A Virtual Experiment to Investigate Habituation to Fire Drills

Project Report submitted in support of the degree of Bachelor of Engineering

Jack Bellamy
Supervised by Dr N. Bode

April 21, 2023

Abstract

Fire drills are performed to practice emergency procedures during a fire scenario, aiming to minimize an individuals evacuation time. This report creates a virtual experiment to investigate habituation in fire drills, investigating how people respond to evacuations in a simulated environment and whether their responses change over time as they become more familiar with the environment. The model was formed using a cellular automaton to simulate a maze, creating a controlled environment for participants to navigate. The maze can be obstructed by external crowd agents which have been mathematically modelled with a correlated random walk. The treatment for this experiment is early or late disturbance, which was implemented through the use of crowd agents. These agents block the participants shortest path, forcing the participants to find an alternative route. This was performed to explore whether early or late disturbance was a factor in habituation. Data was recorded for 20 participants, aiming to observe their reactions in the simulated environment. Mathematical figures and linear regression models are applied to visualise and test for habituation, exploring navigation and time analysis. For navigation analysis, the report considers whether participants returned to their familiar route after experiencing the disturbance. For time analysis, the three successive attempts with no habituation were investigated to see if repeated actions decreased the egress time of the participants. The results show statistically insignificant evidence to suggest there is correlation when testing for these relationships, however important concepts are considered and explained.

Contents

1 Introduction

Fire drills are practical exercises that test fire safety equipment and inform individuals on what to do in an emergency. Thus, are vital for peoples safety. It is crucial that individuals feel prepared for emergencies, ensuring rational thinking in life-threatening scenarios. A report by Romanova *et al.* [1] found that as populations increase, the demand for more buildings increases, leading to more high-rise buildings being built such as offices, residential and mixed-use buildings. In high-rise buildings, evacuation time in the event of a fire increases due to larger evacuation distances. A statistical report by Hall *et al.* [2] stated that an average of 15,700 fires were reported in high-rise buildings per year in the USA, causing a total of 53 deaths, 546 injured, and $235 million in direct property damage per year. Despite the number of deaths being relatively low, the consequences of a high-rise building fire is made significantly worse by the number of people present, as exits can become easily blocked. Virtual experiments can provide an insight into the behaviour of individuals during fire drills, without putting peoples lives in danger. The findings from these experiments can be used to form safer and more effective evacuation routes in high-rise buildings.

1.1 Motivation

Habituation is defined as 'the process of people or animals becoming used to something so that they no longer find it unpleasant or think it is a threat' [3]. Individuals who develop habituation towards regular fire drills could perceive that there is no real danger during a drill and ignore alarms. Repeated drills may exacerbate this effect, reducing awareness in the event of a genuine threat resulting in dangerously slow egress times. It is therefore crucial to avoid habituation in order to ensure individuals are responsive in the event of real danger. This report aims to observe habituation in fire drills to locate when it occurs. This would allow for improved safety training, emergency response planning and building safety to minimise the chances of fatalities. This will be conducted by the use of a virtual experiment, so no participants are injured in the research process of this investigation.

Findings of this study will create a better understanding of habituation, helping save lives, money and time. An experiment will be conducted which simulates an environment where a participant can move through a maze to the exits. The rationale of a maze experiment is to study habituation through the process of the participants repeating the same maze layout across multiple attempts. Using a maze additionally creates a controlled environment, allowing for manipulation of pedestrian crowds and the affect that this has on the participant decisions. The results of this experiment can be analysed to understand how many fire drills are needed before the effects of habituation occur. Furthermore, the findings from this report can be used to optimise sensitization, which is the quality of the response to the stimuli.

The use of virtual experiments is common in many fields, as they are an efficient and a low cost method to test for a variety of different hypotheses, without the need for expensive equipment and a suitably period of time. Using virtual experiments to perform fire scenarios would allow the experiment to be performed without risk of fatality, as real fire scenarios can be very hazardous.

Real-life experiments for fire scenarios would have to satisfy safety protocols which, increases the time period of the experiment. However, with the use of virtual experiments, environments can be simulated to analyse participants in a fire drill in a safe and controlled manner. This approach could test for habituation to fire drills and explore various factors that may impact this process, without risking the safety of participants or interfering with real-life emergency protocols.

1.2 Existing Work

Previous work has considered human behaviour during evacuations with the majority focusing on exit choice. These studies have identified potential weaknesses in evacuation techniques to help improve emergency plans, communication and training strategies to ensure the safety of the participants in future fire scenarios. However, these studies lack deep analysis of habituation in fire drills, this would consider the point of which habituation occurs to then optimise the usage of fire drills.

Reviewing a psychological article by Rankin *et al.* [4] gives more understanding of habituation and how it occurs. The report defines habituation as, 'when a response to a stimulus weakens after repeated presentations to the probability of a behavioural response to a repeated stimulus'. The report states the primary factors that impact habituation are change, duration, frequency and intensity. The report additionally introduces other characteristics such as stimulus specificity, dishabituation, spontaneous recovery and sensitization; the quality of responding to certain stimuli in a respectable behaviour. A key observation made is that habituation is an example of non-associative learning, implying that there is no reward or punishment associated with the stimulus. This paper provides an understanding of habituation and what are the contributing factors.

Another study that explored habituation in fire drills is by Kuligowski *et al.* [5]. The report evaluates the psychological, social, and cultural factors that influence human behaviour in fire evacuations. The study considers five key factors; fire dynamics, human perception and decision-making, occupant behaviour, fire safety design and evacuation. Kuligowski explains the importance of understanding human behaviour in fire evacuations to develop effective fire safety strategies. It additionally discusses the challenges of conducting research in this area and provides insights into any potential future analysis in this field.

There are a wide variety of methods that can be applied to investigate for different behavioural attributes. A study by Feng *et al.* [6] states different techniques that can be used for data collection; the three main types were surveys, field observations and controlled experiments. The study concluded that a combination of methods may be necessary to obtain a comprehensive understanding of pedestrian behaviour in different scenarios.

Surveys are low-cost method of collecting data from a diverse population, and are additionally simple to analyse. Haghani *et al.* [7] used a survey to collect data on participants' exit choice in different scenarios to investigate social influence and perceived danger. The study involved a virtual experiment where the environment had different exits to choose from, and a survey which included questions on social influence and the perceived danger on why participants used certain exits. Participant responses were then used to validate the findings from the virtual experiment.

A study that implemented a field observation method was conducted by Moussaid *et al.* [8]. This study was performed by using a combination of experimental and simulation methods to analyze the walking behaviour of individuals in different social groups. The experimental part observed and recorded the walking behaviour of participants in the different groups in their natural setting; a field observation data collection method. The participants were observed walking along straight paths with a fixed distance, recording walking speed and position data. The simulation part used an agent-based model to simulate pedestrian flows in different scenarios. It was based off the aspects observed from the field observation, used to investigate the affect of social groups on crowd dynamics. The combination of experimental and simulation methods allowed Moussaid to gain a thorough understanding of walking behaviour, and the ability to test different scenarios and predict the behaviour of larger crowds.

Controlled experiment models are performed by changing a certain variable to investigate whether there is a cause and effect relationship between these variables. A study by Zhang *et al.* [9] used a cellular automata with controlled variables to investigate bottleneck effects for different types of facilities such as corridors and staircases. The variables that can affect pedestrian behaviour are walking speed, population and the obstacles. This was a controlled experiment as they would vary one parameter at a time to observe its effects. In this experiment they varied the width of the bottleneck or number of pedestrians to see the effect on the flow rate. The model also used field observation data for validation. The combination of methods used in this study explores different scenarios and tests hypotheses of pedestrian behaviour in a controlled and safe environment.

While many approaches are used to study pedestrian behaviour in evacuations, virtual experiments stand out as they offer experimenters a high level of control whilst being easy to implement, as well as cheap and safe to run. Because of these properties, this experimental paradigm was selected for this project. As technology continues to advance, opportunities to conduct research through virtual experiments increases. A recent study by Kinateder *et al.* [10] discusses the potential use of virtual reality for fire evacuations. Kinateder argues that virtual reality is a suitable approach to test human behaviours in scenarios that would be considered too dangerous if done in the real world. It continues to carry out SWOT analysis (strengths, weaknesses, opportunities and threats) of virtual reality, concluding that it could be used in future research to understand human behaviour in fires to improve fire safety. Virtual reality is argued to be a powerful research tool and has been used in studies to model experiments.

Recent studies have started to explore the behavioural aspects of humans in fire evacuations by the use of virtual experiments. A study by Bode *et al.* [11] implements a virtual experiment to study human behaviour. The design was a two-dimensional model, where participant movement was represented by mouse clicks. The layout was a symmetrical room with two exits, with the independent variables being the width of the exits, the proximity of other individuals and the presence of obstacles. The data collected was the number of participants who chose each exit route, the time it took for participants to evacuate and the distance traveled by participants during the evacuation process. The study additionally collected data on participants ratings of the perceived safety and efficiency of the different exit routes. The data collected was analysed to identify factors that influenced exit route choice and to assess the impact of these factors on evacuation times and participant behaviour, evaluating how the user reacts to and follows a crowd by considering their exit choices. Bode states that this result can only be achieved by assuming participants show similar behavioural aspects in virtual reality to real-world scenarios.

Another study that considered exit routes was in 2018 by Kinateder *et al.* [12]. The report investigated the influence of neighbour behaviour on the participant's decisions during an evacuation scenario. This was achieved by simulating a room with two exits and observing whether the participant used the same exit they used to enter the room. A neighbouring crowd agent was represent in the simulation having a controlled behaviour of standing next to the exit in one of the scenarios. This paper provides important insights, as the results conclude that neighbours' behaviour would impact the user's egress route. It was found that participants were more likely to use the familiar exit if no neighbour was present. If neighbours were present, the participants were likely to follow them through the unfamiliar exit. This suggests that familiarity with exits and the behaviour of others can impact an individual's decision making in the event of an evacuation. An improvement to the study could be to test if the positions of the doors affect the outcome, or if the participant changes their behaviour solely due to the neighbouring agent.

A study that explored a specific aspect of human behaviour was by Bode *et al.* [13]. The report investigates how the perceived costs of helping behaviour affects individuals willingness to help others during a virtual evacuation. Bode designed a virtual experiment with the aim of investigating the participants helping behaviour by modelling a crowd agent and participant agent who had to go to a trigger button to release each other. The independent variable of this experiment was the distance to the trigger button. The study concluded that the increase in perceived costs reduced helping in a gradual state. This implied that people's willingness to help in evacuations can be influenced by perceived costs. This paper provided insightful perspectives on human behaviour, such as the observation that younger and male participants were more likely to help in an evacuation scenario. The experiment was performed on 632 participants; a large enough sample size to draw statistically significant conclusions.

Another study by Bode *et al.* [14] used a two-dimensional model with key clicks, simulating a differing idea to the previous paper. This paper considers the abstract idea of collecting coins before evacuating the room. The independent variables were the number of neighbours and exit signs which also analysed previously by Kinateder *et al.* [12]. These concepts explore whether participants take the familiar route or the route where the arrows direct them. Familiar routes is an aspect many studies have explored to analyse to show different traits. The data collected from this study additionally involved whether the exit signs were shown and the presence of other crowd agents. Other variables collected were the time it took for participants to begin moving towards the exit once they were instructed to evacuate, the time it took participants to reach the exit, the number of collisions that occurred and the participants ratings of the urgency of the situation. This allowed for thorough analysis into factors that contributed to pre-movement delays.

The mentioned studies use virtual experiments in evacuation scenarios, all collecting data on the number of neighbours, key clicks and egress time. Additionally, some of the reports consider alternative data specific to the investigation. For example, Bode *et al.* [14] recorded the number of coins collected per attempt, in order to evaluate pre-movement delays by studying the number of escaped participants to coins collected. This found that participants were taking a risk by collecting coins when they should be evacuating.

Most of the studies discussed are mersive virtual experiments, meaning the interface is a limited and controlled virtual reality experience. Conversely, immersive virtual experiments involve the use of virtual reality technology to create a fully immersive environment where users can interact with virtual objects and environments. A study by Liu *et al.* [15] proposes a simulation method that combines an agent-based model with 3D visualisation to simulate individual and crowd behaviour during earthquake evacuations. The model uses agents to represent individual evacuees and simulates their decision-making process based on a set of rules and environmental factors such as the location of exits and the level of panic. The model also accounts for social influence and crowd dynamics such as crowd density, avoidance behaviour, and collisions. The simulation results provide insights into evacuation performance and can be used to inform the design of buildings and evacuation plans.

Virtual experiments have been conducted in many different ways, meaning there are a variety of methods to code and represent models. A significant study by Reynolds *et al.* [16] in 1999, researched the field of crown movement. The paper introduces different steering behaviours that can be used to simulate the movement of agents. It experiments with the coding aspect for a virtual experiment, exploring different methods such as steering, flocking and agent behaviours. Each method is described in detail with mathematical equations and suitable applications are proposed. It concludes that an autonomous agent has limited ability to perceive the environment, is able to process the information from its environment, calculate an action and do not have a leader. These characteristics are precisely what is needed for modelling crowd behaviour, stating critical ideas on how an individual should move. Furthermore, this paper suggests the analysed methods can be used to represent real-life movement in simulations.

1.3 Research Questions

RQ1: To what extent does repeated exposure to virtual fire drills lead to habituation?

RQ2: Are there different behavioural concepts present in habituation to virtual fire drills, and if so how do they contribute to habituation?

RQ3: Are participants engaged with the virtual experiment, and if so how does this affect their behaviour?

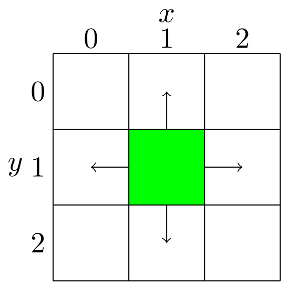
2 Method

The focus of this section is to explore the key framework and ideas of the virtual experiment designed to test for habituation in fire drills. The virtual model was accomplished through a cellular automaton, which is a mathematical model which is built upon a grid of cells and can be used to create agent based models. A study by Clarke *et al.* [17] summarises the use of such cellular automata, stating they have significantly advanced the role of modelling simulations in science. To simulate a cellular automaton, three different matrices are required; a wall, collision and floor field matrix these were acknowledged by Alizadeh *et al.* [18]. Each cell of a cellular automata requires a state that evolves over time according to the set of rules given to the model. The state of each cell in the grid is updated at discrete time steps according to the rules. These rules are simple and local, meaning they only involve a cell's immediate neighbours and are not affected by the global state of the system. Despite the simplicity of the rules, a cellular automaton can exhibit complex behaviours that are difficult to predict. The constructed cellular automaton is a collection of cells arranged in a 20 by 20 grid to form a two-dimensional maze such that each cell changes state as an agent enters or leaves a cell. The collision matrix is used to determine if an agent enters a cell, changing the status to occupied so no other agent can enter. If the agent leaves to a neighbouring cell, the cell state is updated to empty. This provides the concept that humans are not able to overlap each other, making the virtual experiment more realistic. The wall matrix for the maze was constructed such that no agents are allowed to enter the designated wall cells, establishing that these cell states should always be seen as occupied. This implements the concept of familiarising routes from the study by Bode *et al.* [11] previously mentioned as the model creates a controlled environment where behaviour and route patterns can be studied, this will help answer **RQ2**.

The participant is represented as an agent, with the addition of modelled crowd agents to represent other pedestrians in the scenario. The use of a floor field matrix allows for the crowd agents to navigate in a seeking manner to reach a target location, in this instance the exit cells of the maze. This introduces randomness and uncertainty to the model to mimic human behaviour. The objective for the participant and agents are to navigate the maze from the left side to the right, evacuating the maze as quickly as possible and will repeat this five times. However, the participant will experience the crowd agents blocking their shortest route to the exit of the maze making the participant adapt by finding a new route to take, this disturbance will occur either on the participant's second or fourth attempt splitting the results into two groups, early and late disturbance. This allows for an investigation into whether there are differences between the two groups to explore if and when habituation occurs to answer **RQ1**. To achieve this outcome, linear regression models will be used to investigate if the results are statistically significant; this would suggest a strong correlation between the testing variables.

2.1 Cellular Movement

In a cellular automaton there are many ways to create the transition rule to represent how an agent moves. To simplify the model, the movement equations were limited to four directions. This was done in order to optimise the participants performance as they would be able to easily understand the movement patterns. Implementing this would allow an agent to move horizontally or vertically through pressing the arrow keys on the key board to create a functional interface. The implemented maze layout was trivial making the shortest path easy to find, again allowing the user to optimise their egress times without many repetitions. The cellular automata is made up of a small number of rules to implement the characteristics of a real-life environment.



$$\begin{aligned} Left : x[i] &= x[i] - 1, \\ Right : x[i] &= x[i] + 1, \\ Up : y[i] &= y[i] - 1, \\ Down : y[i] &= y[i] + 1. \end{aligned} \tag{1}$$

The Equation (1) shows how agents, denoted i, move in the vertical (y) and horizontal (x) directions. This means that the equations with respect to the cellular automata matrix would simply be complete by adding or subtracting the value 1 in the respected movement plane. With no other rules, this would simulate a simple isotropic random walk. This is the most basic type of walk for agents and is unbias when direction probabilities are equal. However, this would result in the agents aimlessly wondering which is not an accurate representation of a real-life scenario, thus a modification to their random walk must be made.

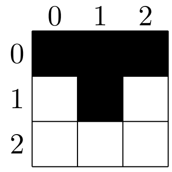
Algorithm 1 User Key Clicks

```
for Every time step do
    Override
    if Key is pressed then
        Add one to click counter and record position of the click
        End thinking time and start clicking time
        Agent's direction of movement is the arrow pressed
    end if
    if Key is released then
        End clicking time and start thinking time
        Agent's direction of movement is to stop
    end if
end for
```

The virtual environment is populated by a simulated crowd and the participant's controlled agent. The pseudocode modelled in Algorithm 1 shows how the participant interacts with the environment via keyboard inputs to change the direction of the agent and how far they move. This code implements an override function which overrides the current variables to the newly pressed key inputs to change the behaviour of the participants agent. Additionally, this function records the thinking and clicking times of the participant for future analysis. The crowd movement is discussed in a later section.

2.2 Wall Matrix

To create the maze wall elements of the cellular automaton, a rule to reject agents from moving into the wall cell is required. This meant that a binary matrix could represent the different cells an agent could move into.

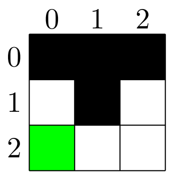


$$\rightarrow \begin{bmatrix} 0 & 0 & 0 \\ 1 & 0 & 1 \\ 1 & 1 & 1 \end{bmatrix} \tag{2}$$

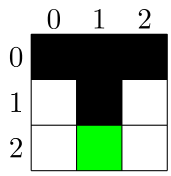
In Equation (2) the black squares represent the walls and white squares represent the empty spaces. This was translated to a matrix by setting wall elements to 0's and empty elements to 1's, creating a 20 by 20 binary matrix. This allows for easy manipulation between visual and computational components. The outer boundary of the grid also needed to be expressed in terms of walls to keep the agents in the cellular automaton, increasing the matrix to a size of 22 by 22. The full wall matrix is shown in Appendix A.

2.3 Collision Matrix

The next rule that needed to be added was to stop agents from overlapping to make the model more realistic to an evacuation as you can not pass through people to get to an exit. This therefore meant an agents movement needed to be tracked in a way that could be evaluated at each discrete time step to see if agents are overlapping. This was achieved by duplicating the wall matrix then making agent occupied cells also equal 0. The binary matrix needed to be updated after every agent move; putting the collision equations in a nested loop meant it would update every frame one agent at a time. This meant that the agents have the same rules of the walls but are also able to move freely in the environment.



$$\rightarrow \begin{bmatrix} 0 & 0 & 0 \\ 1 & 0 & 1 \\ 0 & 1 & 1 \end{bmatrix}$$



$$\rightarrow \begin{bmatrix} 0 & 0 & 0 \\ 1 & 0 & 1 \\ 1 & 0 & 1 \end{bmatrix} \tag{3}$$

In equation (3) the green square represents an agent and the black squares represent the walls. The green square has moved one cell to the right resulting in the collision matrix needing to be updated. The updated collision matrix can be seen, the matrix will stay like this until the agent moves again.

2.4 Different Types of Walks

The use of random walks have been implemented to give the agents a target to avoid them walking aimlessly, as their goal is to reach the other side. The study by Codling *et al.* [19] considers different forms of movement models. The first being uncorrelated random walks (URW) meaning the direction of movement is completely independent of the previous directions moved, making this the most simplest model. Another type, correlated random walks (CRW), demonstrates how each step tends to point in the same direction as the previous one. This type of model is used to model animal paths. Lastly, biased random walks (BRW), which is when paths contain a consistent bias towards a given target. The use of such random walks would replicate movement behaviour in the crowds to mimic human behaviour and processes. The study states a correlated random walk with waiting times uses the equation,

$$p(x, t + r) = p(x, t)(1 - l - r) + p(x - \sigma, t)l + p(x + \sigma, t)r, \tag{4}$$

where t is the time step, σ is the distance to the left or right with probabilities l and r, respectively, or stays in the same location, with probability $1 - l - r$. There are three possibilities for its location. When $x + \sigma$ moves to the right, when $x - \sigma$ moves to the left, and when x it does not move at all. This equation was adapted as it is currently one-dimensional, while the model in this report is two-dimensional. The y plane must be added to Equation (4), forming the following equation,

$$\begin{aligned} p(x, y, t + r) = p(x, y, t)(1 - l - r - u - d) + p(x - \sigma, y, t)l \\ + p(x + \sigma, y, t)r + p(x, y - \sigma, t)u + p(x, y + \sigma, t)d. \end{aligned} \tag{5}$$

The constants used in the model were, $\sigma = 1$ as it moves 1 cell of the automata at any discrete time step, $r, l, u, d = 0.2$ begin the directions left, right, up and down respectively, setting them to 0.2 means all the outcomes have the same probability so the agents do not favour one outcome. The use of Equation (5) with the specific constants creates a controlled walk for the agents. It allows for pauses to represent the agent thinking as a human would do. However this does not solve crowd agents aimlessly walking around by itself.

2.5 Floor Field Matrix

The idea behind having a floor field is to assign a value to each element of the cellular automaton to change the random walk that happens in a two-dimensional space to represent cells as targets. When an agent moves it has five choices; left, right, up, down and stay. These choices are effected by external factors such as if an agent is trying to move into a wall or if the agent is trying to move on top of another agent. These rules are applied to every frame of the simulation. This would be done randomly without a floor flow matrix as implementing this into the cellular automata would simulate crowd agents having a seeking behaviour to navigate to a better cell in the maze.

A floor field matrix is a mathematical representation of a virtual environment that is commonly used in the field of robotics and artificial intelligence. The matrix is a grid-like structure that is often two-dimensional, but can also be three-dimensional. Each cell in the matrix represents a specific location in the environment and contains a value that represents the cost or desirability of moving to that location. The floor field matrix is used to simulate the behaviour of the agents making them move towards the target side of the maze. Using the equation,

$$P_{i,j} = \frac{(b-a)(x_{i,j} - min)}{max - min} + a, \tag{6}$$

to convert to values where P is the cell value, x is element in matrix, i is row, j is column, $min = 14 + 8\sqrt{2}$, $max = 1$, $a = 0.1$ and $b = 1$. The values of the matrix were calculated by setting the target values to 1. Starting from the target cells and considering the neighbouring cells by adding a value of 1 to the adjacent cells or a value of $\sqrt{2}$ to the diagonal cells. This process was then repeated from the outer cells to create a matrix which could then be scaled to represent the cell values between a and b to create an increasing gradient to the target cells for the crowd agents to navigate.

$$\begin{bmatrix} 14+8\sqrt{2} & \dots & 1 \\ \vdots & \ddots & \vdots \\ 14+5\sqrt{2} & \dots & 1 \end{bmatrix} \rightarrow \begin{bmatrix} P_{1,1} & \dots & P_{1,20} \\ \vdots & \ddots & \vdots \\ P_{20,1} & \dots & P_{20,20} \end{bmatrix} \rightarrow \begin{bmatrix} 0.100 & \dots & 1.000 \\ \vdots & \ddots & \vdots \\ 0.257 & \dots & 1.000 \end{bmatrix} \tag{7}$$

The full floor field matrix can be seen in Appendix B. The agents now have a seeking manner to the exit cells, in this case to cells with a higher value, this was achieved by the agents seeing if their intended walk direction also suits the floor field by making sure the next cell has a higher value than the current cell, if so the agent will move to the next cell then repeat. The floor field matrix can be adapted at any point to change the target of the agents resulting in their walk paths changing. This could be used to study different traits and behaviours.

Algorithm 2 Crowd Movement

```
for agent = 1, 2, ..., N do
    Update agent's current cell position in collision matrix to empty
    Pick random direction the agent is going to move in (l,r,u,d or stay put)
    if New cell is already occupied or floor field matrix gets worse then
        Continue
    else
        Apply movement to Equation (5)
    end if
    Update agent's new cell in collision matrix to occupied
end for
```

The pseudocode in Algorithm 2 shows the framework of the crowd movement. It implements the use of the collision matrix, crowd random walk and floor field matrix to fully achieve the human-like behaviour for all the agents with the simple use of an if statement embedded in a for loop to cover all the agents. The use of a for loop means the positions of the agents are updated one after the other, the order of which is never changed. This is known as an asynchronous update scheme for agent-based models.

2.6 Early or Late Disturbance

The independent variable for this experiment is to deliberately block off the shortest route the participant can use to see the effect, this assumes the user converges to the usage of the shortest path during the experiment. The participant will partake in a total of five attempts of the maze getting from the left side to the right side as quickly as possible. Then on their second or fourth attempt they will experience the agents blocking off their shortest path. This situation is unexpected and occurs to see how they react to the shortest route becoming unusable. It was expected that participants who experienced the early disturbance to take longer throughout their five attempts as they will be more warily. It was additionally expected that participants with the late disturbance to have quicker attempts but disrupted more by the experience, expecting them to develop habituation before it occurs. A run-through of the virtual experiment can be seen via https://youtu.be/8wT2YWWsmAI, which used JAVA files found in [20]. The run-through experiences the disturbance on the fourth attempt.

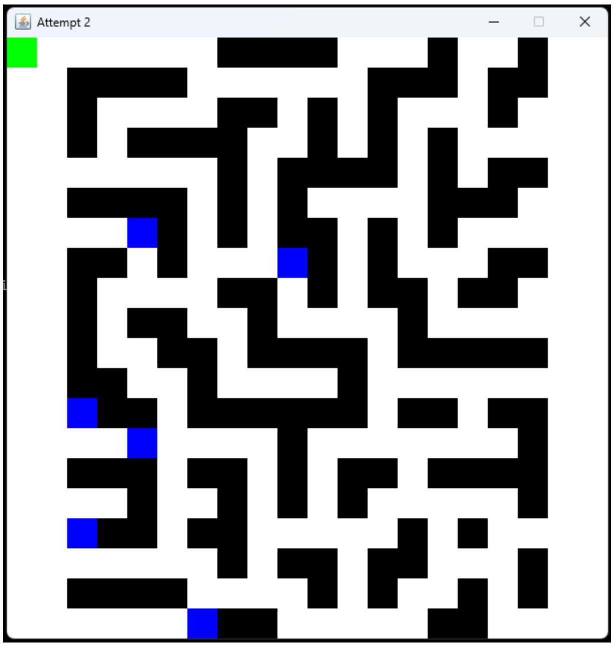


Figure 1: Virtual experiment model - disturbance attempt

The Figure 1 shows a picture of the virtual experiment, where the walls can be seen in black, the user agent is green and crowd agents are blue. It also shows the positions of where the crowd agents stay on the disturbance attempt to block off the shortest path for the participant. When analysing the layout of the maze it is clear to see the quickest route from the users start position (top left) is to move down then right however this can lead to being obstructed by the crowd agents. Making it quicker o move right across the top then down towards the center before moving right again with the target being the fourth exit. In some cases if the user was not quick enough they were effected by the movement of the crowd due to the rule that you cannot move through one another.

2.7 Participant Process

The participants were recruited then asked to read through the participant information (Appendix C) and complete the consent form (Appendix D). If consenting to participate to the experiment (Figure 1) they would complete the task five times then followed by a questionnaire (Appendix E) where they were also asked if they consented to the use of the questionnaire and experiment data being used in this study.

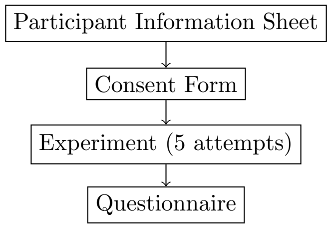


Figure 2: Participant Process

The Figure 2 shows a diagram of the step by step process the participants under took, completing one task at a time. Participants were made to complete the experiment by themselves without any communication and could only be a candidate if they had not experienced or witnessed the experiment before.

2.8 Data Extrapolation

The virtual experiment outputs the desired variables from the participant and crowd agents into a CSV file to then be statically analysed in MatLab. The variables decided to take into consideration were; click time, defining this by how long a key was pressed at once. Along with think time, the time between each key was pressed. The sum of these 2 variables corresponds to total time to complete the attempt. The direction of the clicks, whether the direction was left, right, up or down with the addition of the co-ordinates of the clicks represented in a two-dimensional fashion allowed for a full representation of the paths walked by the participant or crowd agents. Other variables that are outputted are attempt number and the number of the disturbance attempt.

The questionnaire is performed after the experiment and can be found in Appendix E, the main aspect of this is to get the general data of the participant such as age and gender to broader questions such as gaming experience. It also has three observational questions; 'what was the colour of the other agents?', 'how many other agents were there?' and 'how many exits were there?'. The participant is not aware of these questions until asked in the questionnaire after the experiment. This was purposely done to allow evaluation of attentional focus which is a concept involved in **RQ2** and **RQ3**.

3 Results

The data collected from the virtual experiment gives insights to the two components, navigation and time to help answer **RQ1**. The outputted data from the experiment along with the questionnaire allowed for a critical evaluation of whether people habituate to fire drills through navigation or time. To analyse the data thoroughly, different techniques were used such as linear regression models in order to visualise and evaluate the data to reach the final conclusion.

3.1 Data Collection

Before data collection, experimental procedures were submitted for ethical review and approved by the Faculty of Engineering Research Ethics Committee (application ID: 13827). During the experiment all participants were treated the same. A sample size of ten people were collected for each different type of treatment. The experiment conducted has two treatments, early and late disturbance therefore at least twenty people were needed.

From the participants who partook they all consented to their data being used. A total of 20 partook in the experiment, of them 80% were male and 20% were female. Half of the participants were assigned to early disturbance while the other half were assigned to late disturbance. The age ranged from 19 to 22 with the mean of 20.8.

This represents a small census formed mostly of university students which is a form of opportunity data collection, when no recruiting is performed and participants are in the right place at the right time. This can provide valuable insights into the behaviours of the population, however it is important to keep in mind that the results obtained throughout may not be representative for the entire population as it could have limited diversity.

The observational questions in the questionnaire answer **RQ3**. From the answers 100% of participants got the colour of the crowd agents correct (the correct answer was blue) with 15% getting the number of crowd agents correct (the correct answer was 6) with the average answer of 4.6. Followed by 15% getting the number of exits correct (the correct answer was 6) with the average answer of 3.9. Of these 0% got both questions correct, this proves the theory of attentional focus and shows the participants were engaged answering **RQ3**. Concluding when participants experience stressful scenarios they process less unnecessary environmental information focusing on the task in hand, in this case fleeing the environment.

3.2 Navigation Analysis

The use of navigation analysis is to evaluate the structure of the maze and how participants navigated the layout. Navigation analysis involves using the data of the users behaviour, such as clicks and click positions. This section looks to investigate for habituation in key clicks and familiar routes to explore if there are any patterns between early and late disturbance that could be caused by habituation.

3.2.1 Key Clicks

The aim of exploring key clicks is to show repeated actions decreases arousal levels [21], another concept considered for **RQ2**. In this instance assuming arousal is directly proportional to number of key clicks, implying repetitions of the experiment will decrease the number of clicks and arousal level if habituation occurs.

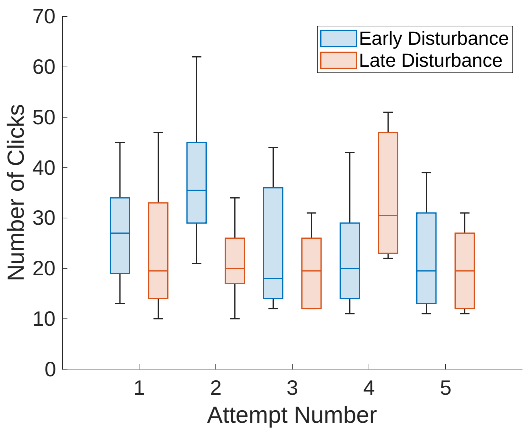
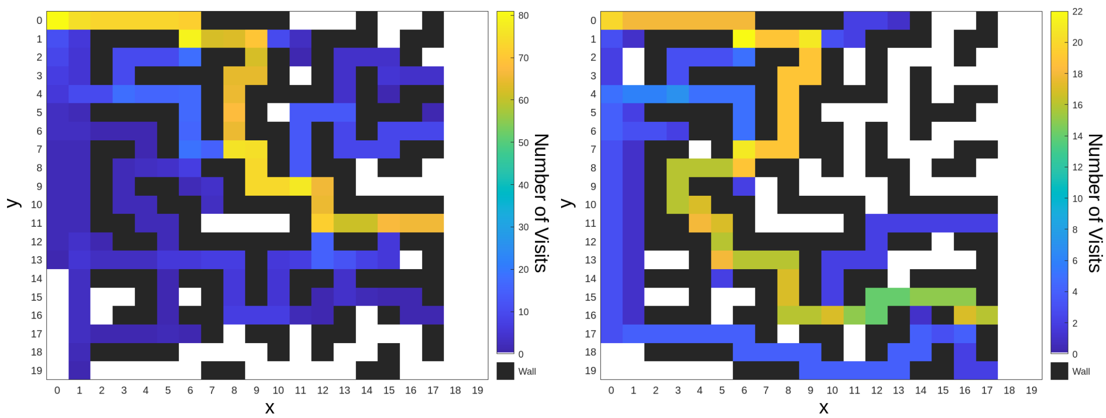


Figure 3: Box plots of number of clicks per attempt.

The Figure 3 shows the box plots of clicks per attempt. Separating the clicks into two groups, early and late disturbance. Studying the early disturbance shows the most clicks in the second attempt as expected, however after expecting the disturbance the mean of clicks drastically drops. This could be because they have now calmed to the environment and know how they want to navigate the maze. The late disturbance group click mean increases as attempts increases. This was unexpected and could be due to the lack of urgency created by the virtual experiment. When they experience the disturbance their clicks increased and afterwards also dropped a considerable amount to which the mean was better after.

3.2.2 Navigation Through The Maze

This section considers the navigation concept of the experiment focusing on the familiar route theory which was studied by Bode *et al.* [11]. It was expected that participants to use the shortest route.



(a) Routes with no disturbance

(b) Routes with disturbance

Figure 4: Heat map of routes taken by the participants.

The shortest and quickest path became clear and obvious to the participants after repeating the experiment as the model is simplistic. This is shown in Figure 4, it reveals that the majority of the participants would use the shortest route in Figure 4a defining this path as the familiar route. Then when re-directed by the disturbance most participants would then take the next shortest route whilst some would merge back onto the familiar route shown in Figure 4b. There is not enough evidence from these figures to suggest participants stick to one route as four out of the possible six exits were used in the routes with no disturbance.

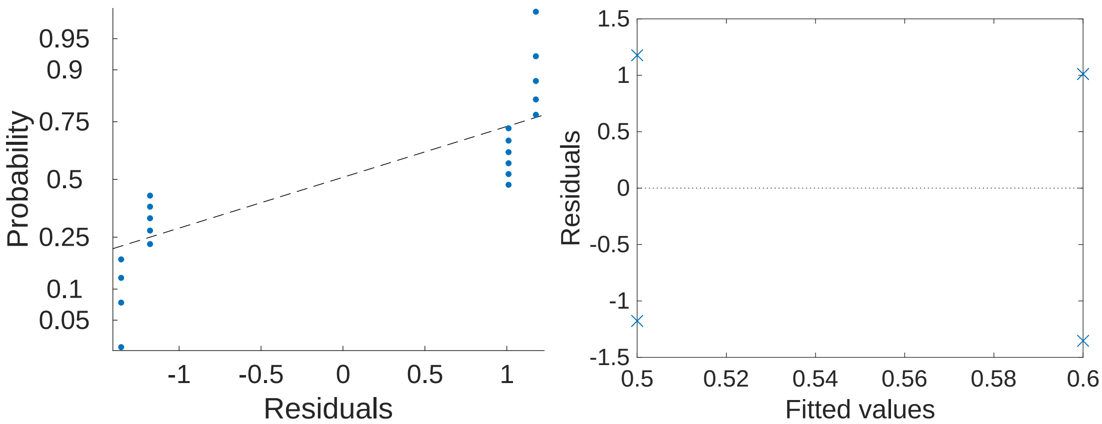
3.2.3 Returning to Familiar Route

To test whether there is correlation between returning to the familiar route after the disturbance attempt a linear regression model can be used. Linear regression models are a statistical model that are widely used for predicting the relationship between a dependent variable and one or more independent variables. To be able to use a linear regression model the linearity assumption must hold which is the relationship between the independent variable and the dependent variable is linear, which means that the change in the dependent variable is directly proportional to the change in the independent variable. A linear regression model uses the equation,

$$Y_i = \beta_0 + \beta_1 x_i + \epsilon_i, \tag{8}$$

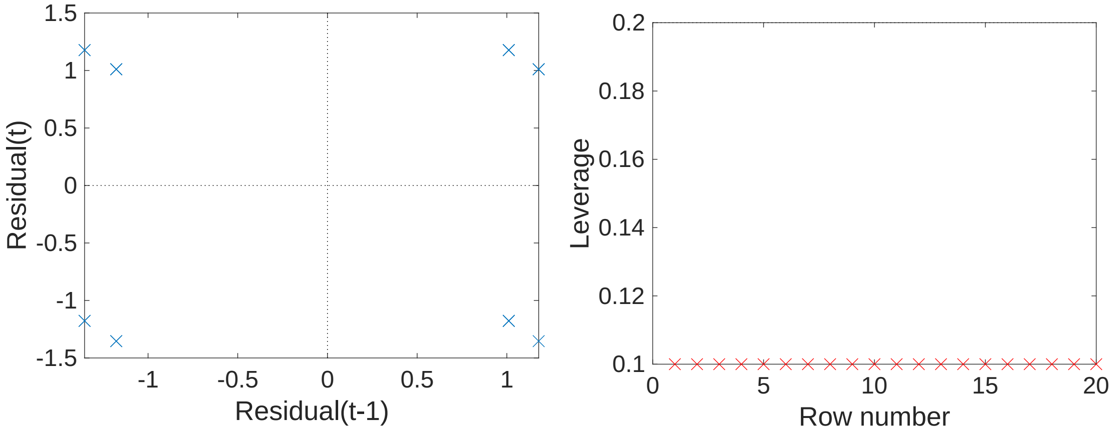
where Y_i is the dependent variable, X_i is the independent variable(s), β_0 is the intercept, β_1 is the slope, and ϵ_i is the error term. The error term represents the random variation in the dependent variable that cannot be explained by the independent variable.

To fit a model to explore familiar routes it uses one independent variable, the blocked attempt and one dependent variable, if the path was returned to, this is represented as a binary matrix where 1 represents yes and 0 represents no. As both the variables are discrete this makes them categorical variables, meaning a binomial generalised linear regression model should be used as a binomial distribution observes success or failure, in this case the success is whether participants return to the familiar route and the failure is if they do not. When using binomial distribution the logit link function is used to model the relationship between the predictor variables and the probability of a successful outcome. This creates the null hypothesis of, there is no relationship between experiencing the early or late disturbance and returning to the familiar route.



(a) Normal probability plot of residuals

(b) Plot of residuals vs fitted values



(c) Plot of residuals vs lagged residuals

(d) Case order plot of leverage

Figure 5: Plots to show whether there is correlation between participants returning to there usual route after expecting early or late disturbance.

In Figure 5a it shows the Q-Q plot to see if the residuals are normally distributed, in this case it normality does not hold, this is due to the variables being categorical with two outcomes therefore this plot should be interpreted cautiously. Figure 5b shows the relationship between the fitted values and the residuals, it shows a random scatter of points centered around zero verifying the assumption, however the lack of data points should be considered as four points is not enough to be fully certain that this assumption holds therefore should also be interpreted cautiously. Figure 5c shows no correlation between the data points, therefore the independence of errors assumption holds. Figure 5d shows the data points forming a horizontal line at a low value, indicating that most observations have low leverage and are not highly influential meaning the data has been fitted well. Overall when ignoring Figure 5a due to both variables being categorical therefore concentrated mainly on residual values. The assumptions hold for this model however it could be improved by the use of more data points to be more certain.

	Estimate	SE	tStat	pValue
(intercept)	6.7709e-16	0.63246	1.0706e-15	1
blocker_4	0.40547	0.9037	0.44867	0.65367

Table 1: Binomial generalised linear regression model with logit link function; response variable: Boolean indicating whether participants used the same route before and after they experienced the disturbance.

Studying the model summary (Table 1) shows that the p-values are both greater than 0.05 therefore there is not enough evidence to reject the null hypothesis. Thus, there is no correlation between when disturbance occurs and whether participants return to the familiar route.

3.2.4 Random Walks

Having discussed different types of random walks in Section 2.4, this section analyses the different types of walks and how long each type would navigate the maze before reaching the exits. This was completed to create a crowd movement model for the agent behaviour to mimic humans to create an environment that seemed natural to the participant. It would also allow comparisons with which movement pattern the participants best resemble.

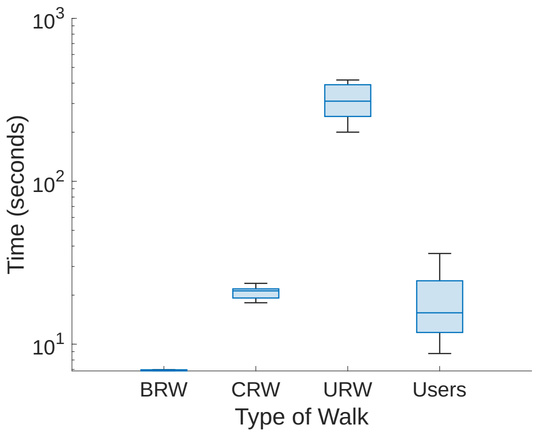


Figure 6: Time of the different types of walks.

In Figure 6 the three types of walks considered for agent behaviour were BRW, CRW and URW. Each of these walks were tested in the exact maze layout found in Figure 1, each type of walk was tested fives times with the addition of participant times being plotted. From this graph we can grasp the level of bias of each random walk by analysing the box plots. The BRW is seen to be completely bias as it has times with no deviation from each other and an egress time of 6.7 seconds. The URW shows the agents acting completely lost and eventually reach the exit after an average of 320 seconds, this walk had a wide range of times due to the outcome being down to randomness. The CRW can be seen to mirror the times of the participants with a mean egress time of 20.1 seconds, acting in the participants lower quartile range, indicating that the CRW was the best fit for the agents to resemble a human crowd. This implies the participants resembled a correlated walk as their times cover the range of the CRW and are not as efficient as the BRW. The Figure 4 shows that the participants were able to find the shortest path which was used by the BRW. However, the BRW resembles no thinking time, just clicking time, whereas the participants are human therefore will navigate along the shortest route but have to find the path and they may have not completely pre-planned their route which introduces delays and variability which means the participants movement is not as efficient as the BRW. The participant attempts also had crowd agents represent which meant if the participant ended up behind a crowd agent on the shortest path this would delay them from reaching the exits as the crowd agents had a CRW which is slower than the BRW. This graph shows the CRW resembles the walk of the participants best but in a fire drill the aim is to minimise egress time which could be achieved by the BRW. As previously stated neighbour walks can impact the direction of participants, they can also impact the speed of participants as people are more likely to follow a neighbour than navigate alone in a fire situation, this is also known as the bandwagon effect, studied by Schmitt *et al.* [22]. This could potentially see the participant egress times decrease if the pedestrian crowd resembles a BRW and should be considered when answering **RQ2**.

3.3 Time Analysis

The use of time analysis is to evaluate how the participants egress times using the thinking and clicking times to test if participants perform quicker due to experiencing habituation in repetition.

3.3.1 Total Time

Having shown that increasing repetitions decreases arousal in Section 3.2.1, now to explore if using the times of the experiment will give a clear indication whether habituation occurred or not. The null hypothesis is, the egress times are not affected by number of attempts, however the routes with disturbance will be longer due to the fact the participants have to cover a longer distance plus the additional thinking time for adapting to the situation. Therefore when investigating this hypothesis the disturbance attempt will have to be ignored.

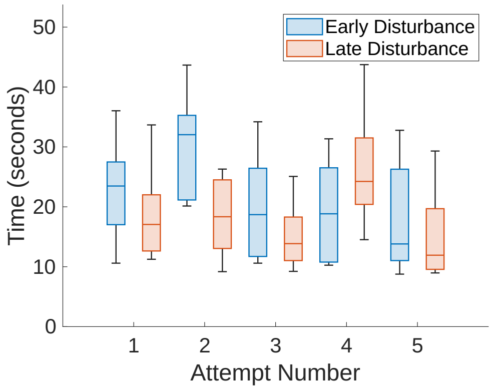


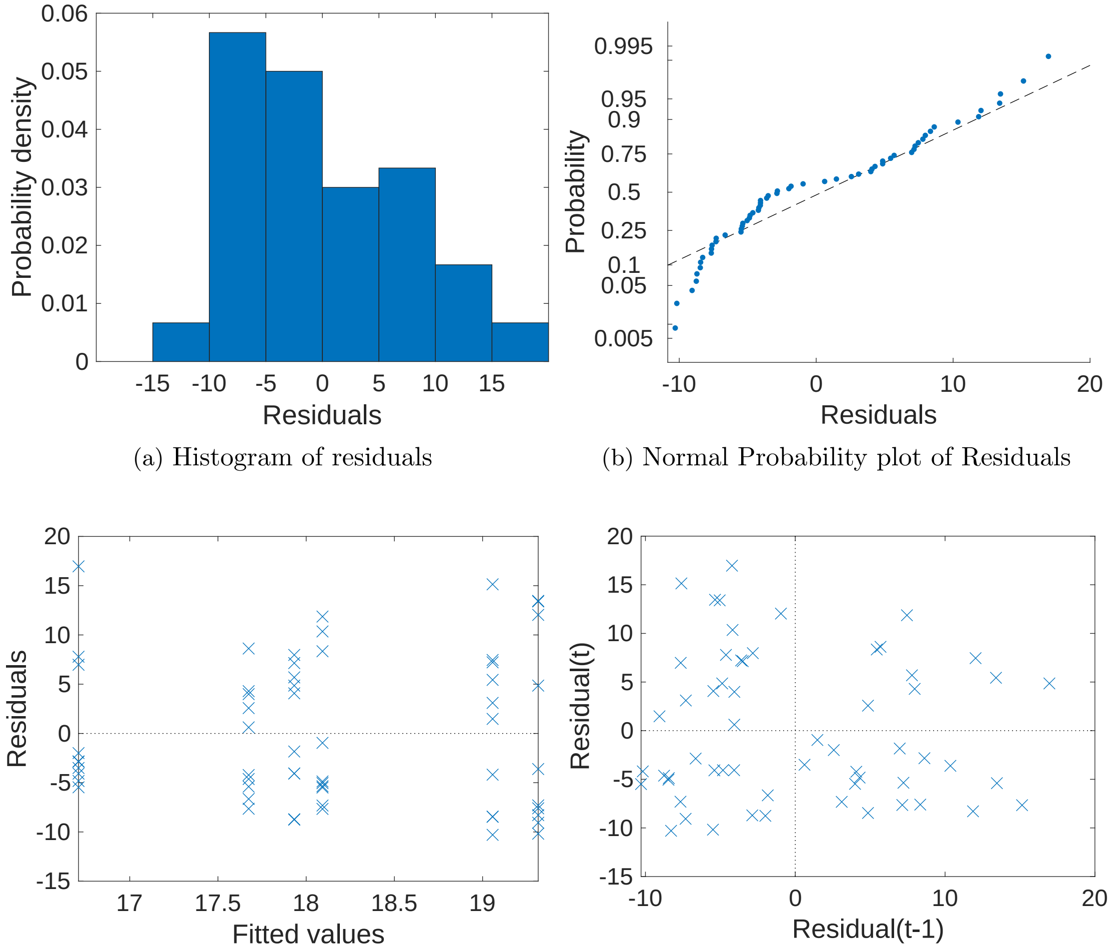
Figure 7: Box plots of total time per attempt.

From the Figure 7 we can see that the routes with disturbance (blue attempt 2 and red attempt 4) took longer however this was expected as the disturbance route is longer with the addition of the thinking time when experiencing the new scenario. When studying if total time decreased over the repeated attempts comparing attempts 1 and 5 median suggests that this hypothesis is true; however the range of the times did not decrease as significantly as suggested meaning there is no clear indication that egress time decreases with number of repeated attempts. Further analysis would have to be completed to come to a conclusion.

3.3.2 Successive Attempts

To conclude, the hypothesis of whether egress time decreases with repeated attempts a multiple linear regression model can be used. This model is a linear regression model however uses two independent variables, blocked attempt and attempt number, and one dependent variable, egress time. The two independent variables are categorical data points but the dependent variable is continuous data. With the linearity assumption holding as egress time decreases with attempts a linear regression model can be used as the normal distribution is valid. This model uses the identity link function which is a linear link that assumes that the linear predictor and response variable are on the same scale. This benefits the model as the response variable is continuous.

This forms the null hypothesis of, there is no correlation between successive attempts and decrease in total time to complete the maze.



(a) Histogram of residuals

(b) Normal Probability plot of Residuals

(c) Plot of residuals vs fitted values

(d) Plot of residuals vs lagged residuals

Figure 8: Plots to evaluate whether participants are able to complete the maze quicker when increasing attempts.

In Figure 8a, it shows the distribution of residuals, the mean is skewed to the left indicating that the residuals are not normally distributed, therefore the normality of errors assumption does not hold. Figure 8b shows the Q-Q plot to check for normality, the data points do not follow the straight line therefore also violates the normality assumption. Figure 8c shows the difference between fitted residuals against actual values, from this we can see the data is centered on zero, however there is a linear relationship between the residuals violating the linearity assumption. Figure 8d shows no correlation between data points meaning the independence of errors assumption holds. Overall, this model does not fully satisfy some of the assumptions, this could be due to the data sample being small or other external factors affect the dependent variable therefore results should be interpreted cautiously with further investigation necessary.

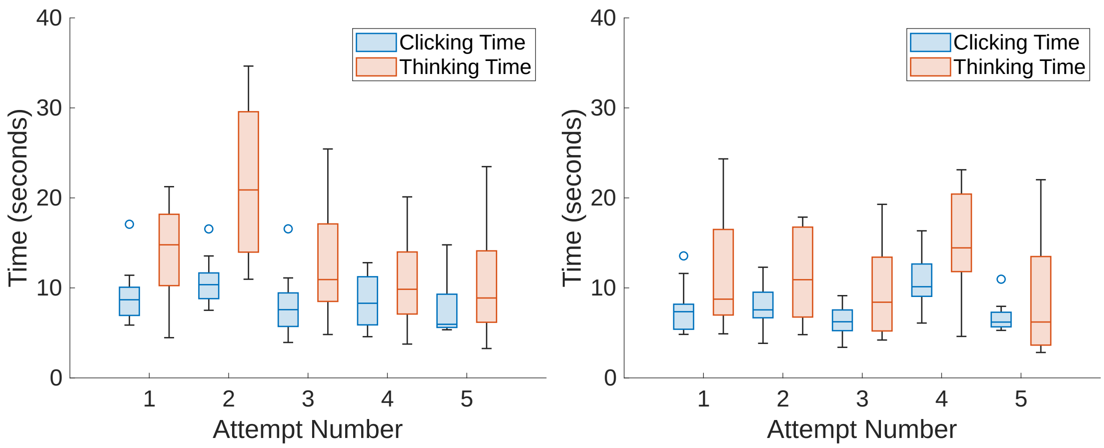
	Estimate	SE	tStat	pValue
(intercept)	19.057	1.968	9.6835	1.4476e-13
blocker_4	-1.3827	1.968	-0.70262	0.4852
attempt_2	-0.96245	2.4103	-0.40006	0.69063
attempt_4	0.25835	2.4103	0.10719	0.91502

Table 2: Multiple linear regression model with normal distribution and identity link function; response variable: continuous total times of the participants three successive attempts.

The model summary (Table 2) shows the p values for variables. Three of the variables have a p value greater than 0.05 therefore not enough evidence to reject the null hypothesis meaning there is no clear correlation between the variables to suggest participants become quicker with repeated attempts.

3.3.3 Thinking and Clicking Time

Analysing the egress times of the attempts did not capture any correlation between the successive attempts and the times taken indicating it should be researched more precisely. Total time in a virtual experiment is the addition of the thinking and clicking times. When separating these two aspects you can gain a better understanding of the cognitive and motor processes involved in the interaction.



(a) Early disturbance (b) Late disturbance

Figure 9: Box plots of thinking and clicking times per attempt.

In Figure 9 box plots have been drawn for the clicking and thinking times for the individual attempts. From this it shows that the participants who experienced the early disturbance (Figure 9a attempt 2) shows their thinking time increased drastically. The participants who experienced the late disturbance (Figure 9b attempt 4) were quicker to think and adapt to the situation compared to those who experienced the early disturbance. This indicates that these participants were more aware of the situation and did not think for long before redirecting to a new route to evacuate the maze.

Having re-ran the successive attempt model with binomial distribution and logit link function but considering thinking times instead of egress times. This changed the null hypothesis to, there is no correlation between successive attempts and thinking times. The model produced similar results to Figure 8 with a p value of 0.958, therefore, not enough evidence to reject the null hypothesis. To conclude there are numerous possibilities to why there was no significant evidence to reject the null hypothesis. One of the possibilities is that the complexity of the model was too simplistic therefore the participants were able to master it in the first attempt. Or perhaps a lack or urgency could have meant the participants did not partake in the experiment seriously.

3.3.4 Gaming Experience

From the questionnaire the gaming experience was a scale where the participant would state their gaming experience in the range of 1 to 10. Overall, the gaming experience had a mean of 5.9 and a ranged from 1 to 10, this indicates a good spread of gaming experiences in the data census.

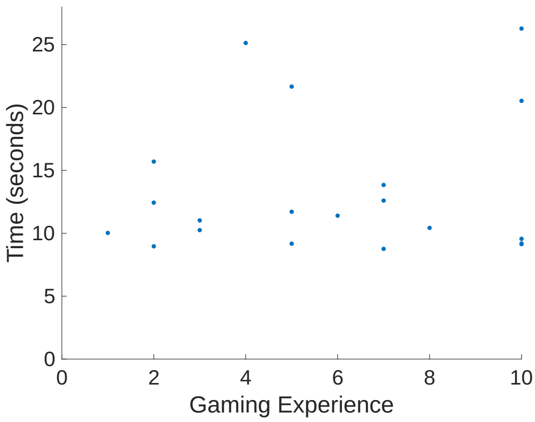


Figure 10: Quickest attempt against participants gaming experience.

From the Figure 10 it was expected to show the better the gaming experience the better the time however this is not the case in this situation as no correlation is shown. This could be due to the fact they judged their gaming experience on their own accord however as there are many data points that could be called anomalies this is very unlikely. It could be due to decision making skills, this could see people with high gaming experience make the wrong choices in the experiment which has no interlink with gaming smartness and would be down to the levels of the participants initiative.

4 Discussion

To answer the question **RQ1** of whether habituation occurred from the virtual experiment, analysis of navigation and time analysis was performed. The study analysed navigation to evaluate how participants navigated the maze layout with the key idea being whether they found the shortest route and if they would remain on the path. When studying the participant routes from Figure 4, it showed participants would familiarise themselves to one route. When testing whether participants returned to the familiar route by using the generalised linear regression model, The Figure 5 shows signs that the data has been fitted well. Linear regression models are a simple and powerful model that can provide accurate predictions of the dependent variable, however it is sensitive to outliers and overfitting, as the sample size was small this could mean the data has been incorrectly fitted. The assumptions and the Table 1 suggests there was not significant evidence to state there was correlation answering **RQ1**. This could be due to the lack of data points or due to the independent and dependent variables being categorical making it difficult to see any correlation.

Using the thinking, clicking and egress times. Time analysis was used to evaluate how long it takes to complete the maze and to test if a participants delayed response was a factor of habituation. The concept of time analysis was observed through a multiple linear regression model firstly using total time, as shown in Figure 8, these graphs gave cautious representations of the data and the Table 2 showed no significant evidence to suggest there was correlation indicating further analysis would be needed to conclude the null hypothesis. This experiment used the variable, egress time as the sum of the thinking and clicking times shown in Figure 9, this graph suggested that clicking times were similar throughout the attempts. To fully test whether delayed response is a factor of habituation meant repeating the successive attempt (Section 3.3.2) statistical model to conclude if there was any relationship between repeated attempts and a decrease in thinking time. The outcome of the model did not give significant evidence to suggest this relationship, also answering **RQ1**. This concludes the more repeated attempts does not mean participants become faster in the concept at navigating the maze. To be more certain of these results increasing the data sample would give a clearer understanding of the data and relationships.

The implementation of a simulated crowd in Section 2.4 raised the question of whether participant times were similar to the crowd agents (shown in Figure 6) as participants would replicate the behaviour and movement of the crowd. A study by Hu *et al.* [23] reviews and analyzes multiple studies on this topic and states that social groups can have a significant impact on egress times, with larger groups and groups with young or elderly members experiencing longer egress times. This explains why the participant times were similar to the crowds, suggesting the bandwagon is a concept of habituation **RQ2** and potentially hindered the egress times of the participants. This now leaves room for consideration of the affect of different crowd walks on participants in virtual experiments.

Carrying on from the crowd behaviour creating the psychological bandwagon effect in the experiment, another psychological aspect explored was arousal levels, this concept was stated in Figure 3 assuming number of key clicks is directly proportional to arousal. Over the five attempts, number of key clicks decreased suggesting arousal levels decreased as participants settled into the environment and would increase when experiencing disturbance. In fire scenarios arousal levels would be high simulating the fight or flight response, there is no clear indication that this experiment created enough urgency to affect a participants arousal levels therefore there is no clear answer to **RQ2** for arousal. A study by Baker *et al.* [24] introduced the crisis of reproducibility, this refers to the growing concern in scientific research about the ability to replicate or reproduce the results of published studies. There is increasing evidence that many scientific studies investigating social and behavioral characteristics are difficult or impossible to replicate, leading to concerns about their validity and reliability.

A virtual experiment study which was able to test for a characteristic was by Kinateder *et al.* [12], this study looked that the bandwagon effect investigating familiar route and the impact of a neighbouring agent. This study found that participants were more likely to choose exits that were familiar to them, rather than less familiar ones. Additionally, participants were influenced by the behaviour of their neighbours and those surrounded by more active neighbours were more likely to follow them to the unfamiliar exit. Kinateder suggests that these findings have implications for the design of emergency management strategies, and that familiarity with all exits should be achieved in fire drills. Another study was a study by Bode *et al.* [13] where Bode tested for a more complex characteristic, helping behaviour in participants. The study found that increasing costs reduced helping behaviour and found that the decrease in the frequency of helping behaviour was gradual rather than a sudden change of a cost level. The study went on to state younger and male participants were more likely to help and helping opportunities where conducted by cost-benefit trade-offs by spontaneous decision making. Bode summarises by suggesting that the findings have implications for understanding of social behaviour in emergency situations.

The outcome of visualising and statistically modelling the data concluded that this experiment followed the crisis of reproducibility theory and would be more clear to acknowledge if the data sample was bigger. Furthermore, 75% of the participants said they felt like they were in the experiment, consolidating that the participants were engaged (**RQ3**). This commends the use of virtual experiments. From the results the model used to test for habituation did not give significant evidence to confirm habituation, however, it demonstrated the use of virtual experiments as a tool to model real life scenarios whilst testing for specific traits and characteristics.

4.1 Limitations

From this virtual experiment it can be seen that the correlation is weak for determining whether habituation occurs. This would be easier to confirm if there were more participants. The lack of participants does not make it reliable enough. Another limitation is the age of the participants. Due to it being word of mouth this meant most the participants were university students and therefore can only demonstrate university students responses to the simulation and not the response of the general population. This could mean the fact the virtual experiment is represented as a computer game, older generations who struggle with technology may not be able to understand a virtual scenario. This would therefore mean in further years virtual experiments would be a stronger yield. It was assumed that habituation occurs within five trials. This seemed to be true, however more trials would be needed to consolidate this theory. The experiment is highly abstracted and it's possible that a more immersive experiment is needed to elicit stronger habituation in participants.

There is a lack of urgency to complete the maze. This therefore means the panic levels one experiences in this experiment is extremely different to a level of panic that is experienced in a real fire scenario. If the participant knows the fire scenario is actually a fire drill then they will have a relaxed approach similar to the virtual experiment. Additionally, the margin of the maze walls does not allow agents to move past each other representing corridors in the maze to evaluate the users behaviour when blocked. This could be changed to consider people moving at a faster pace in wider areas, such as main lobbies in buildings.

4.2 Future Work

This report evaluates potential usage of virtual experiments to model fire drills to train peoples responses. The investigation could progress further by modelling different wall matrices, representing a building as a three-dimensional cellular automata model or implementing a more immersive approach to show stronger correlations. Virtual reality has the opportunity to change the world in large ways. This study has only managed to scratch the surface of the beginnings of virtual experiments to test for traits.

Furthermore, the study could be repeated with more trials to ensure participants pass the point of habituation. This would ensure that participants experience habituation in the environment and would give move data points, stretching the search of 10 attempts would give more precise and reliable scores. Then moving early or late disturbance to the third and seventh attempt.

4.3 Contributions

C1: Implemented the virtual experiment from scratch using a range of technical and creative skills.

C2: Conducted a thorough ethics review and obtained approval for the experiment.

C3: Collected data from 20 participants where they completed the virtual experiment.

C4: Analyzed the data using appropriate statistical models to investigate relationships in habituation.

C5: Discussed the findings from the virtual experiment to whether habituation occurred.

5 Conclusion

Fire drills are an important safety precaution. Making sure people are correctly trained to evacuate the fire scenario is vital for their safety and the safety of others. This report used a cellular automata to analyse participants behaviour in a virtual reality experiment to understand if the use of virtual simulations are beneficial for training of fire drills. Analysing whether habituation occurred was the main factor in this report, this was to optimise the sensitization response. This study created a virtual experiment to record participant data from the simulation and then critically evaluated the results by the use of statistical models. The experimental design of the cellular automata was simple and considered representing the crowd with a correlated random walk to mimic human behaviours. The data was formed by 20 participants and was analysed through visual and statistical models using two different types of linear regression models, multiple linear regression and generalised linear regression. These models could only be used when certain assumptions withheld to generate the outcome of whether habituation occurred.

From this the findings were statistically insignificant, suggesting there is no relationship between repeated attempts and habituation. Having also explored different concepts that could contribute to habituation it is suggested that the pedestrian crowd can affect participants and further research should be conducted to investigate to what extent this concept affects participants in virtual experiments. Overall, the participants were engaged with the virtual experiment therefore virtual experiments can be used for investigating behavioural aspects in dangerous environments. However, a more immersive approach should be suggested as this abstract model was unclear in investigating habituation in fire drills.

References

[1] Elena Romanova. Increase in population density and aggravation of social and psychological problems in areas with high-rise construction. In *E3S Web of Conferences*, volume 33, page 03061. EDP Sciences, 2018.

[2] John Raymond Hall. *High-rise building fires*. The Association, 2000.

[3] Dictionary definition of habituation. https://dictionary.cambridge.org/dictionary/english/habituation. Accessed 2022-10-04.

[4] Catharine H Rankin, Thomas Abrams, Robert J Barry, Seema Bhatnagar, David F Clayton, John Colombo, Gianluca Coppola, Mark A Geyer, David L Glanzman, Stephen Marsland, et al. Habituation revisited: an updated and revised description of the behavioral characteristics of habituation. *Neurobiology of learning and memory*, 92(2):135–138, 2009.

[5] Erica D Kuligowski and Erica D Kuligowski. *The process of human behavior in fires*. US Department of Commerce, National Institute of Standards and Technology, 2009.

[6] Yan Feng, Dorine Duives, Winnie Daamen, and Serge Hoogendoorn. Data collection methods for studying pedestrian behaviour: A systematic review. *Building and Environment*, 187:107329, 2021.

[7] Milad Haghani and Majid Sarvi. Human exit choice in crowded built environments: Investigating underlying behavioural differences between normal egress and emergency evacuations. *Fire Safety Journal*, 85:1–9, 2016.

[8] Mehdi Moussaïd, Niriaska Perozo, Simon Garnier, Dirk Helbing, and Guy Theraulaz. The walking behaviour of pedestrian social groups and its impact on crowd dynamics. *PloS one*, 5(4):e10047, 2010.

[9] Jun Zhang and Armin Seyfried. Quantification of bottleneck effects for different types of facilities. *Transportation Research Procedia*, 2:51–59, 2014.

[10] Max Kinateder, Enrico Ronchi, Daniel Nilsson, Margrethe Kobes, Mathias Müller, Paul Pauli, and Andreas Mühlberger. Virtual reality for fire evacuation research. In *2014 federated conference on computer science and information systems*, pages 313–321, 2014.

[11] Nikolai WF Bode and Edward A Codling. Human exit route choice in virtual crowd evacuations. *Animal Behaviour*, 86(2):347–358, 2013.

[12] Max Kinateder, Brittany Comunale, and William H Warren. Exit choice in an emergency evacuation scenario is influenced by exit familiarity and neighbor behavior. *Safety science*, 106:170–175, 2018.

[13] Nikolai WF Bode, Jordan Miller, Rick O'Gorman, and Edward A Codling. Increased costs reduce reciprocal helping behaviour of humans in a virtual evacuation experiment. *Scientific reports*, 5(1):1–13, 2015.

[14] Nikolai WF Bode and Edward A Codling. Exploring determinants of pre-movement delays in a virtual crowd evacuation experiment. *Fire technology*, 55(2):595–615, 2019.

[15] Tingting Liu, Zhen Liu, Minhua Ma, Tian Chen, Cuijuan Liu, and Yanjie Chai. 3d visual simulation of individual and crowd behavior in earthquake evacuation. *Simulation*, 95(1):65–81, 2019.

[16] Craig W Reynolds et al. Steering behaviors for autonomous characters. In *Game developers conference*, volume 1999, pages 763–782, 1999.

[17] Keith C Clarke. Cellular automata and agent-based models. *Handbook of regional science*, pages 1217–1233, 2014.

[18] Rahim Alizadeh. A dynamic cellular automaton model for evacuation process with obstacles. *Safety Science*, 49(2):315–323, 2011.

[19] Edward A Codling, Michael J Plank, and Simon Benhamou. Random walk models in biology. *Journal of the Royal society interface*, 5(25):813–834, 2008.

[20] J Bellamy. Virtual experiment files. https://github.com/JackBellamy/EvacGame, 2023.

[21] Dictionary definition of arousal. https://www.collinsdictionary.com/dictionary/english/arousal#:~:text=Arousal%20is%20a%20state%20in,reaction%20More%20Synonyms%20of%20arousal. Accessed 2022-10-04.

[22] Rüdiger Schmitt-Beck. Bandwagon effect. *The international encyclopedia of political communication*, pages 1–5, 2015.

[23] Yanghui Hu and Nikolai WF Bode. A systematic review and meta-analysis on the effect social groups have on the egress times of pedestrian crowds. *Transportmetrica A: transport science*, pages 1–20, 2021.

[24] Monya Baker. Reproducibility crisis. *Nature*, 533(26):353–66, 2016.

Appendix

A Wall Matrix

Shows the wall matrix of the model, where the wall cells are represented as 0 and the empty cells are represented as 1 to form a binary matrix.

$$
\begin{bmatrix}
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 0 & 0 & 0 & 0 & 1 & 1 & 1 & 0 & 1 & 1 & 0 & 1 & 1 & 0 \\
0 & 1 & 1 & 0 & 1 & 1 & 1 & 1 & 0 & 0 & 1 & 0 & 1 & 0 & 1 & 1 & 1 & 0 & 1 & 1 & 1 & 0 \\
0 & 1 & 1 & 0 & 1 & 0 & 0 & 0 & 0 & 1 & 1 & 0 & 1 & 0 & 1 & 0 & 1 & 1 & 1 & 1 & 1 & 0 \\
0 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 0 & 1 & 0 & 0 & 0 & 0 & 1 & 0 & 1 & 0 & 0 & 1 & 1 & 0 \\
0 & 1 & 1 & 0 & 0 & 0 & 0 & 1 & 0 & 1 & 0 & 1 & 1 & 1 & 1 & 0 & 0 & 0 & 1 & 1 & 1 & 0 \\
0 & 1 & 1 & 1 & 1 & 1 & 0 & 1 & 0 & 1 & 0 & 0 & 1 & 0 & 1 & 0 & 1 & 1 & 1 & 1 & 1 & 0 \\
0 & 1 & 1 & 0 & 0 & 1 & 0 & 1 & 1 & 1 & 1 & 0 & 1 & 0 & 1 & 1 & 1 & 0 & 0 & 1 & 1 & 0 \\
0 & 1 & 1 & 0 & 1 & 1 & 1 & 1 & 0 & 0 & 1 & 0 & 1 & 0 & 0 & 1 & 0 & 0 & 1 & 1 & 1 & 0 \\
0 & 1 & 1 & 0 & 1 & 0 & 0 & 1 & 1 & 0 & 1 & 1 & 1 & 1 & 0 & 1 & 1 & 1 & 1 & 1 & 1 & 0 \\
0 & 1 & 1 & 0 & 1 & 1 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 1 & 1 & 0 \\
0 & 1 & 1 & 0 & 0 & 1 & 1 & 0 & 1 & 1 & 1 & 1 & 0 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 0 \\
0 & 1 & 1 & 1 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 1 & 0 & 0 & 1 & 1 & 0 \\
0 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 0 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 0 & 1 & 1 & 0 \\
0 & 1 & 1 & 0 & 0 & 0 & 1 & 0 & 0 & 1 & 0 & 1 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 1 & 1 & 0 \\
0 & 1 & 1 & 1 & 1 & 0 & 1 & 1 & 0 & 1 & 0 & 1 & 0 & 1 & 1 & 1 & 1 & 1 & 0 & 1 & 1 & 0 \\
0 & 1 & 1 & 1 & 0 & 0 & 1 & 0 & 0 & 1 & 1 & 1 & 1 & 1 & 0 & 1 & 0 & 1 & 1 & 1 & 1 & 0 \\
0 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 0 & 1 & 0 & 0 & 1 & 0 & 0 & 1 & 1 & 1 & 0 & 1 & 1 & 0 \\
0 & 1 & 1 & 0 & 0 & 0 & 0 & 1 & 1 & 1 & 1 & 0 & 1 & 0 & 1 & 1 & 0 & 1 & 0 & 1 & 1 & 0 \\
0 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 0 & 0 & 1 & 1 & 1 & 1 & 1 & 0 & 0 & 1 & 1 & 1 & 1 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0
\end{bmatrix}
$$

B Floor field matrix

Shows the floor field matrix of the model, where the wall cells are represented as 0 and the empty cells are assigned a value between 0.1 and 1, cells with the value of 1 are known as the target cells as they have the highest value. This was done to create a gradient of increasing values towards the target cells for the agents to navigate.

$$
\begin{bmatrix}
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0.100 & 0.137 & 0.122 & 0.115 & 0.153 & 0.189 & 0.226 & 0 & 0 & 0 & 0 & 0.263 & 0.226 & 0.189 & 0 & 0.799 & 0.784 & 0 & 1 & 1 & 0 \\
0 & 0.137 & 0.152 & 0 & 0 & 0 & 0 & 0.242 & 0.279 & 0.316 & 0.331 & 0.316 & 0.279 & 0 & 0 & 0 & 0.837 & 0 & 0 & 1 & 1 & 0 \\
0 & 0.174 & 0.189 & 0 & 0.263 & 0.248 & 0.211 & 0.226 & 0 & 0 & 0.368 & 0 & 0.263 & 0 & 0.780 & 0.837 & 0.874 & 0 & 0.963 & 1 & 1 & 0 \\
0 & 0.189 & 0.226 & 0 & 0.300 & 0 & 0 & 0 & 0 & 0.420 & 0.405 & 0 & 0.226 & 0 & 0.784 & 0 & 0.889 & 0.926 & 0.963 & 1 & 1 & 0 \\
0 & 0.205 & 0.242 & 0.279 & 0.316 & 0.353 & 0.390 & 0.405 & 0 & 0.457 & 0 & 0 & 0 & 0 & 0.747 & 0 & 0.874 & 0 & 0 & 1 & 1 & 0 \\
0 & 0.211 & 0.248 & 0 & 0 & 0 & 0 & 0.442 & 0 & 0.494 & 0 & 0.658 & 0.695 & 0.732 & 0.747 & 0 & 0 & 0 & 0.963 & 1 & 1 & 0 \\
0 & 0.226 & 0.263 & 0.300 & 0.337 & 0.353 & 0 & 0.479 & 0 & 0.531 & 0 & 0 & 0.680 & 0 & 0.784 & 0 & 0.889 & 0.926 & 0.963 & 1 & 1 & 0 \\
0 & 0.211 & 0.248 & 0 & 0 & 0.390 & 0 & 0.494 & 0.531 & 0.569 & 0.584 & 0 & 0.643 & 0 & 0.800 & 0.837 & 0.874 & 0 & 0 & 1 & 1 & 0 \\
0 & 0.196 & 0.211 & 0 & 0.368 & 0.405 & 0.442 & 0.479 & 0 & 0 & 0.621 & 0 & 0.673 & 0 & 0 & 0.837 & 0 & 0 & 0.963 & 1 & 1 & 0 \\
0 & 0.159 & 0.174 & 0 & 0.353 & 0 & 0 & 0.442 & 0.427 & 0 & 0.636 & 0.673 & 0.710 & 0.726 & 0 & 0.852 & 0.889 & 0.926 & 0.963 & 1 & 1 & 0 \\
0 & 0.168 & 0.183 & 0 & 0.316 & 0.316 & 0 & 0 & 0.390 & 0 & 0 & 0 & 0 & 0.763 & 0 & 0 & 0 & 0 & 0 & 1 & 1 & 0 \\
0 & 0.205 & 0.220 & 0 & 0 & 0.353 & 0.368 & 0 & 0.353 & 0.337 & 0.300 & 0.263 & 0 & 0.778 & 0.815 & 0.852 & 0.889 & 0.926 & 0.963 & 1 & 1 & 0 \\
0 & 0.220 & 0.257 & 0.294 & 0 & 0 & 0.405 & 0 & 0 & 0 & 0 & 0 & 0 & 0.763 & 0 & 0 & 0.874 & 0 & 0 & 1 & 1 & 0 \\
0 & 0.236 & 0.272 & 0.309 & 0.346 & 0.383 & 0.420 & 0.457 & 0.494 & 0.510 & 0 & 0.673 & 0.710 & 0.747 & 0.784 & 0.821 & 0.837 & 0.821 & 0 & 1 & 1 & 0 \\
0 & 0.220 & 0.257 & 0 & 0 & 0 & 0.405 & 0 & 0 & 0.547 & 0 & 0.658 & 0 & 0 & 0.784 & 0 & 0 & 0 & 0 & 1 & 1 & 0 \\
0 & 0.226 & 0.263 & 0.279 & 0.263 & 0 & 0.390 & 0.374 & 0 & 0.583 & 0 & 0.658 & 0 & 0.763 & 0.800 & 0.837 & 0.874 & 0.911 & 0 & 1 & 1 & 0 \\
0 & 0.242 & 0.279 & 0.316 & 0 & 0 & 0.427 & 0 & 0 & 0.599 & 0.636 & 0.673 & 0.710 & 0.747 & 0 & 0.821 & 0 & 0.926 & 0.963 & 1 & 1 & 0 \\
0 & 0.257 & 0.294 & 0.331 & 0.368 & 0.405 & 0.442 & 0.479 & 0 & 0.584 & 0 & 0 & 0.695 & 0 & 0 & 0.837 & 0.874 & 0.911 & 0 & 1 & 1 & 0 \\
0 & 0.242 & 0.279 & 0 & 0 & 0 & 0 & 0.494 & 0.531 & 0.569 & 0.606 & 0 & 0.680 & 0 & 0.784 & 0.821 & 0 & 0.911 & 0 & 1 & 1 & 0 \\
0 & 0.257 & 0.294 & 0.331 & 0.368 & 0.405 & 0.442 & 0.479 & 0 & 0 & 0.621 & 0.658 & 0.695 & 0.732 & 0.769 & 0 & 0 & 0.926 & 0.963 & 1 & 1 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0
\end{bmatrix}
$$

C Participant Information Sheet

Participant Information Sheet

Project title: A Virtual Experiment to Investigate Habituation to Fire Drills

Invitation paragraph
I would like to invite you to participate in my research project. Before you consider participating I would like you to understand why the research is being completed and what would occur if you partake. Feel free to ask me questions at any point to help give you a clear understanding.

What is the purpose of the project?
My project involves a virtual experiment to test for habituation in fire drills for my dissertation for a BA degree. Habituation is a form of non-associative learning where a response to a stimulus decreases with repeated exposure to that stimulus. In my study the stimulus could be seen as the sound of a fire alarm and how people do not react to them anymore which is obviously not desirable.

Why have I been invited to participate?
You have expressed your interest in taking part following our initial informal contact. You have normal or corrected to normal vision and you can use a computer keyboard to complete simple interactive tasks. I aim to recruit around 30 participants in total for my study.

Do I have to take part?
It is completely up to you if you wish to participate in my experiment. I will describe the study, give you a copy of this information sheet and a consent form. Feel free to ask me questions and you can decide to withdraw at any time without giving any reasons.

What will happen to me if I take part and what will I have to do?
If you decide to participate in the experiment, you will have to sign a consent form. The *personal information* you provide on this form (signature) will be kept separate from the *study data*.
The experiment will take roughly 5 mins to complete. It consists of a solo computer-based task (think: simple computer game) where you will control a pedestrian inside a square building. You will have to move from one side of the maze to the other side as quickly as possible using the arrows on the keyboard to steer your avatar. This will be repeated 5 times. There is no time cut-off. After completing this 5 times there will be a questionnaire of 6 questions to fill out with 1 to 2 word answers. The questionnaire does not ask for confidential information from you. The *study data* collected will be your actions inside the simple computer game (e.g. what path you take in the maze) and your answers in the questionnaire. This data will be saved under a file name that is not linked to your consent form. Withdrawal from the study after completion will thus only be possible if you keep a note of the time and day of your participation, or of the file names used to save your study data. Consent forms will be kept in a locked cabinet and will be destroyed on completion of data collection and at the latest on the 14th of April 2023. This date is also the latest possible date for you to withdraw your data.
The study data will be deleted when I complete my course and at the latest on 14th April 2024.

What are the possible disadvantages and risks involved in taking part in the project?
There are no risks beyond what is inherent in everyday activities for participating in this experiment.

What are the possible benefits of taking part?
There are no direct benefits for participating in this experiment. You will be helping me complete my course and contribute to research into human behaviour in fire drills.

Will my participation in this project be kept confidential?
Yes, as described above.

What will happen to the results of the research project?
Information extracted from the study data, such as a statistical analysis of participant behaviour in the game, will be included in my dissertation and if asked I will send a copy of my dissertation when completed.

Who is organising and funding the research?
This is part of the Department of Engineering Mathematics, the name of my course is Engineering Mathematics. There is no funding for this research.

Who has reviewed the study?
My supervisor from the Department of Engineering Mathematics (Nikolai Bode). This study has been approved by the Engineering Faculty Research Ethics Committee at the University of Bristol.

Further information and contact details
My name is Jack Bellamy, email: cc20444@bristol.ac.uk

If participants have any concerns related to their participation in this study please direct them to the Faculty of Engineering Research Ethics Committee, via Liam McKervey, Research Governance and Ethics Officer (Tel: 0117 331 7472 email: Liam.McKervey@bristol.ac.uk)

Figure 11: Participant Information Sheet

D Consent Form

Department of Engineering Mathematics
Jack Bellamy
cc20444@bristol.ac.uk

University of BRISTOL

CONSENT FORM

A Virtual Experiment to Investigate Habituation to Fire Drills

Please answer the following questions to the best of your knowledge

	YES	NO
DO YOU CONFIRM THAT YOU:		
• have not taken part in this experiment before?	☐	☐
• allow the results to be used to in the research of habituation?	☐	☐
HAVE YOU:		
• been given information explaining about the study?	☐	☐
• had an opportunity to ask questions and discuss this study?	☐	☐
• received satisfactory answers to all questions you asked?	☐	☐
• received enough information about the study for you to make a decision about your participation?	☐	☐
DO YOU UNDERSTAND:		
that you are free to withdraw from the study and free to withdraw your data prior to final consent		
• at any time?	☐	☐
• without having to give a reason for withdrawing?	☐	☐

I hereby fully and freely consent to my participation in this study

I understand the nature and purpose of the procedures involved in this study. These have been communicated to me on the information sheet accompanying this form.

I understand and acknowledge that the investigation is designed to promote scientific knowledge and that the University of Bristol will use the data I provide for no purpose other than research.

I understand the data I provide will be **anonymous**. No link will be made between my name or other identifying information and my study data.

Participant's signature: ______________________________ Date: ______________

If you have any concerns related to your participation in this study please direct them to the Faculty of Engineering Human Research Ethics Committee, via Liam McKervey, Research Governance and Ethics

Figure 12: Consent Form

E Questionnaire

Virtual Experiment Questionnaire

Participant number	
Age	
Gender (male/female/other)	
What colour were the other agents?	
How many other agents were there?	
How many possible exits were there?	
Did you feel like you were in the experiment? (yes/no)	
Did you get bored? (yes/no) If so which round did it occur? (1/2/3/4/5)	
Gaming experience (scale of 1-10) (1 being phone only, 10 being pc gamer)	
Do you consent to the experiment data being used? (yes/no)	
Do you consent to the questionnaire data being used? (yes/no)	

Figure 13: Participant Questionnaire