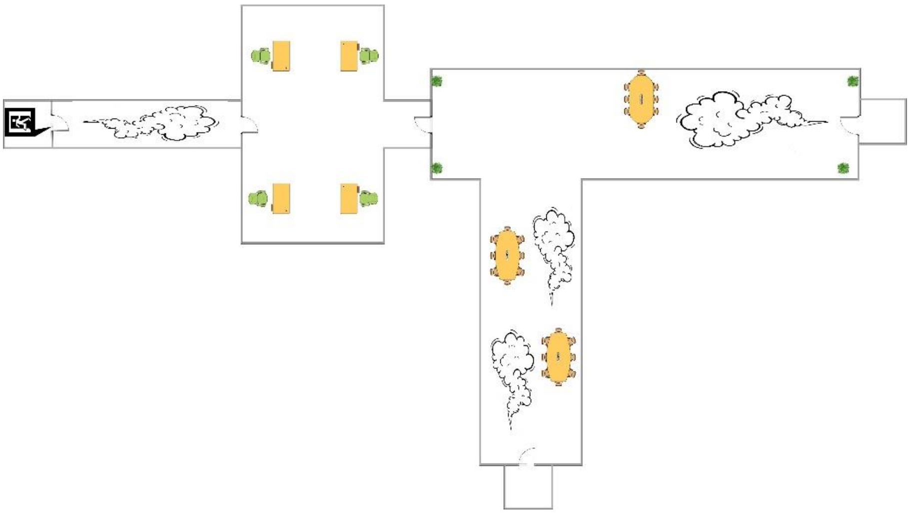


Figure 47: floorplan of the environment of simulation 5, where the emergency exit is located in the left hallway, while the smoke is in front of all three exits.

The between-subject factor was the intensity of the smoke. The participants all went through the five environments, but either experience low or high density of smoke in each environment. The low density is see through, making it still possible to see the exit sign and the door. However, when experiencing high density, the exit signs in the smoke filled corridors are not visible. In Figures 48 and 49, the difference between the intensity of the smoke can be seen.

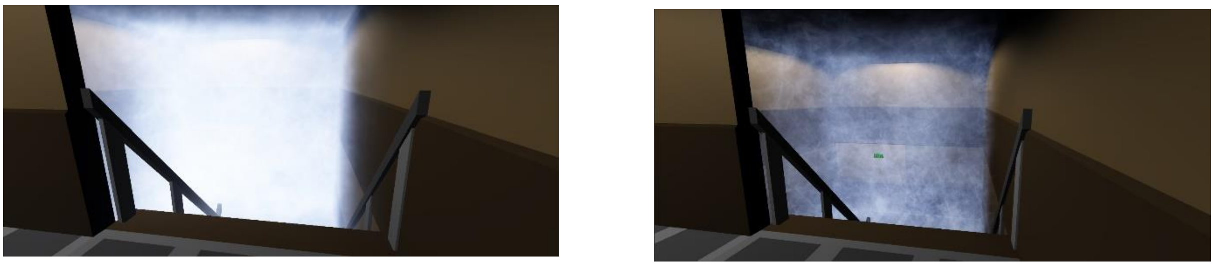


Figure 48 and 49: the two levels of intensity of the smoke, with respectively high and low density.

5.2.1. Immersion results

The immersion scores, as explained in section 4.2.2.4, of the participants in the VR experiments varied between 38 and 68, with an average of 55,9 and a standard deviation of 9,5038. The immersion scores of the non-VR experiments varied between 23 and 42, with an average of 34,2 and a standard deviation of 5,9404. These statistics can be seen in table 3. Additionally, in figure 50, the distribution of the immersion scores for both the VR and the non-VR groups can be seen. The scores of both groups were computed against each other using the SPSS-software. As stated in the methodology, an independent samples test was used. The results of this test can be seen in table 4. This test resulted in a t-score of 6,123, with a significance of p=.000, indicating there is a statistically significant difference between the immersion scores between the VR and the non-VR groups. In other words, the participants in the VR group have a statistically significantly higher mean score on immersion (55,9) than those in the non-VR group (34,2). Another test was run to test for correlation between the immersion scores and age of the participants. The results of this test can be seen in table 5. This test resulted in a Pearson correlation of -0,06. This score indicated that age shares 0,36% of its variability with the immersion scores. With a significance of 0.800, this test implies that age and the immersion scores are not significantly correlated.

Group Statistics

	Group	N	Mean	Std. Deviation	Std. Error Mean
ImmersionScore	VR	10	55,9000	9,50380	3,00537
	non-VR	10	34,2000	5,94045	1,87853

Table 3: the group statistics of both the VR and the non-VR group and the immersion scores.

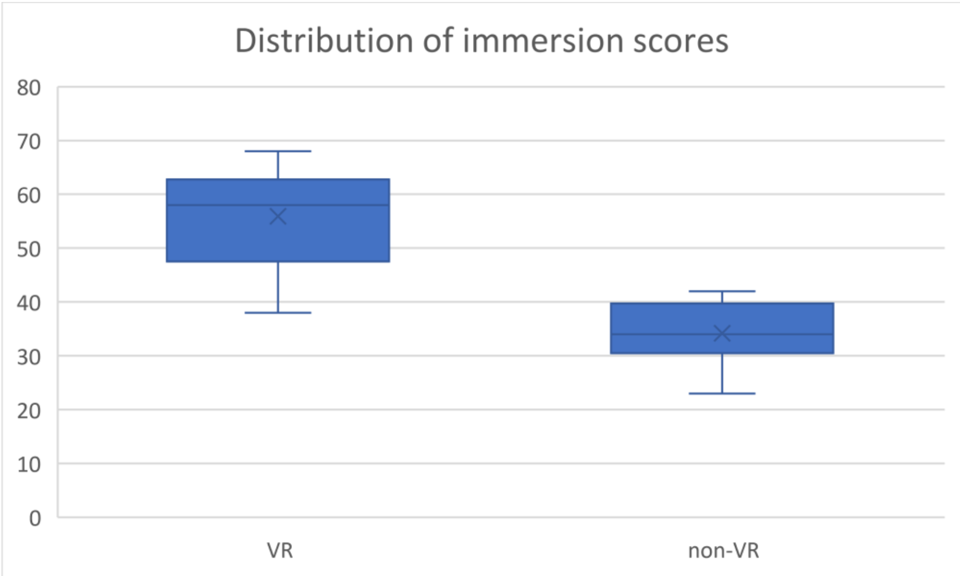


Figure 50: the distribution of the immersion scores for both groups.

Independent Samples Test

		Levene's Test for Equality of Variances		t-test for Equality of Means						
									95% Confidence Interval of the Difference	
		F	Sig.	t	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference	Lower	Upper
Immersion	Equal variances assumed	1,419	,249	6,123	18	,000	21,70000	3,54417	14,25398	29,14602
	Equal variances not assumed			6,123	15,101	,000	21,70000	3,54417	14,15020	29,24980

Table 4: The results of the Independent Samples Test between the immersion scores and the groups.

Correlations

		Age	ImmersionScore
Age	Pearson Correlation	1	-,060
	Sig. (2-tailed)		,800
	N	20	20
ImmersionScore	Pearson Correlation	-,060	1
	Sig. (2-tailed)	,800	
	N	20	20

Table 5: the results of the correlation test between the immersion scores and the age of the participants.

5.2.2. Behaviour when encountering smoke

Upon encountering a smoke filled hallway, 50% of the participants chose to enter the smoke, while the other 50% chose to find another way. 83% of the participants that went into the smoke, continued to the end, while 17% chose to go back after some time inside the smoke. When the other exit was clear of smoke, all of the participants took the other exit. When the other exit was not clear of smoke, all the participants who looked for another exit, took the main emergency exit. The behavioural choices can be seen in a flowchart in figure 51.

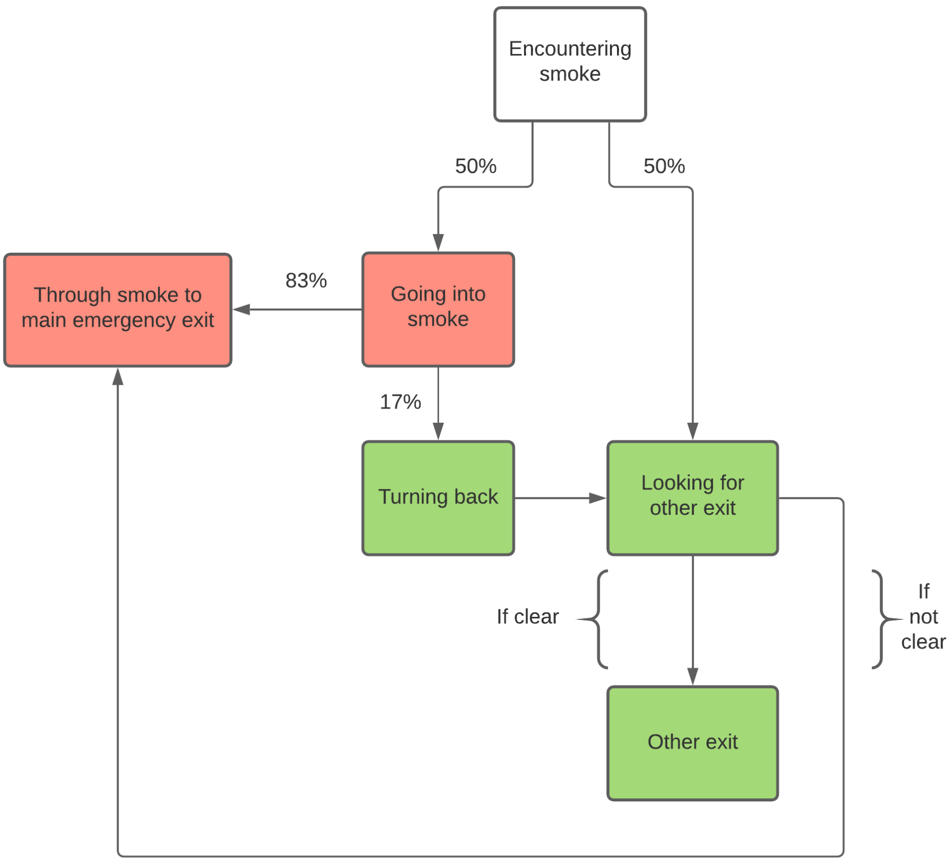


Figure 51: the different choices made by participants when encountering smoke in the VR experiments, with the corresponding percentages.

5.2.3. Density

In the experiments, the density of the smoke differed. Each participant went through all five environments, with either high or low intensity of smoke. Based on the results, analysis was done on the intensity related to the choice made when encountering smoke. The participants made two choices; either go through the smoke, or turn back and find another exit. The percentage of participants that perceived the smoke as a risk and activated their coping appraisal (turning back) with a low density, was 61%. The percentage that perceived smoke as a risk with a high density, was 55%. The percentages of people that perceived no risk was respectively 39% and 45%.

A chi-square test was run in SPSS to test whether there is a relation between the smoke density and the choice made. This test resulted in a Pearson chi-square of 0.157 with a significance of 0,692, indicating there is no statistically significant relationship between the intensity and the choice made when encountering smoke. The crosstabulation and the results of this test can be seen in tables 6 and 7.

		SmokeEncounter2		
		Went back	Went through	Total
Intensity	Low	17	11	28
	High	11	9	20
Total		28	20	48

Table 6: the crosstabulation of the smoke intensity and the choice upon encountering smoke.

Chi-Square Tests

	Value	df	Asymptotic Significance (2-sided)	Exact Sig. (2-sided)	Exact Sig. (1-sided)
Pearson Chi-Square	,157[a]	1	,692		
Continuity Correction[b]	,010	1	,921		
Likelihood Ratio	,156	1	,692		
Fisher's Exact Test				,771	,460
Linear-by-Linear Association	,153	1	,695		
N of Valid Cases	48				

a. 0 cells (0,0%) have expected count less than 5. The minimum expected count is 8,33.

b. Computed only for a 2x2 table

Table 7: the results of the Chi-Square tests for the relationship between the smoke intensity and the choice upon encountering smoke.

5.2.4. Questionnaires

In this section, the results from the second questionnaire are presented. As stated in the methodology, a coding system was created to make an analysis of the questionnaire possible. This coding was done using the QDA Miner software. The codes that were used can be found in Appendix 2.1. The codes were formulated after carefully reading all the answers. The coding system followed the structure of the questionnaire, which was already categorized in different sections. For example, the first two questions were about the exit signs, the third question was about the smoke encountering, and the fourth question was about going through the smoke. The same categories were used in the coding system. Sub-categories were created based on themes in the answers to make sure all the answers could fit into a category. By adding the codes to the relevant text segments, a frequency analysis was performed. The results of this analysis can be seen in table 8. In Appendix 2.2, the text segments that were placed under each code can be seen. For example, the statement "not go there, but the exits were on it " was placed under the code "focus on exit sign".

As can be seen in table 8, 60% of the participants stated that they followed the exit signs, while 40% stated they sometimes followed them. None of the participants said they did not follow the signs, hence there is no code for this. As to why the exit signs were followed, the participants were not uniform. One participant did not fill in a reason, while the other 90% were divided. Thirty percent did so because they noticed the signs, 20% followed them because the voice over the intercom told them to, another 20% was focused on getting out and 10% did so because of previous experience with evacuating.

Upon encountering the smoke, the first reaction 80% of the participants was to turn around and look for another exit. Twenty percent of the participants were focused on the exit signs, while encountering the smoke. Regarding going through the smoke, 50% did so because the exit signs were pointing in that direction. The other 50% went through the smoke because there was no alternative. This was the case in the fifth simulation, where there was smoke in front of all the exits. When going through the smoke, 80% stated they went through with hesitation, while the other 20% claimed they did not hesitate at all.

The main reason for not taking the risk of going through the smoke, was because it is dangerous. This was stated by 50% of the participants. Twenty percent wrote down they did not go through the smoke, because of the smoke. The last 20% decided not to go through, because smoke usually means there is fire as well, and they did not want to be facing this situation.

Codes	Cases	% Cases
Followed exit signs		
- Yes	6	60%
- Sometimes	4	40%
Thought when encountering smoke		
- Danger, turn around	8	80%
- Focus on exit sign	2	20%
Reasons for going through smoke		
- Exit signs were there	5	50%
- No alternative	5	50%
Hesitation		
- With hesitation	8	80%
- Without hesitation	2	20%
Reasons for not going through smoke		
- Danger	5	50%

- Because of smoke	2	20%
- Smoke means fire	2	20%

Table 8: the code frequency analysis.

5.2.5. Location of the smoke

The location of the smoke was in each environment the same. The smoke was located on the emergency exit. As can be seen in table 9, in four of the five simulations the percentages of participants that turned back or went through were similar. Only in the second simulation the difference is notable. In this simulation the smoke was located in a staircase, it is possible that this leads to a higher risk perception than a regular hallway or room. However, no comments were made about this in the questionnaire after the experiments.

Simulation	Walked through	Turned back
1	**55%**	**45%**
2	**80%**	**20%**
3	**60%**	**40%**
4	**45%**	**55%**
5	**50%**	**50%**

Table 9: the percentages of participants that waled through the smoke or turned back per simulation.

5.3. Sub-objective c

How can the agent-based model be improved by adding micro-level behavioural data and how do the VR and ABM experiments compare to each other? (4)

The behavioural data that is collected through the VR experiments can be divided into three groups:

- General smoke encountering behaviour
- Density of the smoke
- Location of the smoke

For each group, experiments were setup with the smoke evacuation model. The results of the experiments with the ABM are presented in this section. The results of the experiments are then compared to the results of the VR experiments.

5.3.1. Experiment 1: General Smoke Behaviour

This experiment aims to test how many agents turn around and how many walk through the smoke. The smoke density is set to 50, and the smoke is in a random location each time.

For this experiment two new variables were introduced to the leavers: **Been On Smoke (BOS)** and **turned-back**. BOS turns to "1" in case the agent walks through the smoke, while turned-back turns to one when the agent turns around. If BOS = 1, the agents report "went through smoke", and if turned-back = 1, the agents report "turned back". The sum of leavers that encounter smoke is calculated as well as the percentage that walks through.

For each run, the results vary. In some cases only one agent encounters the smoke, in other cases up to 26 leavers encounter smoke. This can be seen in table 10.

Evacuation time	Went through	Turned back	% through	% back
8:07	1	5	16,7	83,3
7:26	14	6	70	30
7:26	13	13	50	50
7:49	10	13	43,5	56,5
7:29	4	16	20	80
5:32	3	7	30	70
5:25	1	0	100	0
7:56	1	1	50	50
7:56	4	1	80	20
7:46	5	1	83,3	16,7

Table 10: the results from the general smoke behaviour experiment

On average, the percentages are 54,3 that goes through and 46,7 that turns back. The VR experiments showed that 50% of the participants turned around when encountering smoke, while the other 50% went through.

5.3.2. Experiment 2: Smoke Density

In this experiment, a number of test runs are done, to see how many agents walk through the smoke when the density of the smoke differs. Two sets of tests are done:

- Low density: smoke density is set to 25
- High density: smoke density is set to 75

Each set is run 5 times and the amount of leavers that walk through and that turn around are counted. The smoke in this experiment is on a random location each time.

The results of the experiment can be seen in table 11. It shows the crosstabulation with the intensity and the decision that could be made. Table 12 shows the chi-square test that was run to see if the intensity and the decision are related. With a p =0,000 and a chi-square value of 29,739, it can be concluded that there was a significant association between the intensity and the decision upon encountering smoke.

		Decision		
		Went through	Turned back	Total
Intensity	Low	38	9	47
	High	21	50	71
Total		59	59	118

Chi-Square Tests

	Value	df	Asymptotic Significance (2-sided)	Exact Sig. (2-sided)	Exact Sig. (1-sided)
Pearson Chi-Square	29,739[a]	1	,000		
Continuity Correction[b]	27,723	1	,000		
Likelihood Ratio	31,447	1	,000		
Fisher's Exact Test				,000	,000
Linear-by-Linear Association	29,487	1	,000		
N of Valid Cases	118				

a. 0 cells (0,0%) have expected count less than 5. The minimum expected count is 23,50.

b. Computed only for a 2x2 table

Tables 11 and 12: the crosstabulation of the intensity and the decision and the results of the chi-square test.

In the VR experiments, it was found that there was no significant effect of the density on the choice to turn around or not.

5.3.3. Experiment 3: Location of the Smoke

In the third experiment the influence of the location of the smoke on the amount of leavers that perceive risk is measured. Five runs were done with the smoke on the left emergency exit and five runs were done with the smoke on the right emergency exit. Results show that 53% perceives risk and turns back from the smoke and 47% does not perceive risk. They continue on their path to their exit of preference.

In four of the five VR simulations the results are similar. In simulation 2 the percentage of people that walk through the smoke Is notable different. As stated before, this might be due to the staircase on which the smoke is located. However, no evidence was found to confirm that there is a relation between the staircase and the risk perception.

5.3.4. Data Integration

The data from the ABM experiments and the VR experiments match on some point, while on other points they differ notably. The percentage that perceives risk when encountering smoke is similar. In the ABM experiments the density was positively associated with the risk perception, while the VR experiments showed no association.

The behaviour when encountering smoke is regulated by the smoke density and the SDAL in the ABM. In the ABM experiments the smoke density was set to 50, while the SDAL is randomly assigned. This led to similar results as the VR experiments, thus nothing was should be changed.

The smoke density had no significant effect on the behaviour, according to the VR experiments. However, the ABM experiments did show a significant association. In the ABM experiments, two sets of runs were performed where the smoke density was set to 25 and to 75. To recreate the random behaviour of the participants in the VR experiments regarding smoke density in the ABM, the smoke density could be deleted from the model. This would erase the influence of the smoke density on the behaviour of the agents. However, as the regular behaviour is also regulated by the smoke density and the SDAL, this would be problematic.

Having the smoke located on or around the emergency exits led to the same results for both the VR and the ABM experiments. Thus, there is no need to change anything in the behaviour of the agents.

6. Conclusion

This thesis aimed to explore the possibilities of VR for collecting micro-level behavioural data and to enhance an existing ABM with a dynamic environment and input from VR experiments. In this section the research questions, as defined in chapter 2, are answered.

6.1. Sub-objective a

6.1.1. How can the environment, the agents and the processes of the current evacuation model be described?

Describing an ABM is done by using the ODD-protocol, as seen in figure 10. The purpose of the model as presented by Augustijn-Beckers et al. (2010) was to test the influence of variation in pre-evacuation time and exit choice on evacuation time. The model consists of two low-level entities: individuals and an environment. The individuals are characterized by several state-variables, such as student or staff, pre-evacuation time, walking speed, exit choice and interaction time. The environment was prepared using a network following the centrelines of the corridor, the walls and walkable space (indicating where agents can /cannot move), emergency exits, and a set of raster cost distance layers that will guide the leavers and officers to the emergency exits.

The evacuation model consists of three types of breeds: leavers, followers and officers. All breeds have different evacuation behaviour. The leavers evacuate by themselves, after a while (pre-evacuation time) or after they are prompted by an officer. They evacuate by moving to their preferred exit, either the main exit or the nearest exit. The followers follow an officer or leaver or evacuate themselves if they are within eye distance of an exit. Th officers move through the building to make sure everyone starts to evacuate and then evacuate themselves by moving towards the nearest exit.

The movement of the three breeds is based on different movement models. The leavers move based on a free-space model, the officers move over a network of lines and the followers move either by following the officers or on a free-space model if they are within eye-distance of an exit.

One run in the model equals around six minutes, or 7000 ticks. Spatially, the model represents the ITC building.

6.1.2. How can a dynamic environment (fire – smoke) be integrated into the ABM model?

The evacuation ABM was enhanced by adding a smoke dispersion model. The smoke model of this thesis was an adaptation on the smoke dispersion model as presented by Corrêa et al. (2019).

The smoke is generated by creating a potential field. This potential field is generated from a randomly selected starting location, heading towards the exits. The smoke then disperses from the starting location towards the exits based on the potential field values. It spreads until 20000 patches are filled with smoke, after which the evacuation starts. The smoke density is simulated via a new global variable.

The agent behaviour was adjusted by introducing risk perception and coping appraisal. This was done for both the **leavers** and the **officers.**

Leavers compare their own smoke density acceptance level (SDAL) with the global smoke density to either perceive risk, or continue their path. When they do not perceive risk, they continue to their exit of preference through the smoke. If they do perceive risk, they turn around and find their way to another exit by changing their *exitchoice.*

Officers start by performing their checking round by following the centreline network. In case they encounter smoke, they act as if their round is finished, regardless of any followers or leavers left. They will walk back over the network for a certain amount of time, after which they will start to evacuate to the nearest exit. If they encounter smoke again on their way to the nearest exit, they too try to find another exit by changing their *exitchoice.*

Verification checks were conducted to see if the changed behaviour worked as intended and these were successful.

6.2. Sub-objective b

6.2.1. Which data is needed to implement agent – environment interactions and how can a realistic VR environment for VR experiments be created that matches the available ABM?

Some evacuation behavioural data is still missing. The VR experiments that were conducted for this thesis, aimed to collect data on encountering smoke. Three important elements were identified:

- General smoke encountering behaviour
- Smoke density
- Location of the smoke

The Unity3D software was used to create a VR environment. Five different simulations were build, to test the influence of the location of the smoke. Furthermore, smoke was added to the simulations, differing in density. The density was either low or high. In the simulations with low density, the exits were still visible through the smoke. In the simulation with high density, the exits were not visible through the smoke.

VR experiments were setup by building a simulation in the Unity3D-software. The experiments consisted of letting test persons walk through different VR environments, to test the behaviour when encountering smoke, the impact of smoke density and the location of the smoke. During the simulations, the participants were confronted with smoke and exit signs indicating the exits, to see how they would react.

Results from the experiments showed that participants in this study experienced the simulation in VR significantly more immersive than the same simulation on a regular computer. Age was found not to be correlated to the immersion scores. Furthermore, the smoke density had no significant effect on the choice people make when deciding whether to go through the smoke or not. Additionally, the location of the smoke did not seem to influence the choice to move through the smoke or to turn back. Microlevel behavioural data that was collected showed that 50% of the participants went through the smoke upon encountering, while the other 50% went back to find another way.

Results from the simulation and the questionnaire afterwards do not completely match. For example, 80% of the participants stated that their first reaction was to turn around, as they perceived risk, but in the simulation only 50% turned back.

6.3. Sub-objective c

6.3.1. How can the agent-based model be improved by adding micro-level behavioural data and how do the VR and ABM experiments compare to each other?

Three experiments were conducted with the ABM to link the VR experiments with the evacuation model. One was based on behaviour when encountering smoke, the second one was based on the smoke density and the third one was based on the location of the.

The results of the general smoke behaviour experiments show that 54,3% of the leavers go through the smoke and 46,7% turns around to find another exit. In comparison with the VR experiments the results are similar. In the VR experiments the distribution was 50% going through and 50% turning around. To match the ABM with the data of the VR experiments, no changes are needed.

The result of the smoke density experiment shows that density of the smoke and risk perception and coping appraisal are significantly associated with each other. The VR experiments however did not show any association between the two. To match the results, the smoke density would have to be deleted, thus eradicating the influence of the density on the behaviour of the agents.

The third experiment was difficult to conduct, as the environments of the simulation do not match the environment of the ABM. However, in the VR experiments the smoke was located on the emergency exit each time. To compare, ABM experiments with the smoke located on either the left or right emergency exit were conducted. Results show that 53% perceives risk and 47% does not. As these results are similar, no changed are needed.

6.4. Main research question

In this thesis, the main research question was the following:

How can Virtual Reality be used to collect behavioural data to enhance agent-based models?

This thesis has shown that VR experiments can be used to gather behavioural data for situations that are difficult to simulate in real life. A simulation run with a VR headset was found to be significantly more immersive than the same simulation without VR headset. It has also successfully implemented a dynamic environment to an existing evacuation model, by adding a smoke model to the evacuation model. The smoke is generated each run in a random location, creating a dynamic environment which can be different each time.

Matching the VR experiments with the ABM was done via three elements: general smoke behaviour, smoke density and location of the smoke. Experiments with the ABM were conducted to match the behavioural data from the VR experiments to the ABM. To make the model comparable to the VR experiments, the smoke density would have to be deleted. This would eradicate the influence of the smoke density on the behaviour of the agents. However, this is problematic as the general behaviour regarding smoke encountering is also regulated by the smoke density.

Both general smoke behaviour and smoke density are closely linked. When the smoke becomes more dense, the chance that an evacuee turns around becomes bigger. Both are related to risk perception, as the choice the evacuee makes when encountering the smoke depends on his acceptance levels. One person could find dense smoke acceptable, while another sees it as danger. This leads to different behavioural decisions.

7. Discussion

7.1. Objectives

The objective of this thesis was threefold. First, this thesis aimed to enhance an existing ABM with a dynamic environment. This was successfully done, as a smoke model was implemented. This smoke model was based on the smoke dispersion model, as presented by Corrêa et al. (2019). The behaviour of the agents in the model was also successfully changed. This enabled them to react to the smoke, and make a choice on what to do based on their risk perception and coping appraisal.

Second, this thesis explored the possibilities of VR when collecting behavioural data for ABMs. It showed some interesting results, as participants experienced the simulation in VR significantly more immersive than participants in the non-VR simulation. This implicates that using VR experiments to collect behavioural data could be a useful solution in cases where real life data is hard to gather.

The third objective was to see how the data of the VR experiments could be integrated into the ABM and how the data from the VR experiments differ from experiments with the ABM. This was done by performing experiments with the ABM and comparing the results with the VR experiments. Changing the ABM by using input data from the VR experiments proved to be difficult. As stated before, both the general behaviour when encountering smoke (based on a smoke density of 50) and the behaviour regarding a varying smoke density, are based on the global smoke density variable. As the results from the smoke density experiment do not match the VR experiments, the smoke density would have to be deleted. This would also mean that the behaviour when encountering smoke in general would have to be modelled differently. An explanation for the VR experiment results, could be the sample size. In total, there were only ten participants for the experiments. This number might be too low to draw real conclusion. Based on this, the model was not changed.

7.2. Recommendations and limitations

As stated before, this thesis aimed to explore the possibilities of VR regarding behavioural data collection. Based on the results, this work offered a good starting point, however, as the author was new to creating simulations and the Unity3D engine was used, it can be seen as quite basic. As a result of this, the data of the VR experiments should be treated with caution. The goal was to create a realistic environment, to make the participants forget that they are in a simulation. The immersion questionnaire showed good results, but as this was in relation to a non-VR experiment, it does not mean that people forgot they were in a simulation and participant could have seen it as a game. This might have influenced the results, making people choose to go through the smoke, even if they knew it would be dangerous in real life. However, nothing was said about this in the second questionnaire. Further research should take this into account. To enhance the immersion and the realism of the simulations, a game engine could be used which offers more realistic graphics. As this would make the simulation 'heavier', strong hardware is recommended. This goes in line with the use of the VR equipment. In this case, the HTC Vive was used, as this was provided by the university. This setup provides good immersion, as both the point of view and the body of the user is contained withing the simulated environment (Earnshaw & Vince, 1995). However, the user is limited to move within an area of three by three meters. Sometimes the user accidently move outside of the area, disrupting the immersion. Further research could explore the possibilities of using, for example, the CAVE-system, which allows for complete containment in the simulated area. This would result in even more realism. Additionally, the environment should be similar to the environment in the ABM. The fact that the environments are not the same in this thesis makes analysis difficult.

Further research should also conduct the VR experiments with a much larger set of test persons. The current number is too low to draw any real conclusions. Another problem in the current study is the fact that the test persons were not familiar with the environment. In the ABM, the agents are assumed to be familiar with the building.

In the current model, it is possible that the smoke blocks the entrance to the hallway, if an agent is located in a room. This means that they cannot go anywhere from the start. In the experiments, this was not simulated, thus it is unclear what a person would do in such a situation. Additional research is necessary to collect data on this behaviour. The same goes for the officers. In theory, they are taught to stay away from danger, but further research should test whether they actually do this or not. This could be done in combination with a training tool for emergency response officers. Data from these trainings could be used as input data for the ABM. To make these trainings more realistic, group behaviour could also be modelled into the simulations, as this was not part of this research.

The presented smoke evacuation model does not completely offer a dynamic environment, as the smoke stops spreading once the evacuation starts. However, as the smoke is located on a random location every time, it can still be seen as dynamic. Further research could focus on creating an environment that is dynamic throughout the entire simulation. Another interesting direction of future research regarding the smoke model, could be to vary the amount of smoke locations. Further research could also focus on modelling the smoke density in a more realistic way. In the current model, the smoke has the same density in the entire surface. Realistically, when smoke spreads, the density gets lower.

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9. Appendix

9.1. Appendix 1: Questionnaires

9.1.1. Appendix 1.1: Immersion questionnaire

Name: ____

Age: ____

Background: ____

On a scale of 1 to 5, please fill in how much you agree with the following statements:

To what extent did the simulation hold your attention?

Not at all	1	2	3	4	5	A lot

To what extent did you feel you were focused on the simulation?

Not at all	1	2	3	4	5	A lot

How much effort did you put into playing the simulation?

Very little	1	2	3	4	5	A lot

Did you feel that you were trying your best?

Not at all	1	2	3	4	5	Very much so

To what extent did you lose track of time?

Not at all	1	2	3	4	5	A lot

To what extent did you feel consciously aware of being in the real world while playing?

Not at all	1	2	3	4	5	Very much so

To what extent did you forget about your everyday concerns?

Not at all	1	2	3	4	5	A lot

To what extent were you aware of yourself in your real surroundings?

Not at all	1	2	3	4	5	Very aware

To what extent did you notice events taking place around you?

Not at all 1 2 3 4 5 A lot

Did you feel the urge at any point to stop playing and see what was happening around you?

Not at all 1 2 3 4 5 Very much so

To what extent did you feel that you were interacting with the simulation environment?

Not at all 1 2 3 4 5 Very much so

To what extent did you feel as though you were separated from your real-world environment?

Not at all 1 2 3 4 5 Very much so

To what extent did you feel that the simulation was something you were experiencing, rather than something you were just doing?

Not at all 1 2 3 4 5 Very much so

To what extent was your sense of being in the simulation environment stronger than your sense of being in the real world?

Not at all 1 2 3 4 5 Very much so

At any point did you find yourself become so involved that you were unaware you were even using controls?

Not at all 1 2 3 4 5 Very much so

To what extent did you feel as though you were moving through the simulation according to you own will?

Not at all 1 2 3 4 5 Very much so

To what extent did you feel emotionally attached to the simulation?

Not at all 1 2 3 4 5 Very much so

To what extent were you interested in seeing how the simulation's events would progress?

Not at all 1 2 3 4 5 A lot

At any point did you find yourself become so involved that you wanted to speak to the simulation directly?

Not at all 1 2 3 4 5 Very much so

To what extent did you enjoy the graphics and the imagery?

Not at all	1	2	3	4	5	A lot

How much would you say you enjoyed doing the simulation?

Not at all	1	2	3	4	5	A lot

9.1.2. Appendix 1.2: Choice explanation questionnaire

1. Did you see the exit signs in any of the simulations?

   Yes | no

2. Did you choose to follow these exit signs to find you way out, and why?

   ____

   ____

3. When encountering the smoke, what was your first thought?

   ____

   ____

4. Did you choose to go through the smoke to find your way out? (if yes, proceed to question 4a, 4b , if not, continue with question 5)

   a. Why did you go through the smoke?

      ____

      ____

   b. Did you go through it without hesitation, or did you think about other options?

      ____

      ____

   c. At any point in the smoke, did you think about turning back? (if yes, proceed to question 4d, if not, you're now done!)

      Yes | no

   d. At any point in the smoke, did you turn back, and why? (you're now done with the questionnaire!)

      ____

      ____

5. Why did you choose not to go through the smoke?

   ____

9.2. Appendix 2: Qualitative analysis

9.2.1. Appendix 2.2 Coding system

- Followed exit signs
    - Yes
    - No
    - Sometimes
- Why follow exit signs
    - Intercom told me to
    - Because I noticed them
    - Focussing on getting out
    - Evacuation experience
- Thought when encountering smoke
    - Danger, turn around
    - Focus on exit signs
- Reasons for going through smoke
    - Exit signs were there
    - No alternative
- Hesitation
    - With hesitation
    - Without hesitation
- Reasons for not going through smoke
    - Danger
    - Because of smoke
    - Smoke means fire

9.2.2. Appendix 2.2: Text segments belonging to each code

Category	Code	Text
Followed exit sign	Yes	*Yes*
		Yes
		Yes
		Yes
		Yes
		Yes
	Sometimes	*Sometimes I did, sometimes I did not*
		Most of the time
		Sometimes I did
		I only saw it in the last simulation
Why follow exit signs	Intercom told me to	*The voice told me to*
		I followed them because the voice over the intercom told me to
	Because I noticed them	*If I saw them*
		I followed them when I was actively thinking about them, then I saw them
		I saw it in the last simulation
	Focussing on getting out	*I was focused on finding an exit*
		They were the indication to get out
	Evacuation experience	*My previous experience with evacuation taught me to do so*
Thought when encountering smoke	Danger, turn around	*Move away*
		Go the other way
		I am going in the wrong direction
		Turn around
		Avoid, turn around
		Not cool
		Run! Go another direction
		To escape
	Focus on exit sign	*Keep my eye on the exit sign*
		Not go there, but the exits were on it
Reasons for going through smoke	Exit signs were there	*I saw an exit and thought I could make it while holding my breath*
		Because I could see the exit sign through the smoke
		Because the exit was there
		Exit signs were there
		Because I saw no fire and the exit signs were there
	No alternative	*No alternative*
		Because I couldn't find another exit

		There was smoke on all exits
		There was no other exit
		I could not find another safe exit
Hesitation	With hesitation	*At first I tried finding another exit*
		First time I hesitated
		I thought for a small time
		I was unsure about it
		Hesitation at first
		First looked for other exits
		With a lot of hesitation
		Tried other options first
	Without hesitation	*Only option I considered*
		Without hesitation
Reasons for not going through smoke	Danger	*Because it is dangerous*
		Smoke is dangerous
		To avoid danger
		Dangerous
		Dangerous
	Because of smoke	*Because there was smoke*
		Because of the smoke
	Smoke means fire	*Where there is smoke, there is fire*
		Where there is smoke, there is fire