Pedestrian trajectories on a 90° turn in a corridor:

A non-immersive virtual reality study.

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The present project replicates in a non-immersive Virtual Reality experiment referred to as Single VR experiment, a laboratory experiment by Keip & Ries (2009). People walked alone through a corridor with a 90° turn. This laboratory study is considered . Additionally, a second VR experiment (Multi VR experiment) examined how the presence of virtual agents (VA) in the virtual environment (VE) could influence individuals' travel path.

The trajectories obtained by Keip & Ries (2009) and the Single VR experiment were compared. The results showed certain similarities between both experiments concerning the travel path pattern. Differences were also identified, as individuals were more prone to walk closer to the inner wall after the corner in the Laboratory experiment. Furthermore, signs of social influence were difficult to observe in the Multi VR experiment.

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Resumen

Cuando ocurre una emergencia, pueden surgir cuellos de botella en las esquinas de los corredores. Por lo tanto, es importante comprender cómo las personas se mueven a través de geometrías complejas durante la evacuación para mejorar los diseños arquitectónicos. La Realidad Virtual (RV) es una herramienta versátil utilizada para estudios de evacuación, ya que permite replicar rutas de evacuación fácilmente y ofrece altos niveles de control experimental. Estas ventajas son útiles para estudiar las trayectorias de los peatones, que son particularmente cruciales en el contexto de evacuaciones en situaciones emergencia. Sin embargo, los esfuerzos de validación de esta herramient aún están en curso. Por lo tanto, comparar los resultados de los experimentos de laboratorio con los resultados de los experimentos de realidad virtual es una forma de estudiar la validez de esta herramienta como método de investigación.

El presente proyecto replica en un estudio de Realidad Virtual no inmersiva un experimento de laboratorio desarrollado por Keip & Ries (2009), donde las personas caminaban solas por un corredor con un giro de 90 ° en una esquina. Esta replica en el ambiente virtual se catalogó como Single VR experiment. Además, un segundo experimento de realidad virtual (Multi) examinó cómo la presencia de agentes virtuales (AV) en el entorno virtual (EV) podría influir en las trayectorías de los participantes.

Se compararon las trayectorias obtenidas en el experimento de laboratorio(Keip & Ries, 2009) y el experimento Single. Los resultados mostraron ciertas similitudes entre ambos experimentos con respecto al patrón de las trayectorías. También se identificaron diferencias, ya que los individuos eran más propensos a caminar más cerca de la pared interior después del giro en el experimento de laboratorio. Además, los signos de influencia social fueron difíciles de observar en el experimento Multi.

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List of abbreviations

CAVE	Cave Automatic Virtual Environment
CSV	Comma-Separated Values
SG	Serious Game
VE	Virtual Environment
VA	Virtual Agent
VR	Virtual Reality

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1 Introduction

It is known that different types of events can bring together a large number of people inside infrastructures. For this reason, ensuring the safe evacuation of the people in an emergency is of paramount importance. Consequently, pedestrian walking characteristics need to be analyzed and understood to improve architectural designs and management strategies to provide the safety and efficiency of crowd dynamics (Dias, Ejtemai, Sarvi, & Shiwakoti, 2014).

There have been theoretical and empirical studies, e.g., mathematical simulation models (Steffen & Seyfried, 2009) and empirical studies on crowd dynamics (Shiwakoti, Sarvi, Rose, & Burd, 2011; Haghani & Sarvi, 2018) which focus on the behavior of crowds. However, there is still a lack of research highlighting solo walking characteristics, especially when pedestrians walk through complex geometries in evacuation routes, such as corners, where bottlenecks could emerge when an emergency occurs (Dias, Abdullah, Sarvi, Lovreglio, & Alhajyaseen, 2019). It is important to understand solo walking characteristics because people are not always interacting with others when evacuating or just in normal situations. Then, the comprehension of individuals movements could be used to simulate walking paths realistically in pedestrian simulation models, where there are not group interactions

Dias et al. (2014b) already performed a series of laboratory experiments to analyze solo walking characteristics of pedestrians through angled corridors. Keip & Ries(2009) also carried out experimental research to develop a model to predict the dynamics of the flow of people, where one of the experiments focus on solo walking. However, it is still a challenge to obtain data related to solo walking.

Virtual Reality (VR) has become a versatile tool used for evacuation research, which can complement laboratory studies to analyze solo walking characteristics. VR has been defined as a "real or simulated environment in which the perceiver experiences telepresence" (Steuer, 1992). The concept is expansive, but for the purposes of this project, VR is an environment created by using computer technology. VR can be classified as immersive or non-immersive (Rahouti & Lovreglio, 2021) depending of the level of immersion provided. Immersive VR uses head-mounted displays that allow the participants to feel the virtual environment (VE) more realistically. Non-immersive VR (the less immersive application of VR techniques) which is considered in this study, uses a computer screen to expose the participants to a VE. An immersive VR experiment was the preferred approach for this study, but due to safety concerns during the covid pandemic, non-immersive VR was necessary.

VR experiments allow easy replications and provide experimental control as other established research methods (Kinateder, Ronchi, et al., 2014). Additionally, it does not imply ethical restrictions, and it has logistic and economic advantages (Ronchi et al., 2015). VR experiments could realistically replicate evacuation routes to study pedestrian trajectories which are particularly crucial in emergency evacuations. Despite the advantages of VR experiments, validation efforts are still ongoing as the pedestrian trajectories in VR may differ in a real evacuation scenario (Ronchi et al., 2015). One procedure to check the validity of data is to compare outcomes (Arias, Nilsson, & Wahlqvist, 2020) of the VR experiments to existing models or to the results of previous laboratory experimental studies.

Additionally, VR can be used to study individuals' phychological processes when making decisions in a VE. Then, the theory of social influence (Deutsch & Gerard, 1955) wich states that individuals behavior is impacted by how others behave can be analized in VR experiments as has been done in previous studies (Kinateder et al., 2014a; Kinateder et al., 2014b).

1.1 Purpose and objectives

The main objective of this project is to replicate the laboratory experiment EOF-300-1 by Keip & Ries (2009) in a non-immersive VR experiment called "Single VR experiment" and compare the trajectories collected in each. For simplicity, in this document, the non-immersive VR experiments will be referred to as the "VR experiment". Both Laboratory and Single VR experiments focus on solo walking behavior as it could be practical to understand and examine the trajectories of individuals moving through 90° turning corridors.

In a second version, the VR experiment will include three virtual agents, which will emulate the presence of other players who will follow a different trajectory than that produced in the laboratory experiment. This modification from the original laboratory study is done with the goal to determine whether the trajectory of the participant is affected by the presence of virtual agents in the virtual environment (VE). This version of the VR experiment is here called "Multi VR experiment".

The addition of virtual agents will allow observing if participants are also affected by social influence in the virtual environment, as individuals usually are in other experimental studies (Deutsch & Gerard, 1955). The concrete objectives for the study are presented below.

- To determine the pedestrian trajectories through a 90° turning corridor in a VR experiment.
- To assess how well the VR experiment can reproduce the laboratory study results regarding walking paths.
- To observe if social influence affects the participants' walking paths in the virtual environment.

1.2 Methodology

This project was divided into three stages to pursue the objectives proposed, namely literature review, non-immersive VR experiment, and data analysis. First, a literature review was performed where aspects about virtual reality, social influence, and laboratory experiments about pedestrian trajectories around corners were studied. Consequently, and based on the knowledge acquired in this stage, the design and setup of the virtual experiments were performed. After executing the VR experiments, the results were analyzed and discussed.

1.2.1 Literature review

The literature review focused on three main topics, laboratory experiments and models of pedestrian trajectories through 90° turning corridors to understand people's trajectories when they face corners. Also, the description of the experiment EOF-300-1 (Keip & Ries, 2009) was presented within this stage.

Consequently, it was needed to collect information about the novel research tool virtual reality, where different studies were analyzed to support the research. Finally, a description of social influence in people's behavior was shown. This literature review will help the reader to understand the nature of this research.

Approximately 46 papers related to the topics mentioned above were collected. The papers were found by using keywords to search on the web for relevant publications, such as Google Scholar, Lund University Libraries search motor and international journals. The keywords used were: trajectories, turning movements, virtual reality, validation, social influence, corridors, evacuation, etc. The 46 papers were filtered according to their relevance on the study and some were discarded. Then, in total, 26 publications were found relevant for the purposes of this project.

1.2.2 Non-immersive VR experiments.

The Non-immersive VR experiments considered in this study exposed the participants to the VE through a computer screen. Participants moved through the VE using a mouse and keyboard. The layout used in the laboratory study EOF-300-1 (Keip & Ries, 2009) was replicated in VR. The virtual environment was developed in a 3D modeling software. The geometry was modeled in Blender, a free and open-source 3D creation suite (Blender,2021). The game engine software Unity 3D ("Unity - Game Engine," 2021) was used to develop the game.

Two experiments were performed using the same virtual environment. In the Single VR experiment, 60 participants navigated alone through the VE. In the Multi VR experiment, three virtual agents were present in the VE following a specific walking path ahead of the participant; 60 participants were part of the Multi VR experiment.These two samples were likely different from each other.

The samples for the VR experiments were selected by increasing the size of the sample used in the laboratory experiment, where 28 Participants were present. By increasing the size of the sample, the results may not be questionable if a statistical analysis is intented to be performed in future research. Additionally, as the VR experiments were available online, more participants could be recruited as they could be part of the study from home.

1.2.3 Data analysis

At the beginning of the VR experience, they were asked questions about their age, nationality, gender, and country of residence. A CSV file was generated for each participant, which logged the coordinates of their trajectories, and the information that was collected before starting the experiment. The files were then downloaded and safely stored. The data was then analyzed.

The trajectories obtained in the Single VR experiment were then compared with the results obtained in the laboratory experiment (Keip & Ries, 2009). Additionally, the walking paths registered in the Multi-version were compared to the results of the Single VR experiment and analyzed based on the general theory of social influence (Deutsch & Gerard, 1955).

1.3 Limitations

- The information available from the Hermes project (Keip & Ries, 2009) does not provide specific information regarding the environment where the experiments took place, such as the height of the walls and ceiling and its materials. Therefore, some assumptions were required to simulate the space in a non-immersive VE. Also, the characteristics of the participants of the laboratory experiment are not described in detail. Hence, there may be some discrepancies in the results between the Laboratory and the VR experiments.

- Kobes (2010) recommends using a joystick in non-immersive VR experiments when it cannot be ensured that participants can operate the equipment comfortably and therefore move as naturally as they would in reality. Unfortunately, the restrictions during the pandemic required participants to join from their own home, and a joystick could not be required nor provided. Therefore, some participants may have problems moving around the VE, and their trajectories may be affected.

- The VR experiments presented here are not intended to collect data on the movement speed of participants walking through the corridors as it was set as constant for simplicity.

2 Literature Review

2.1 Pedestrian trajectories through 90° turning corridors

Bottlenecks can emerge in transition points in buildings, where the terrain or geometry changes. Examples of these transition points are stairs, doors, and corner. These bottlenecks can occur both in emergencies or everyday situations (Shiwakoti et al., 2011).

Therefore, it is essential to understand how people interact with geometries such as corners to improve architectural design and optimize the flow of people towards an exit. The majority of studies focus on the behavior of crowds, but there are not as many studies focusing on solo walking (Dias et al., 2014b).

Some experiments were performed to analyze solo walking characteristics of people moving through corridors (Dias et al., 2014b). The corridors which were tested had turns with different angles (45°,60°,90°,135°, and 180°), and they were built using tape and safety barriers. Thus, the participants could easily be recorded on video. Additionally, different speed levels were analyzed to identify how the walking characteristics could change. First, participants were told to walk at their normal speed. The results showed that the speed was between 1.10 to 1.70 m/s. Then, they needed to walk somewhat faster (1.75 to 2.25 m/s). Lastly, they were requested to run slowly (2.50 to 3.50 m/s).

The results suggested that participants did not change their direction straightaway when approaching the turning point. Instead, they changed their walking direction sequentially ahead of it. Dias et al. (2014b) identified that segment as "curved path". Additionally, two more segments were identified by Dias et al. (2014b) in the participants' trajectories. First, a segment called "approaching", where individuals start walking until they reach the turn initiation point. Lastly, from the point where people finish turning to the end of the trajectory, it was described as "receding". The segments described above can be seen in Figure 1.

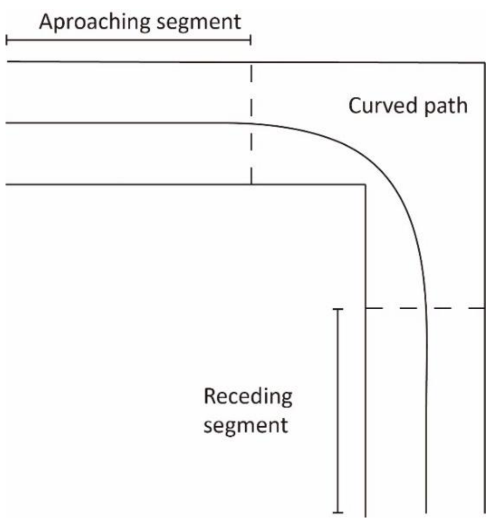


Figure 1. Trajectory segments identified by Dias et al. (2014b)

Besides experimental studies, which are important to gain more insight into human solo walking characteristics, some pedestrian simulation models (Dias et al., 2019; Steffen & Seyfried, 2009; Dias et al., 2014a) have been developed to reproduce walking behavior around angled corridors. Dias et al. (2019) proposed a mathematical algorithm to capture people's movement angled corridors. The results of the mathematical algorithm were validated with the experimental data collected in (Dias et al., 2014b). The predicted paths fit accurately within the trajectories registered in the experimental study for a 90° turning corridor, as seen in Figure 2.

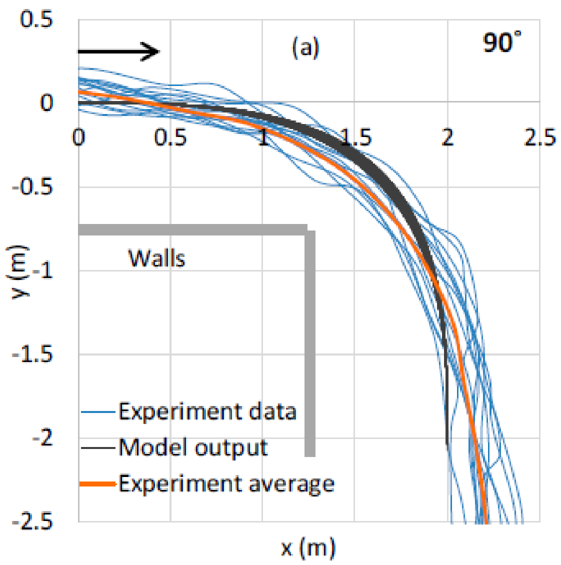


Figure 2. Trajectories of participants compared to predicted paths. Retrieved from (Dias et al., 2019)

Steffen and Seyfried (2009) performed a comparison of different applications of cellular automata (CA) discretized in space, analyzing 180° and 90° bends with varying corridor widths. Dias et al. (2014a) developed a modeling framework considering as (Dias et al., 2019) the experimental results in (Dias et al., 2014b).

2.1.1 Laboratory experiment

The controlled laboratory experiment to be replicated in this VR study is called EOF-300-1. The experiment is part of a series of experiments performed within the Hermes project (Keip & Ries, 2009). The EOF experiment (which stands for Ecke, Offen, Freie: corner, open, free in English) took place in May 2009 in a hall of the Düsseldorf exhibition center. 28 individuals participated in the experiment, which consisted of walking through a 90° turning corridor. They wore a white fabric hood with a black dot that allowed to track their trajectories from the top with video cameras. The hood and the corridor configuration of the experiment is illustrated in figure 3.

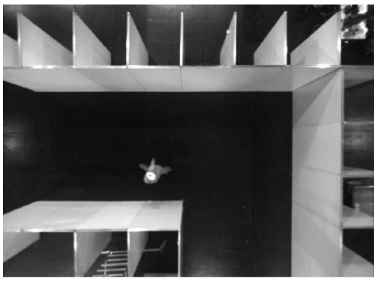


Figure 3. Participant in the corridor configuration wearing the white fabric hood. Retrieved from (Keip & Ries, 2009)

The geometry of the laboratory experiment included a waiting room where the participants were located before the experiment started. The waiting room had a 1.5 m wide opening connecting it to the 90° turning corridor, as shown in Figure 4. The corridor was 3.0 m wide before the corner and 3.6 m wide after it. The wallboards used to construct the corridor were made of white wallboards with metal straps.

Keip & Ries (2009) do not provide information about the design of the waiting room nor the instructions given to the participants. As seen in the video recordings of these experiments ("Pedestrian Dynamics Data Archive," 2009), the participants walked alone through the corridor at an average walking speed.

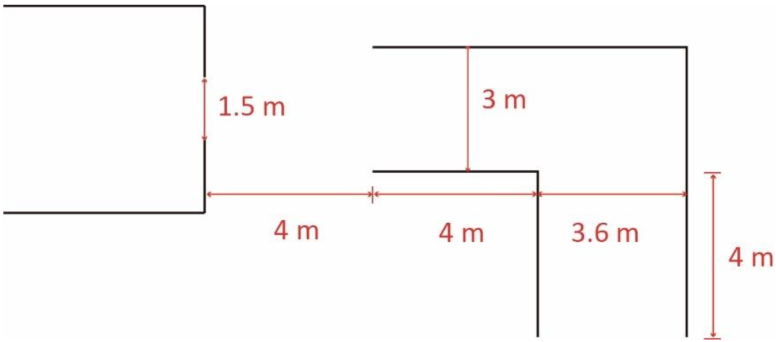


Figure 4. Geometry of the Laboratory experiment EOF-300-1. Taken from (Keip & Ries, 2009)

The experiment was recorded by using two wide-angle stereo cameras. For calculation purposes, everybody was assumed to be 180 cm tall (Steffen & Seyfried, 2009). To extract the camera data and converted it into trajectories, the software PetTrack was used(Boltes & Seyfried, 2013). The video recordings and the trajectories of the experiment are publicly available ("Pedestrian Dynamics Data Archive," 2009).

2.2 Virtual Reality

2.2.1 Definition

Virtual Reality (VR) has become a useful tool that allows to replicate scenarios and provides high levels of experimental control (Kinateder, Ronchi, et al., 2014), it offers a low level of risk to the participants, and it has logistic and economic advantages (Ronchi et al., 2015).

When the words Virtual Reality are mentioned, typically, people think of using computer-generated environments that require technology devices as head-mounted displays to interact within it. Nevertheless, the definition of Virtual Reality is more expansive, and it is not limited to the use of technology. It has been defined as a "real or simulated environment in which the perceiver experiences telepresence"(Steuer, 1992). Therefore, as Kinateder et al.(2014) mentioned, even real-world laboratories could be considered virtual environments because they give the feeling of being present in a created and controlled scenario, yet they are artificial setups. For purposes of this project, Virtual Reality is an environment created by using computer technology.

It was already mentioned how broad the definition of VR is. Similarly, the different types of VR systems that categorize the technology wide depend on the sense of immersion that provides (Costello, 1997). The parameters that influence the immersion are related to the level of interactivity, how complex the image is, the possibility of viewing the objects as three-dimensional. For instance, if a stereoscopic view is provided instead of a monoscopic view of the VE, the sense of immersion that the users feel will be higher (Costello, 1997).

Costello (1997) describes three main categories: Non-Immersive (Desktop) Systems (referred to as Non-immersive VR in this study), Semi-Immersive Projection Systems, and Fully Immersive Head-Mounted Display Systems. The first one refers to the less immersive application of VR techniques, where the users get access to the VE through a standard high-resolution monitor. Usually, the controlling devices to interact within the VE are keyboards, mice, and trackballs.

Semi-Immersive Projection Systems, as its name, can project the VE in either a large screen monitor, a large screen projection system, or multiple television projection systems. Thus, the feeling of immersion that the user faces increases. Lastly, the Fully Immersive Head-Mounted Display system is considered as the category that offers the highest immersion as head-mounted displays transfer images to the user through screens close to the user's eyes. The system can track the position of the head through sensors that permit the user to see and navigate through the VE.

2.2.2 VR validation: previous studies

One procedure to check validity of VR experiments is to compare outcomes of the VR experiments to existing models or to the results of previous laboratory experimental studies (Arias, Nilsson, et al., 2020). Kobes(2010) performed a validation of the use of a serious game called “ADMS-BART” for research into fire safety Psychonomics. The study's goal was to understand how people behave in evacuation scenarios and how the design of the building affected that behavior, specifically in wayfinding.

Kobes (2010) defined a serious game as a game that offers interactive simulation through the use of computer technology. An interactive simulation represents the role of the human being, and the environment which can be modified based on the user’s actions over time. On the other hand, Lovreglio et al. (2018) described that it is a game in which entertainment is not the goal; instead, it has educational purposes. The development of the serious game (Kobes, 2010) was based on a tested platform that is used for emergency training organizations called ADMS (Advanced Disaster Management Simulator) and BART (Behavioural Assessment and Research Tool).

The validation of the ADMS-BART serious game consisted of comparing the results of several evacuation experiments in three scenarios performed in a hotel with the results of the same experiment performed in a virtual replica of the real hotel. The scenarios were classified as basic (no smoke visible-exit signs at ceiling level - normal illumination level), smoke (smoke visible -exit signs at ceiling level - normal illumination level), and low exit sign (smoke visible-exit signs at floor level - normal illumination level). The virtual experiments took place in a room where a small screen of approximately 1.0 by 1.5 meters projected the game. The control device used to navigate around the virtual scenarios was a joystick, as shown in Figure 5.

Figure 5. Virtual experiment setup serious game. Retrieved from (Kobes, 2010)

After comparing the results of the real and virtual experiments and evidencing similar outputs between them, it was concluded that the serious game ADMS-BART could be considered valid as a research tool to analyze wayfinding behavior during fire evacuations in conditions with and without smoke(Kobes, 2010).

A different project attempted to validate a VR evacuation study, where unannounced evacuation experiments took place in a virtual replica of a high rise hotel building (Arias, Frantzich, Mossberg, Nilsson, & Wahlqvist, 2020). The results obtained in VR were then compared to a corresponding field experiment (Mossberg, Nilsson, & Andrée, 2020).

The field experiment was developed in 2018 in a hotel located in Stockholm. The hotel had two evacuation routes: one through elevators and the other through a staircase. The field experiment was based on a previous VR study (Andrée, Nilsson, & Eriksson, 2016) using the same building and a Cave Automatic Virtual Environment. This system projects the VE on three walls and the floor.

As the results found in Andrée et al. (2016) and the outcomes of Mossberg et al. (2020) were not in complete agreement, it was deemed relevant to test if an immersive VR approach using Head-Mounted Displays (HMD) would show different results. After comparing the outcomes of Arias et al. (2020) and Mossberg et al. (2020), it could be observed that experiments using immersive VR equipment gave similar results related to the selection of means of egress (using elevators or the staircase) as the results obtained from the field experiment.

More studies aim to contribute to the validation process of VR as a research tool to understand human behavior in emergencies. For instance, Arias et al. (2020) performed two virtual reality residential fire scenarios where participants were exposed to a fire in a virtual house. The sequence of their actions was analyzed, then the outcomes were compared to the general model of sequences of behavior developed in 1980 (Canter, Breaux, & Sime, 1980). Additionally, Rahouti & Lovreglio (2021) prototyped and validated a Non-Immersive Virtual Reality Serious Game for healthcare Fire Safety training.

Although the previous studies mentioned are VR experiments, the degree of validity is not necessarily the same, as the VR scenarios evaluated, and the VR technology used are different in each study. The road that needs to be walked to validate the VR as a research tool is still long. Thus, this project aims to walk some steps along with it by validating people's trajectories through 90° turning corridors in a VE.

2.3 Social Influence

An individuals' psychological processes are impacted by how others behave. This is called social influence. Deutsch & Gerard (1955) described two types of social influence: normative and informational social influence. Normative social influence is characterized as the individual' will to conform to the expectation of others. Thus, an individual tends to behave like the people around them, which means that they want to act as the group does, and they want to avoid standing out. Informational social influence refers to taking in information received from others to indicate the right thing to do. This means that if the others take specific actions, they may influence how people perceive the situation and how they behave.

According to Deutsch and Gerard (1955), the two kinds of social influence described usually are found together.

A set of unannounced evacuation experiments took place in a cinema theatre to analyze how others influenced the people during the initial phase of a fire evacuation (Nilsson & Johansson, 2009). Two cases were analyzed, case A, where the start of the evacuation was announced by using an alarm bell, and case B, where a pre-recorded message informed that a fire incident had occurred and gave instructions on how to evacuate.

It was observed that people tended to look at others before starting to move when the fire bell alarm rang and when the spoken message was played. This suggests that during the initial phase of a fire evacuation, people are influenced by others. Although for case A, participants looked at others for a longer time. This could be interpreted as social influence is stronger when the given information is limited or not clear enough. The results also indicated that the social influence is higher when the people around are close rather than when the people are farther (Nilsson & Johansson, 2009).

Other than in field experiments, social influence could be studied in VR experiments. A social influence study in a virtual tunnel fire was conducted (Kinateder et al., 2014a). Participants were placed in a VR smoke-filled tunnel with an emergency exit that they could see. Four experiments were considered to analyze social influence. One experiment consisted of the participant alone in the tunnel; the other three experiments placed a virtual agent (VA) into the experiment. The VA could move either to the emergency exit, in the opposite direction of the exit, or stay still. The VA was introduced to analyze how the behavior of the participants may be influenced considering its presence. The results showed that social influence was observed on the VE, and the influence could either have positive or negative effects.

3 Non-immersive VR experiments

3.1 Virtual environment design

The first step to develop the VE was to replicate the geometry of the 90° turning corridor described in the laboratory experiment (Keip & Ries, 2009). Videos from the laboratory experiment were watched to replicate the configuration of the corridor. The 3D model of the 90° turning corridor can be seen in Figure 6. The virtual environment was created using the game engine Unity 2019.4.21f1 (64-bit). Figure 7 shows the virtual environment.

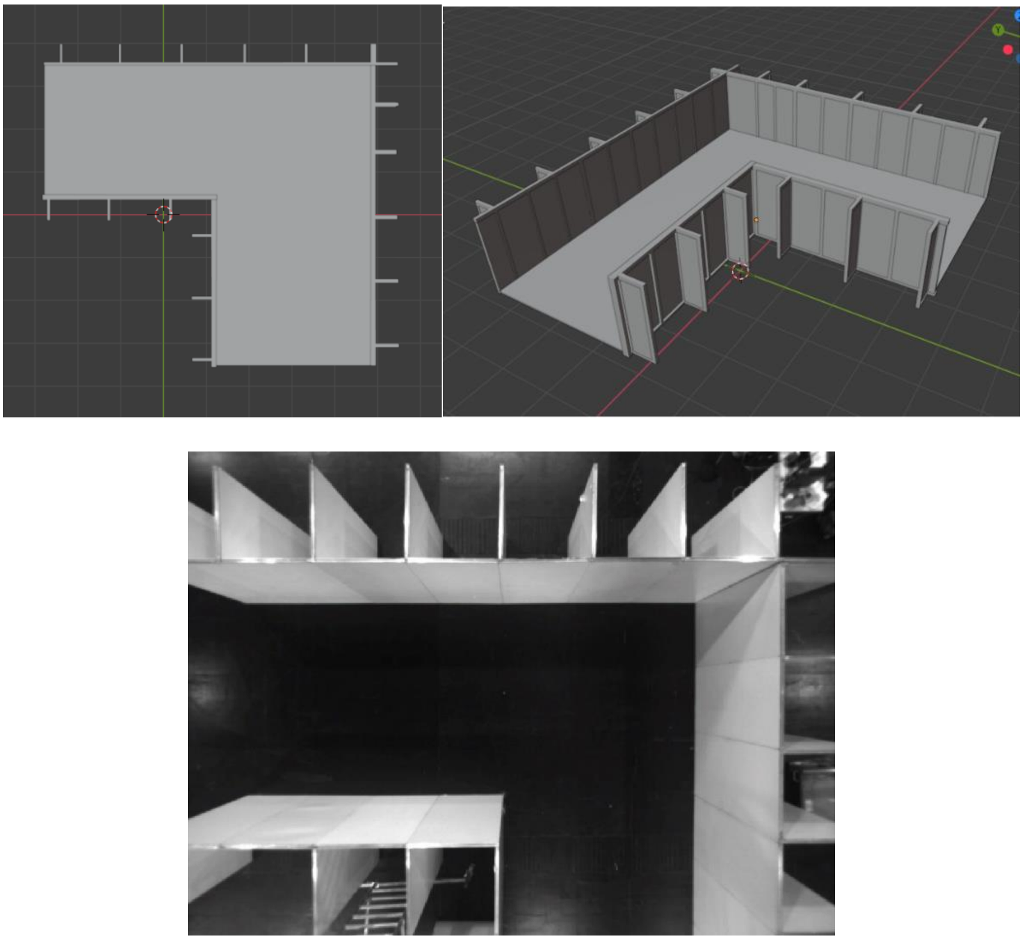
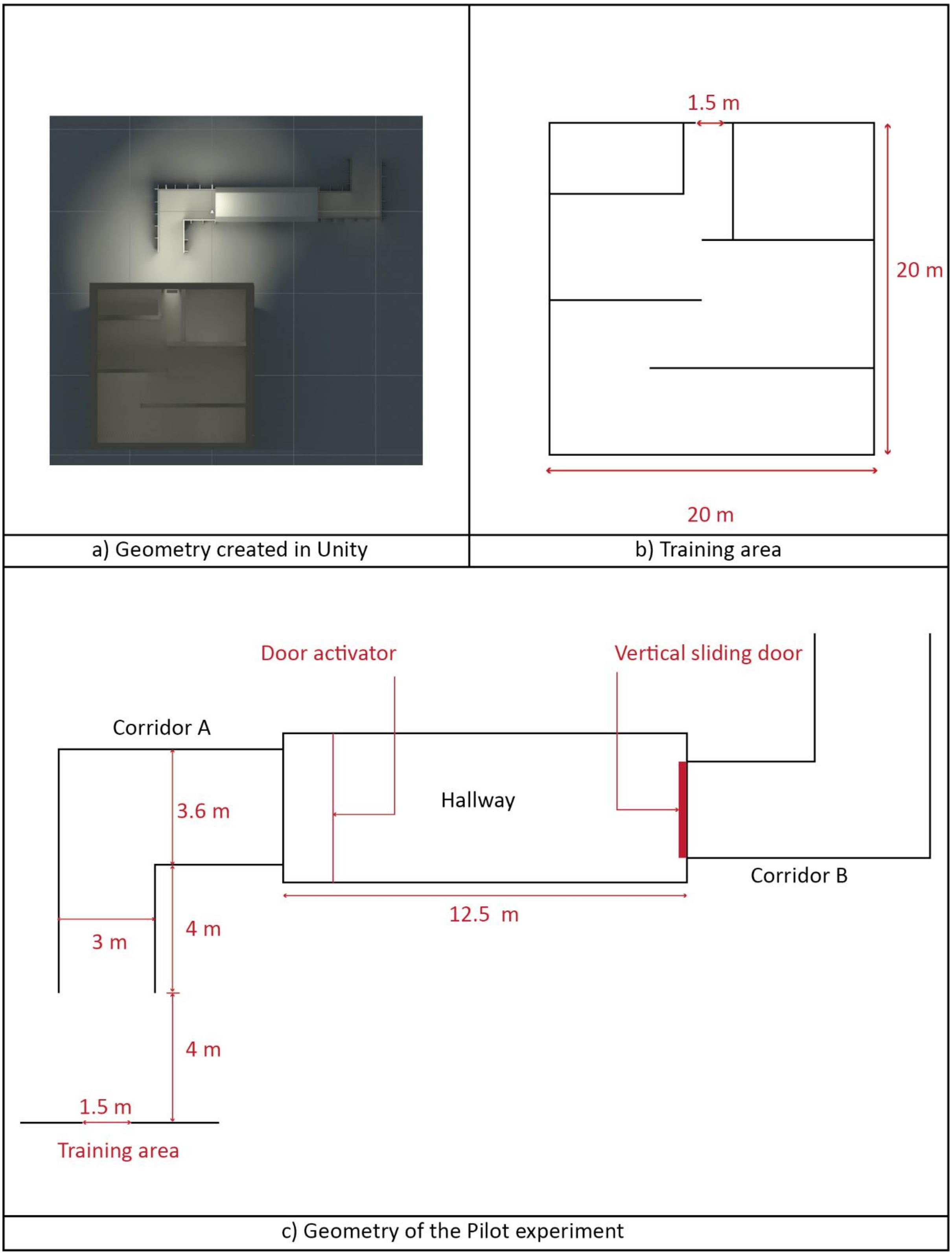


Figure 6. 90° turning corridor: Top(right-left) 3d model developed in Blender

EOF-300-1 Retrieved from ("Pedestrian Dynamics Data Archive," 2009)



a) Geometry created in Unity

b) Training area

c) Geometry of the Pilot experiment

Figure 7. Geometry of the pilot experiment

The VE was divided into 4 sections, as shown in Figure 7(a) and 7(c) above. Training area, corridor A, hallway, and corridor B. First, the training area of 20 m x 20 m was designed to train participants on how to move in the virtual environment and to allow them to try their movements before any data was collected. In this room, participants needed to find the exit by walking through the room. The configuration of the training area is illustrated in Figures 7(b) and 8.

The second section was defined as corridor A, which was the virtual replica of the corridor of the Laboratory experiment(Keip & Ries, 2009). Then the hallway section was a passage that connected corridor A with the last section, known as corridor B. Corridor B was a mirrored version of corridor A. Its purpose was to analyze whether making the participants walk through the corridor twice a learning effect could be achieved. It is essential to highlight how the users interacted within the training area, and the hallway was not considered for this project. Hence, any data was collected there.

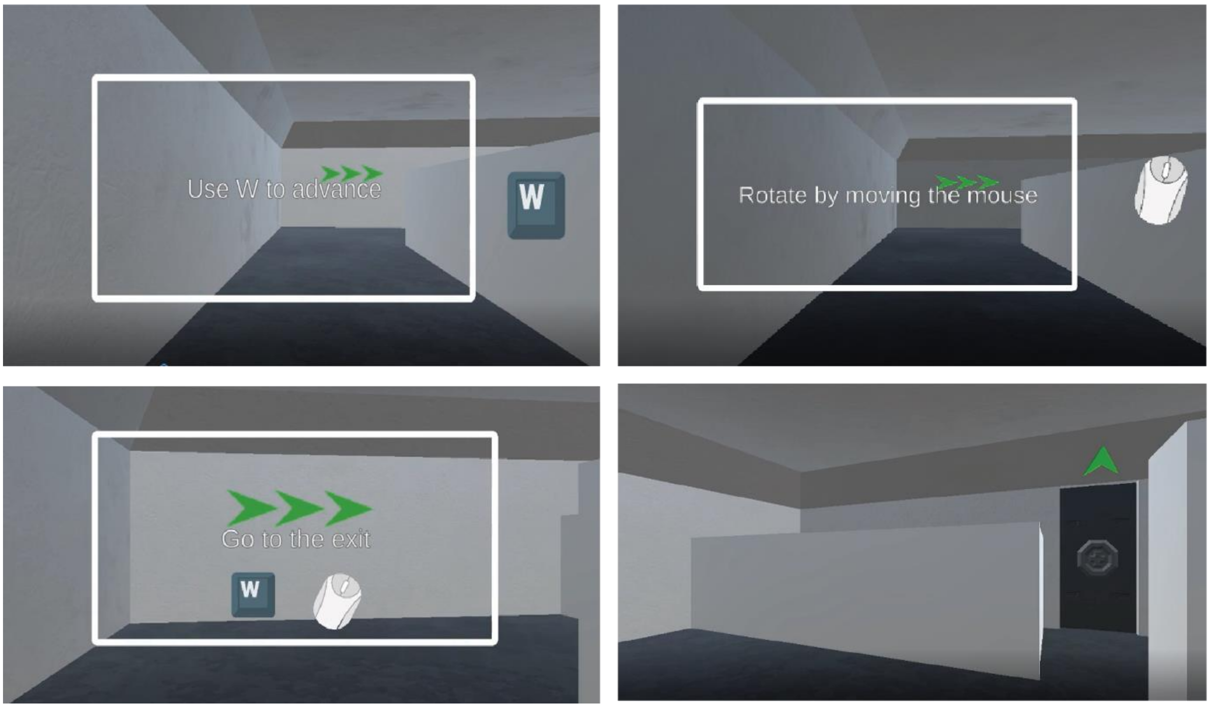


Figure 8. Training area with examples of the training instructions

3.2 Navigation

The camera position was defined as a first-person perspective (Rahouti & Lovreglio, 2021), which means that the player could see through the virtual character's eyes. Therefore, they could feel more immersed in the experiment as the camera view allowed them to feel like they had a virtual body. Participants moved through the VE using a keyboard and mouse. The walking speed was set to a constant speed of 1.4 m/s as it was the mean speed found in the laboratory experiment performed by Dias et al. (2019).

3.3 Pilot experiment

A set of pilot tests was conducted to detect failures in the VE design or the data collection method. Six volunteers were asked to try the VE. The only instruction given to them was that a serious game was being modeled to analyze how people interact in a VE.

When pilot testers reached the door from the training room, they read the instruction: “To start the experience, walk through the corridor in front of you. Other players may be present”. Once the door opened, they did not walk into the corridor. Instead, they started to look around the scenario, and some navigated within the space between the training area and corridor A, as shown in Figure 9.

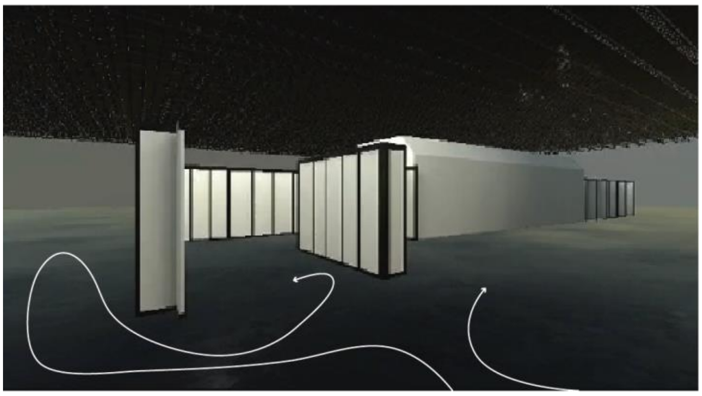
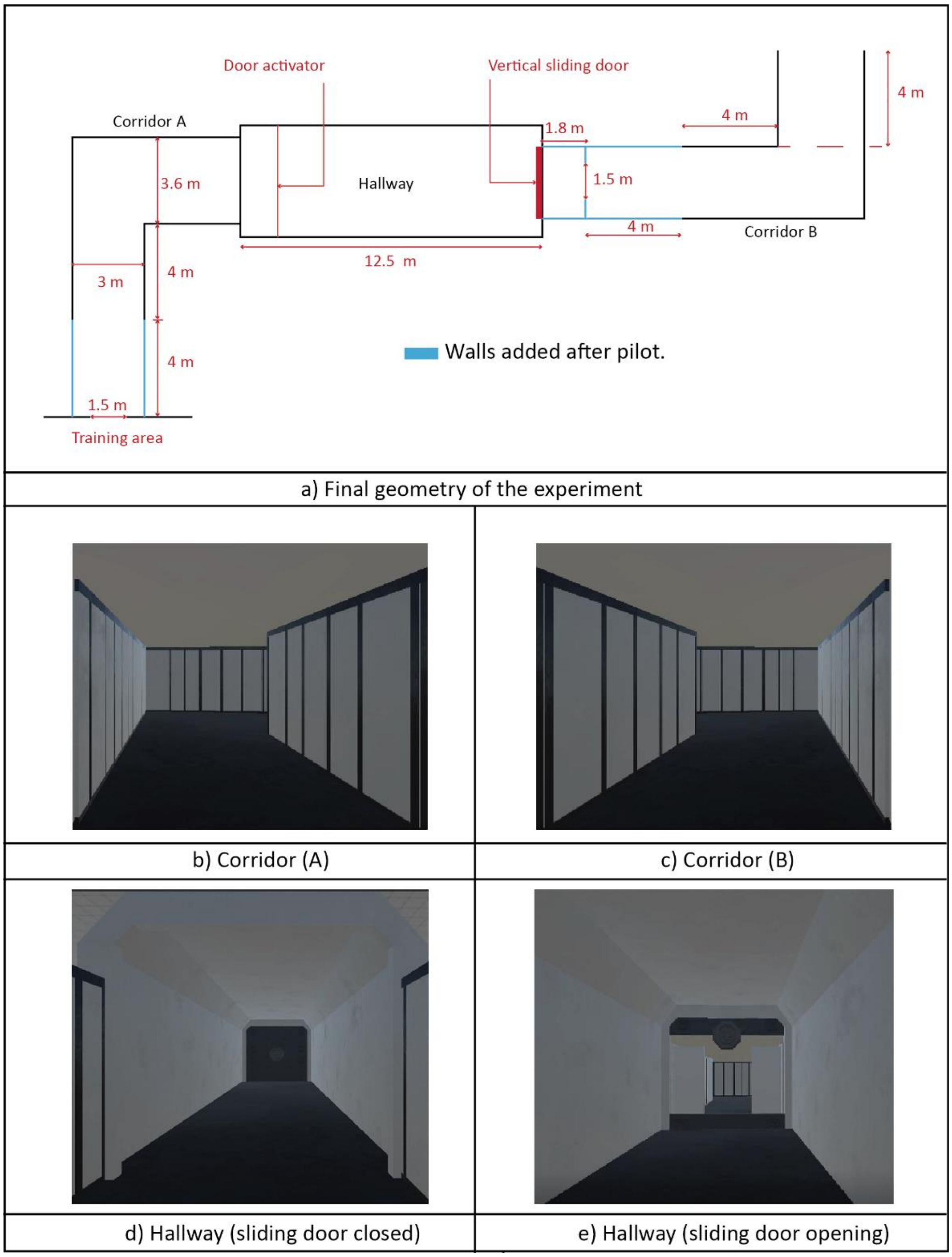


Figure 9. Representation of participants trajectories before reaching corridor A.

The behavior suggested that participants were tented to explore the VE. They hesitated about approaching the corridor. Hence, this open space could cause trouble in the VR experiments as participants may not navigate through the corridors as requested. Thus, to avoid the users navigating outside the corridors, the open space was closed by two walls, as shown in Figure 10.

As can be seen in Figures 10 (a), 10 (d) and 10(e). A sliding door connected the hallway with corridor B. The door remained closed to avoid influencing the participants to exit corridor A through a specific point. The door opened when participants reached the hallway, and they stepped over an activator. Additionally, an opening of 1.5 m was created after the sliding door. In that way, participants were going to emerge from the same point as they do it when leaving the training area's exit.



a) Final geometry of the experiment

b) Corridor (A)

c) Corridor (B)

d) Hallway (sliding door closed)

e) Hallway (sliding door opening)

Figure 10.Final geometry of the VR experiments

3.4 Single and Multi VR experiments

The research was divided into two VR experiments. One experiment was cataloged as “Single VR experiment ”, where participants navigated alone through the VE. The second one called “Multi VR experiment” where three virtual agents were present. They appeared when the door of the training area opened, and they were located at the entrance of corridor A. They moved with a trajectory close to the outer wall. Their pathways were different from the trajectories obtained in the Laboratory experiment (Keip & Ries, 2009), where it was noticed that the participants walked closer to the inner wall. The aim of adding the virtual agents was to analyze if their trajectories influence the pathways followed by the participants. The virtual agents kept a distance larger than 3 m from the participants. Virtual agents were programmed with a faster speed (1.6 m/s) than the player. Therefore, they never interacted directly with participants. Both scenarios can be seen in Figure 11.

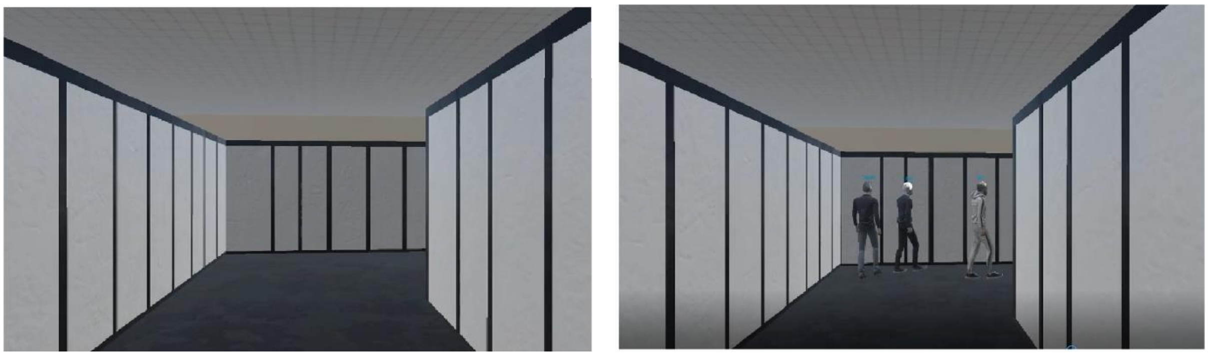


Figure 11. Left: Single VR experiment- Right: Multi VR experiment

3.5 Participants

A total of 120 participants took part in the VR experiments: 60 in the Single VR experiment and the other 60 in the multi-VR experiment. These two samples were likely different from each other. As the VR experiments were available online, it was possible to reach people from different parts of the world. Table 1 presents demographical information about participants. Table 2 presents data on the participants in each sample by country of residence and nationality

Table 1. Demographical information about participants.

	Gender		Age					
Sample	Female	Male	Min	Max	Mean	Std dev	Mode	Median
Single	19	41	18	60	32.83	8.58	35	31
Multi	26	34	18	58	32.57	8.69	28	30
Total	45	75	18	60	32.7	8.59	28	31

Table 2.Country of residence and nationality of the participants

	Single		Multi	
Country	**Residence**	**Nationality**	**Residence**	**Nationality**
Argentina	3	3	3	2
Bangladesh	0	0	0	1
Belgium	1	1	3	1
Bolivia	2	2	0	0
Brazil	18	18	0	0
Canada	1	0	0	1
Colombia	23	26	26	32
Costa Rica	0	0	1	1
Egypt	0	1	0	0
Germany	1	0	1	0
Guatemala	1	1	0	0
Iran	0	0	0	1
Mexico	2	2	0	0
Nigeria	0	0	1	1
Pakistan	0	1	0	0
Paraguay	0	0	1	1
Peru	1	1	4	5
Philippines	0	0	0	1
Portugal	1	1	0	0
Serbia	0	0	0	1
Singapour	0	0	0	1
Spain	1	1	1	1
Sweden	3	0	7	0
The Netherlands	0	0	1	0
UK	1	0	1	0
Uruguay	0	1	2	2
USA	1	0	1	0
Venezuela	0	1	6	7
X	0	0	1	1
Total	60	60	60	60

3.6 Procedure

The VR experiments were performed between March 18 and March 27, 2021. Participants were contacted through social media. They received a message that contained a link that gave access to the VR experiments. There was an independent link for each VR experiment (Single and Multi) to differentiate the samples. Thus, participants who had access to the Single VR experiment could not access the multi-VR experiment. The message sent was written either in English or Spanish. Hence, more people could be reached. The English message is reproduced here.

"A non-immersive virtuality reality serious game which allows participants to walk around a virtual scene with the presence of corridors is being tested. The purpose of the study is to analyze how people interact in the virtual scenario given. Please click the following link to be part of the VR experiment. ***Use mouse and keyboard to be able to participate"***

Once the participants clicked the link, they were directed to the website where the VR experiments were hosted. The informed consent form stated in a general manner what the experiment was about, and by clicking the start bottom, participants confirmed that they had accurately read out the informed consent and agreed to participate. The informed consent was written in English and Spanish accordingly, and it is appended at the end of this document.

Then, the VR experiment loaded, and participants needed to select their preferred language. They filled in a box with their personal information about their age, gender, nationality, and country of residence, as can be seen in Figure 12.

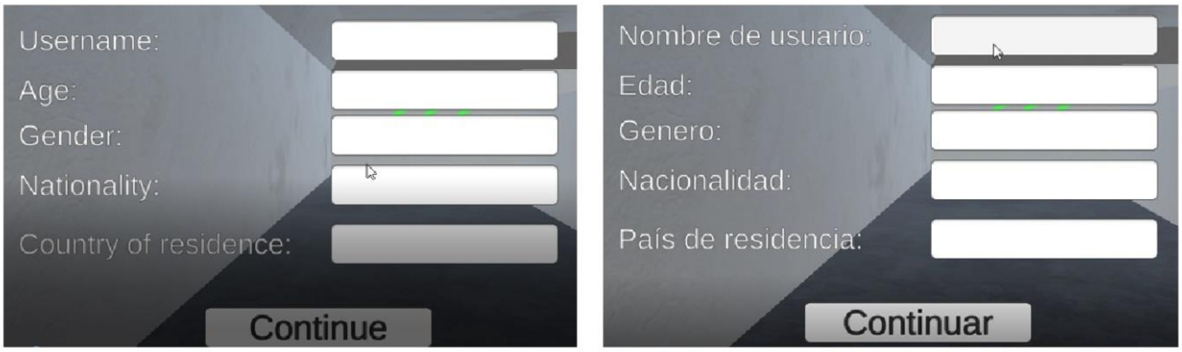


Figure 12. Box where participants filled in their personal information

Afterwards, the training session started, as described in section 3.1. Once participants finished their training, they could reach the training room door where a single instruction was provided, which said: "To start the experience, walk through the corridor in front of you. Other players may be present". The instruction is shown in Figure 13. It is essential to highlight the importance of the last part of the sentence, stating that other players could be present. It was added to give the participants the feeling that the three virtual agents seen in the Multi-VR experiment were the avatars of other users playing simultaneously as them and not virtual agents. Additionally, to make that feeling stronger, the three agents were tagged with familiar names, and their names could be seen on the top of their virtual bodies, as shown in Figure 14.

Figure 13. Instruction provided to start the VR experiments

Figure 14. Virtual agents' names: James, Michael, and David

Participants navigated through the scenario, and their trajectories in corridor A and B were tracked and registered automatically. At the end of corridor B, participants were asked how difficult it was to navigate the scenario. Both the Single and Multi-VR experiment asked that question. However, two additional questions were exclusive to the Multi-VR experiment:

The questions with the corresponding possible answers can be read below:

1. How difficult was it to walk through the corridors? (Single and Multi)

   Easy - Moderate - Difficult

2. Was your walking influenced by the behavior of the people around you? (Multi only)

Yes- No

3. When the 3 virtual agents were walking in front of you, did you believe that they were people playing at the same time as you? (Multi only)

   Yes- No

When the questions were answered, the VR experiment was concluded, and the participants could close the browser. Then, all the personal information with the trajectories were saved as a CSV file, which was available to download by the researcher to be later analyzed.

4 Results

4.1 Single VR experiment

An example of the raw data collected for one participant can be seen in the appendices section (8.3. Single VR experiment data collected).

4.1.1 Pedestrian trajectories

The travel paths of the 60 participants in corridor A and B are plotted in a local system of reference where the inner walls of the 90° turning corridor represent the X and Y-axis, as is illustrated in Figure 15. The corridor width of 3 m which is the entrance is parallel to X-axis. On the other hand, the corridor exit of 3.6 m is parallel to Y-axis. The origin center is located exactly in the 90° turn of the corridor.

As mentioned in chapter 3, corridor B is a mirrored version of corridor A. The travel paths obtained in corridor B were mirrored once again to make them easier to compare to those from corridor A. The trajectories for corridor A are shown in blue lines, and the trajectories for corridor B are shown in red in Figure 15.

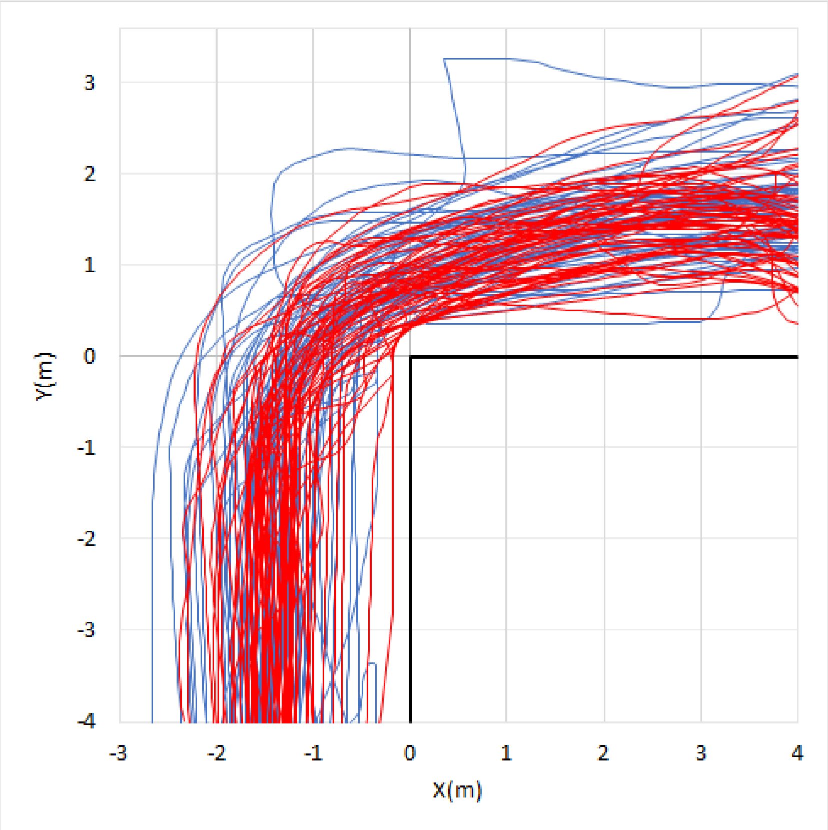


Figure 15. Trajectories Single VR experiment. corridor B (red lines) overlapping corridor A (blue lines)

Figure 15 shows a similar trend in the walking behavior of the participants when they navigate the two virtual corridors. They moved straight at the beginning, and when they were close to the turning point, they changed their direction, gradually forming a curved path. Then, they walked in a straight line again. Hence, the three segments described by Dias et al.(2014b) were also observed in the Single VR experiment.

The access points in corridor B seem to be closer to the inner walls of the corridor than those in corridor A. However, this conclusion can not be drawn with qualitative data. Therefore, these travel paths need to be quantified to obtain results that can be easily understood and generalize conclusions. The process to quantify the trajectories is described in detail in section 4.1.3.

4.1.2 Walking path lengths

The walking path length in each corridor could be calculated using the coordinates collected for each participant. Since the walking speed was constant, the longer the distance walked, the longer the time that it took the participants to navigate through the corridors. Nine intervals of walking path lengths were identified, shown in Figure 16. The shortest walking path length was between 8.5 and 9 m, and the longest was 13.8 m, which represents a single participant in corridor A. 36.67 % of the participants had a walking path between 9.5 to 10 m for both corridors.

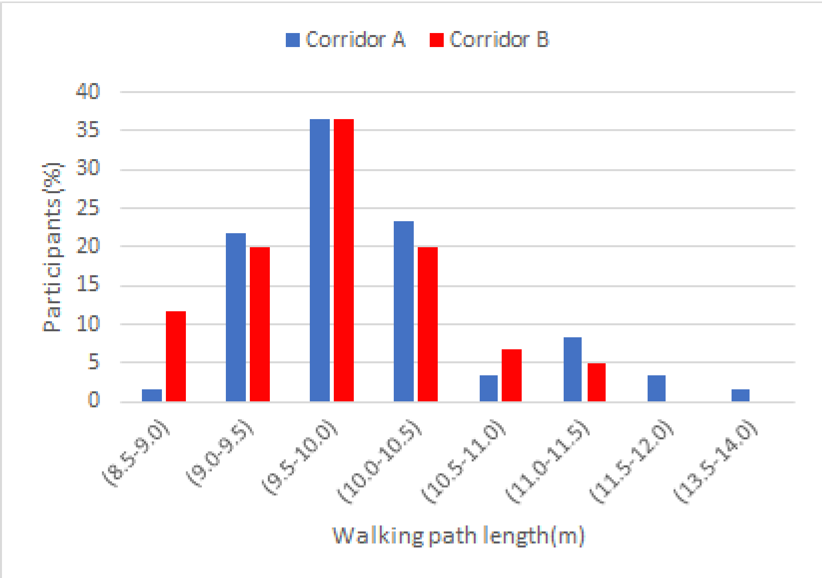


Figure 16. Single VR experiment. Walking path length

4.1.3 Tracking the trajectories within the floor geometry discretized method.

Ronchi et al. (2014) developed a systematic approach to represent the area on stairs landings occupied by evacuees based on travel paths obtained from an evacuation drill. This systematic approach was considered a starting point for tracking the trajectories for the VR and the Laboratory experiments (Keip & Ries, 2009). Moreover, alternative approaches were contemplated in this project as the present study intended to track the trajectories in space, not the area occupied by the participant's body.

By focusing just on the trajectories representing the center of the full-body of participants, it is possible to identify where people were more prone to walk closer to the walls. Hence, the floor of the corridors was discretized into 50 cm by 50 cm grid cells. Then, when the trajectory intersected a grid cell, one participant was assigned to that grid cell.

Figure 17 shows the trajectories of two participants on the discretized floor. As can be seen, both participants walked the grid cell cataloged as "a". For instance, if we consider two participants as the sample, it means that 100% of participants moved through the grid cell a, and 50% navigated through the blue and red grid cells.

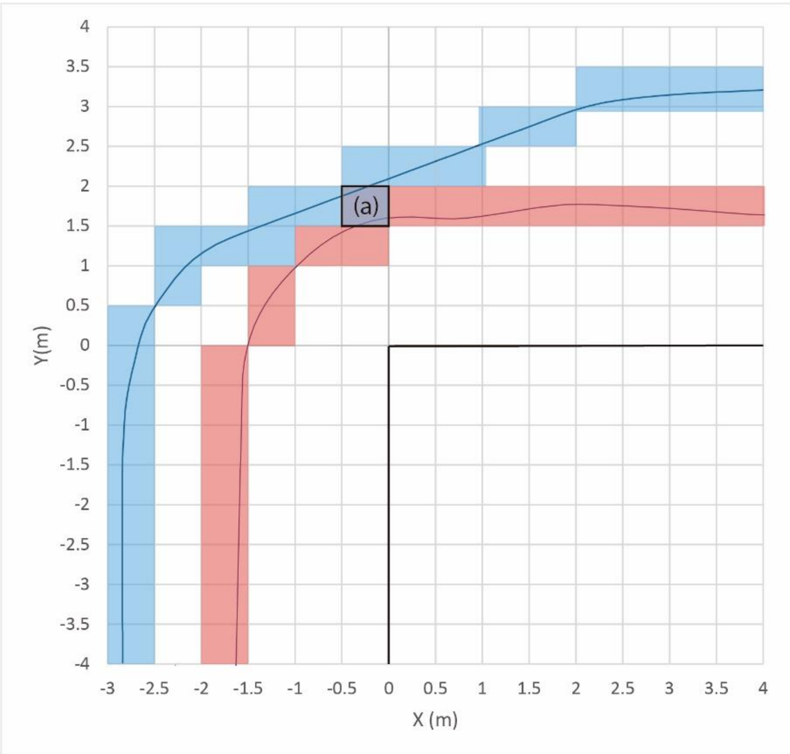


Figure 17. Representation of the trajectories of two participants on the discretized floor. Grid cells: 50 cm by 50 cm

4.1.4 Quantification of the trajectories

In Figures 18 and 19, the trajectories navigated by participants in corridors A and B are presented, respectively. They are shown in terms of fractions, where 1 (100%) represents the 60 participants that took part in the Single VR experiment. To describe the results obtained more effectively, the 90° turning corridor was split into three sections: “Region 1”, “Region 2”, and “Region 3”.

As illustrated in Figure 18, between 40% to 52% of participants navigated Region 1 through lane d, and between 33% to 37% of participants moved along lane c. Both lanes represent the center part of the region. Hence, most of the participants kept a distance higher or equal to 0.75 m from the corridor walls. 2% of participants moved through lane a. This information can be confirmed by looking in detail Figure 16 (left), where the travel path of the participant who walked along that lane is shown. 2% of participants moved close to the inner wall through lane f.

By looking at Region 2, participants did not move close to the outer wall. This statement is illustrated by the white grid cells. In contrast, participants tended to move closer to the inner corner, which can be seen by looking at grid cell f9. In Region 3, participants were prone to move through rows 11 and 12, and they kept distance from the walls. Although the width of the hall increased by 60 cm compared to Region 1, participants did not tend to move along the outer wall. Only 2% of participants moved along row 15.

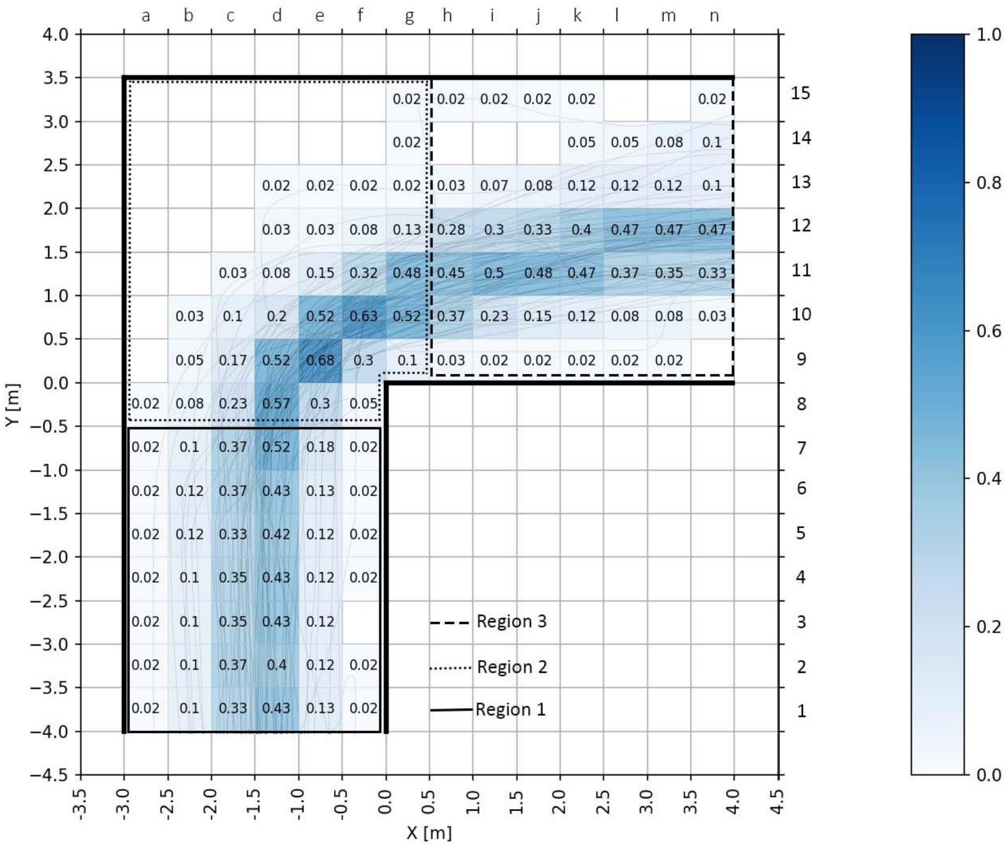


Figure 18. Single VR experiment: Trajectories in corridor A.

As presented in Figure 19, between 45% and 62% of participants navigated Region 1 through lane d, and between 33% and 40% of participants moved along lane c. Both columns represent the center part of the region. Therefore, most of the participants kept a distance higher or equal to 0.75 m from the corridor's walls. Participants did not navigate through lane a, and 3% navigated close to the inner wall represented by lane f.

It can be seen that participants did not approach the outer corner of the wall in Region 2 as it was also observed in the laboratory experiment. The empty area is shown as white grid cells. Participants tended to move closer to the inner corner, as reflected in the grid cell f9. In Region 3, participants were more prone to move through the inner lanes. Hence, between 40% and 58% moved along row 11, and 22% to 45% stepped through row 12.

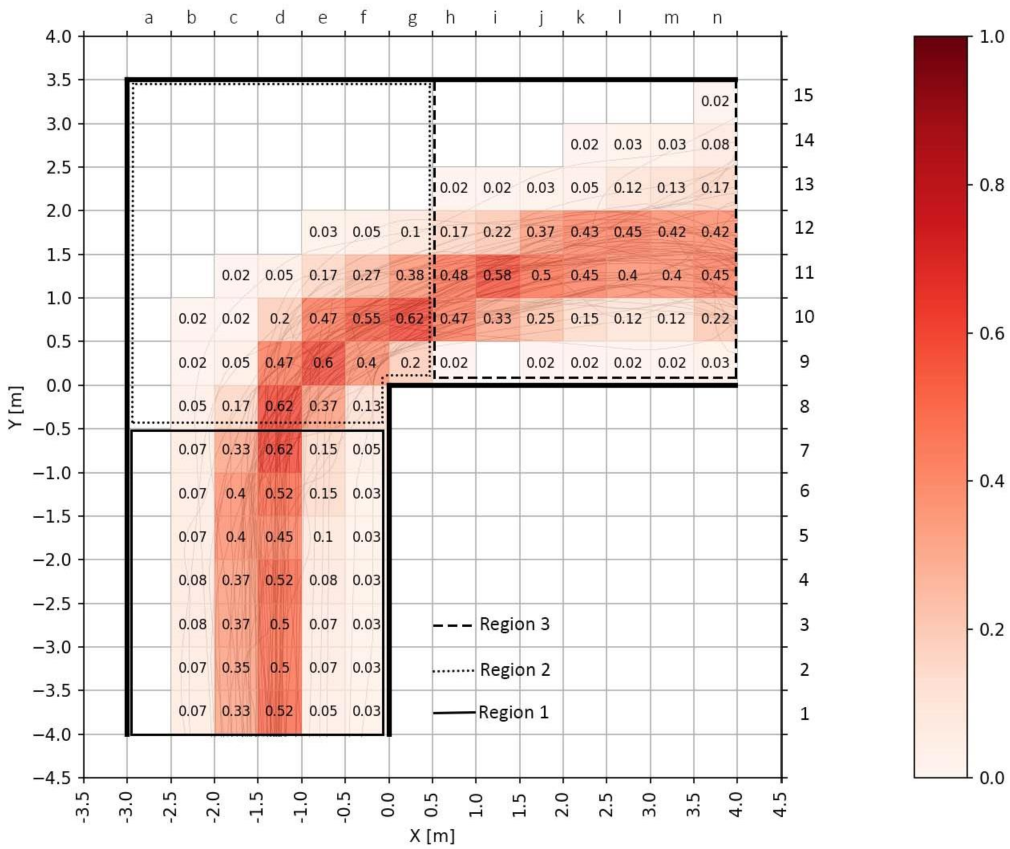


Figure 19. Single VR experiment. Trajectories in corridor B.

4.1.5 Comparison of trajectories between corridor A and corridor B

It was intended to analyze whether making the participants walk through the 90° turning corridor twice a learning effect could be achieved. Then, it is necessary to assess how the trajectories in corridor B differ from those in corridor A. In Figure 20, this comparison is presented.

The numbers shown in Figure 20 represent the offset (in percentage) between trajectories in corridor A and corridor B. Corridor A is considered the base for the calculations. For instance, by looking at lane a in Region 1, it can be seen that there was a participant who walked through it in corridor A, but nobody navigated in lane a in corridor B. Therefore, in this case, 1 (100%) does not represent the 60 participants in the experiment, but the offset between trajectories in corridor A and corridor B.

Negative values mean that fewer people navigated through those grid cells in corridor B. If the values are 0, then the same percentage of participants stepped in the grid cells in both corridors. Positive values mean that more participants move through a specific grid cell in corridor B than in corridor A. The word “inf” indicates that those areas were not navigated by any participant in corridor A, but some participants did in corridor B.

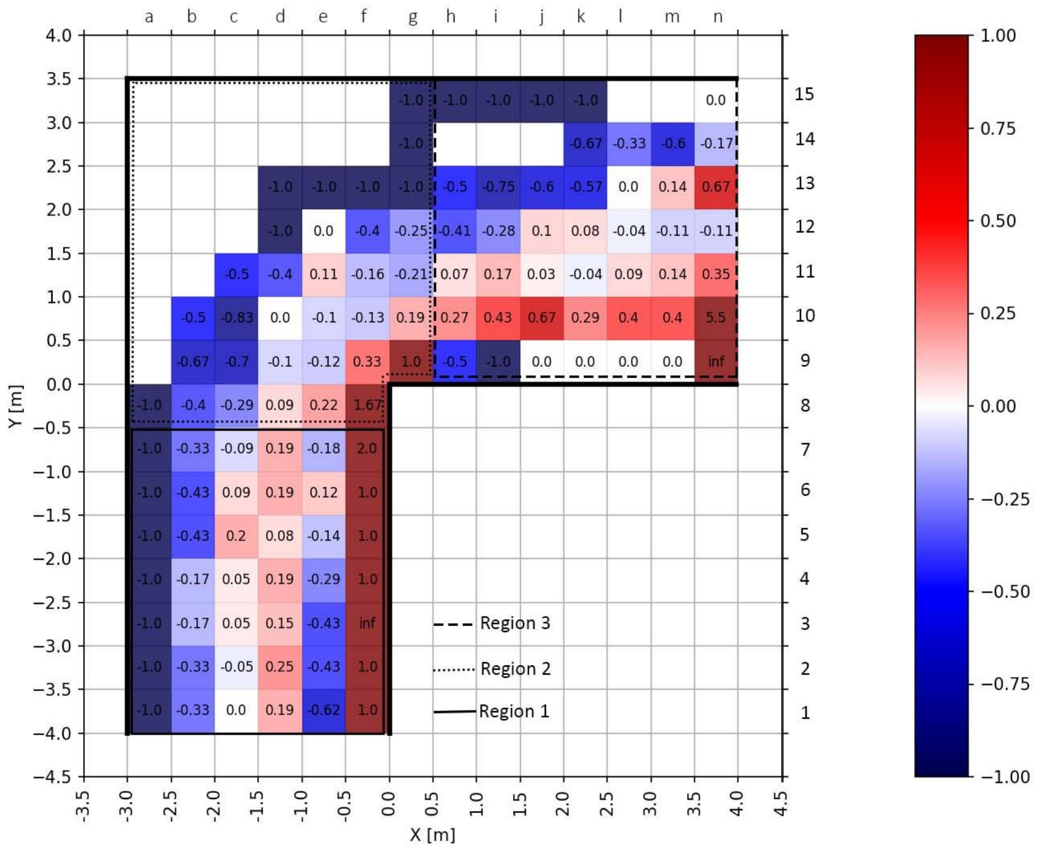


Figure 20. Single VR experiment. Comparison of trajectories between corridor A and corridor B

As illustrated in Figure 20, in Region 1, fewer participants in corridor B tended to move close to the outer wall compared to corridor A. Between 17% and 33% of participants moved less through lane b. Lane c shows a similar trend between both corridors as the percentage difference is between 0% and 9%, although 20% more participants navigated through c5.

In Region 2, it is observed that participants are more prone to move to the inner corner in corridor B. In Region 3, the outer wall is avoided for participants in corridor B. The exact number of participants moved close to the inner wall in both corridors as grid cells j9, k9, and l9 have 0% offset.

4.1.6 Entrance and exit location

In this section, row 1 and lane n represent the entrance and exit of the corridor, respectively. Row 8 and lane g represent the beginning and the end of Region 2, respectively. This configuration is shown in Figure 21.

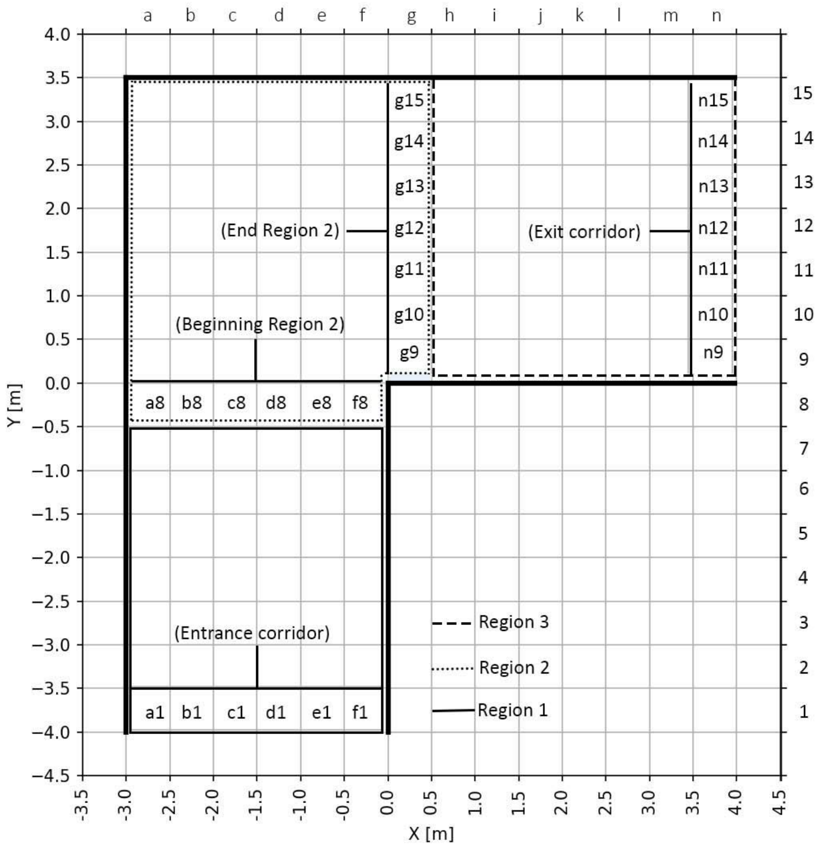


Figure 21. Configuration of entrance and exit location

As it is illustrated in Figure 22, participants tended to enter both corridors through the central lanes (c1 and d1). Less than 12% used the lanes that are close to the walls. When approaching the beginning of Region 2, they changed their path and went closer to the inner corner (grid cells d8, e8, and f8). At the end of Region 2, they kept moving near the inner wall. Finally, when their turning movement was completed, they were prone to move along the center of the corridor (most of them leave the corridor through the grid cells n12 and n11).

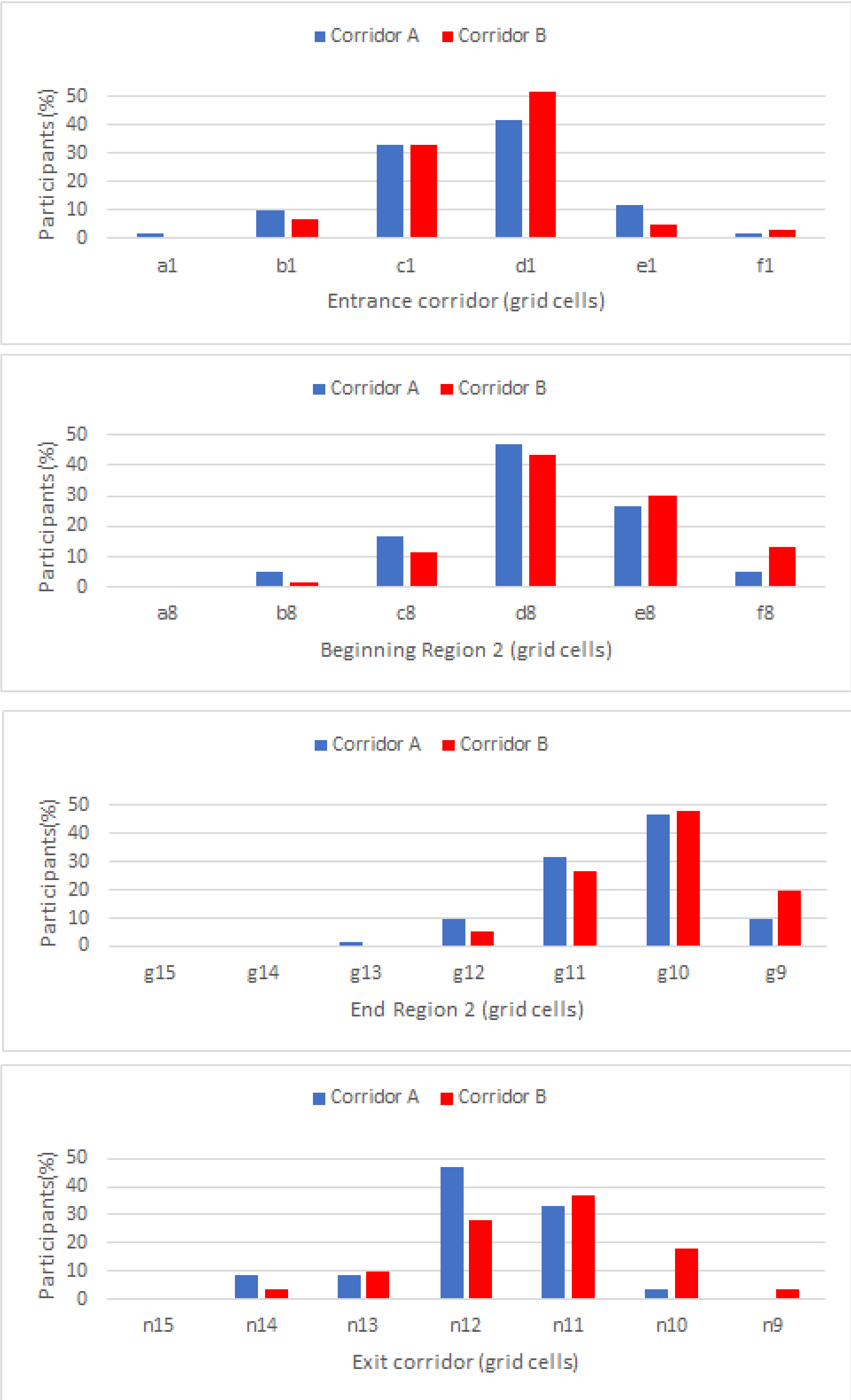


Figure 22. Single VR experiment. Entrance corridor, Beginning Region 2, End Region 2, Exit corridor(grid cells).

4.1.7 Final questionnaire

Participants were asked how difficult it was for them to navigate the VE. In Figure 23, their travel paths in corridor A were plotted according to their answer. 43 participants (72%) reported that they found it easy to walk through the corridors, 16 (27%) replied that the navigation was considered moderate. Just one person (2%) stated that it was difficult to move around.

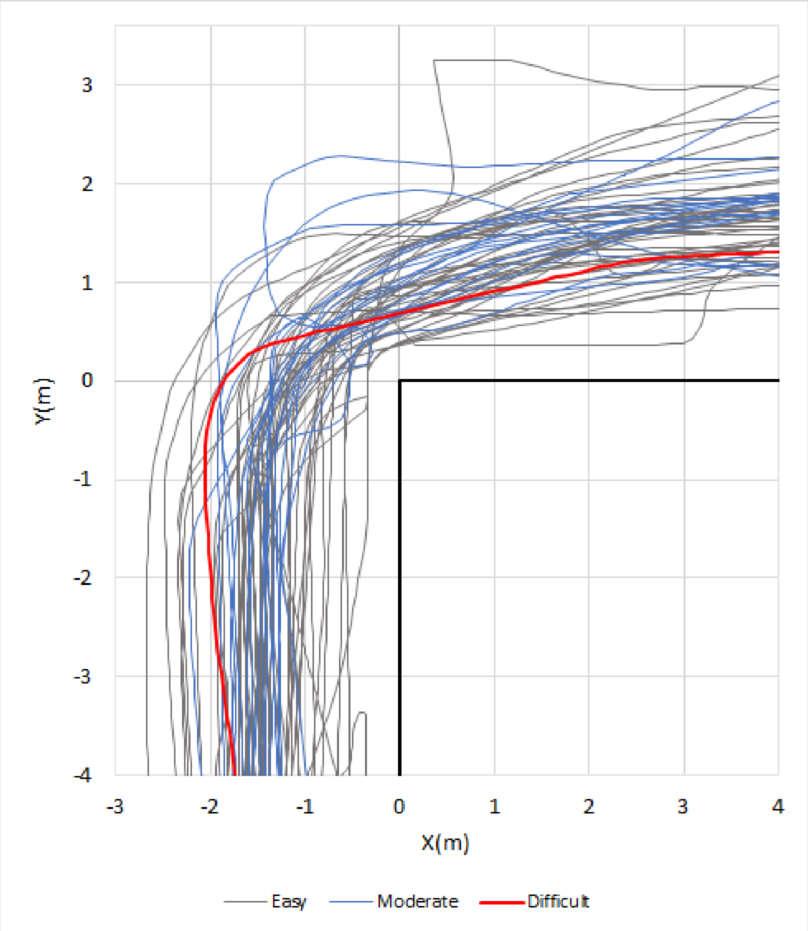


Figure 23.Single VR experiment. Trajectories plotted according to how difficult participants considered it was to navigate the VE

4.2 Multi VR experiment.

An example of the raw data collected for one participant can be seen in the appendices section (8.4. Multi VR experiment data collected).

4.2.1 Pedestrian trajectories

As shown in Figure 24, the travel paths that the participants followed in both corridors followed a similar trend. In the beginning, they walked in a straight manner, followed by a curved path when they are reaching the corner. After the corner, participants moved following straight trajectories until they approached the exit. Although the virtual agents (represented by the yellow line) walked closer to the outer corner, participants do not seem to follow them. Figure 26 shows the travel paths for corridor A and corridor B overlapped.

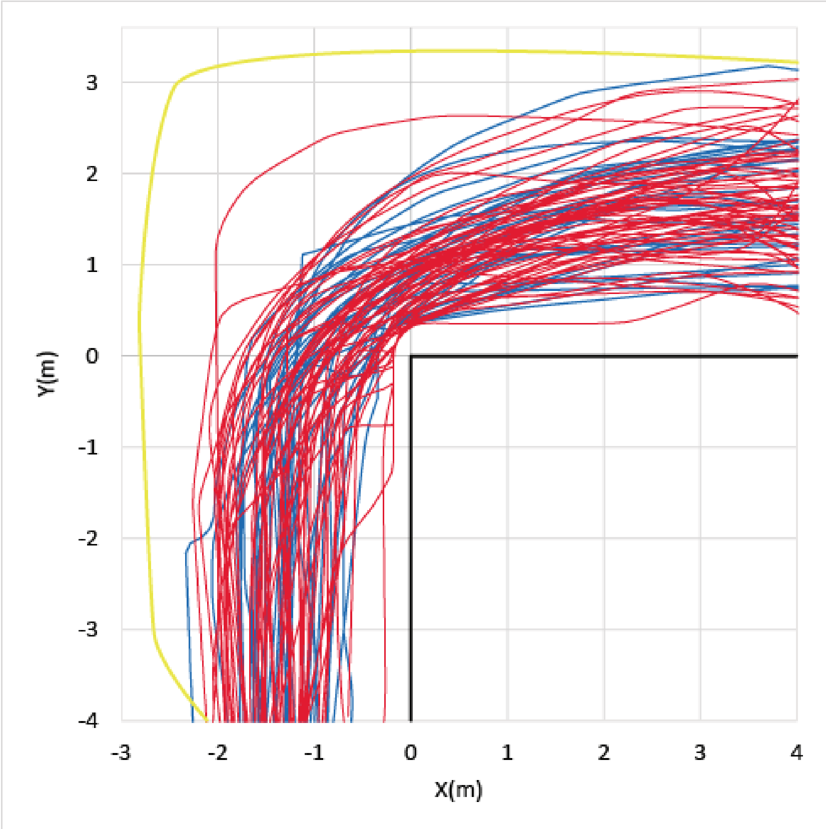


Figure 24. Trajectories Multi VR experiment. Corridor B (red lines) overlapping Corridor A (blue lines). Virtual Agents(yellow)

4.2.2 Walking path lengths

Figure 25 shows the travel lengths obtained in corridor A and corridor B. The shortest walking path length was between 8.5 m to 9 m, and the longest was 14.2 m collected in corridor B. Most of the participants had walking path lengths between 9m and 10 m in both corridors.

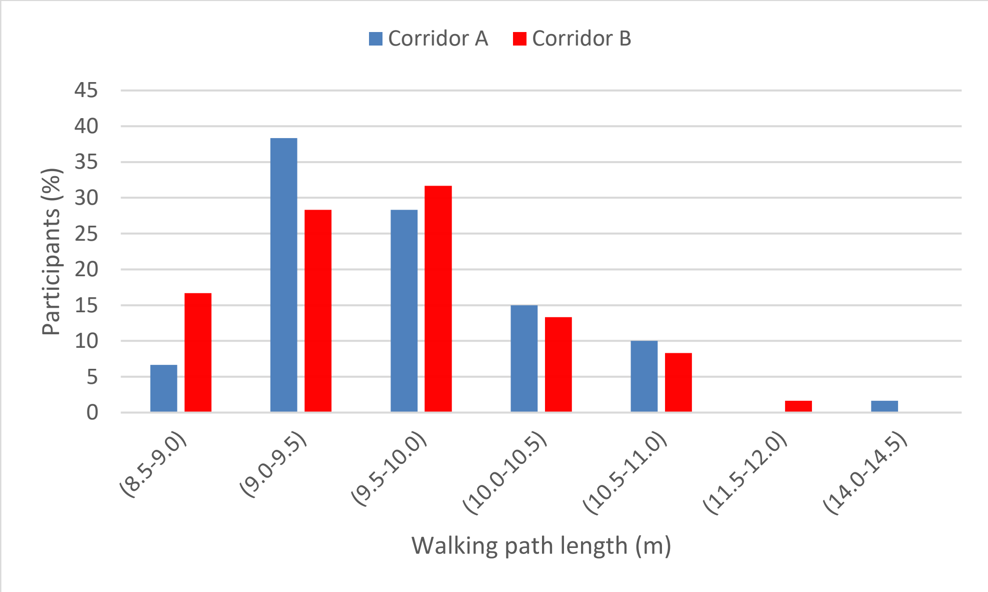


Figure 25. Multi VR experiment. Walking path lengths

4.2.3 Quantification of the trajectories

Figures 26 and 27 present the trajectories navigated in corridors A and B, respectively. They are shown in terms of fractions considering that 1 (100%) represent the 60 participants in the Multi VR experiment. The squares that are highlighted in yellow represent the travel path followed by the virtual agents.

As shown in Figure 26, between 40% to 50% of participants navigated Region 1 through lane d, and between 23% to 30% of participants navigated along with lane c. Both lanes represent the center part of the region. Hence, most of the participants kept a distance higher or equal to 0.75 m from the corridor walls. There is no clear trend to follow the path of the virtual agents, with just 2% of participants moved on the same grid cells as the virtual agents.

By looking at Region 2, participants kept a large distance from the outer corner. In contrast, participants tended to move closer to the inner corner (grid cell f9). In Region 3, participants were more prone to walk through the central rows (11 and 12) and kept distance from the walls. They did not exit through grid cell n15, although the virtual agents did.

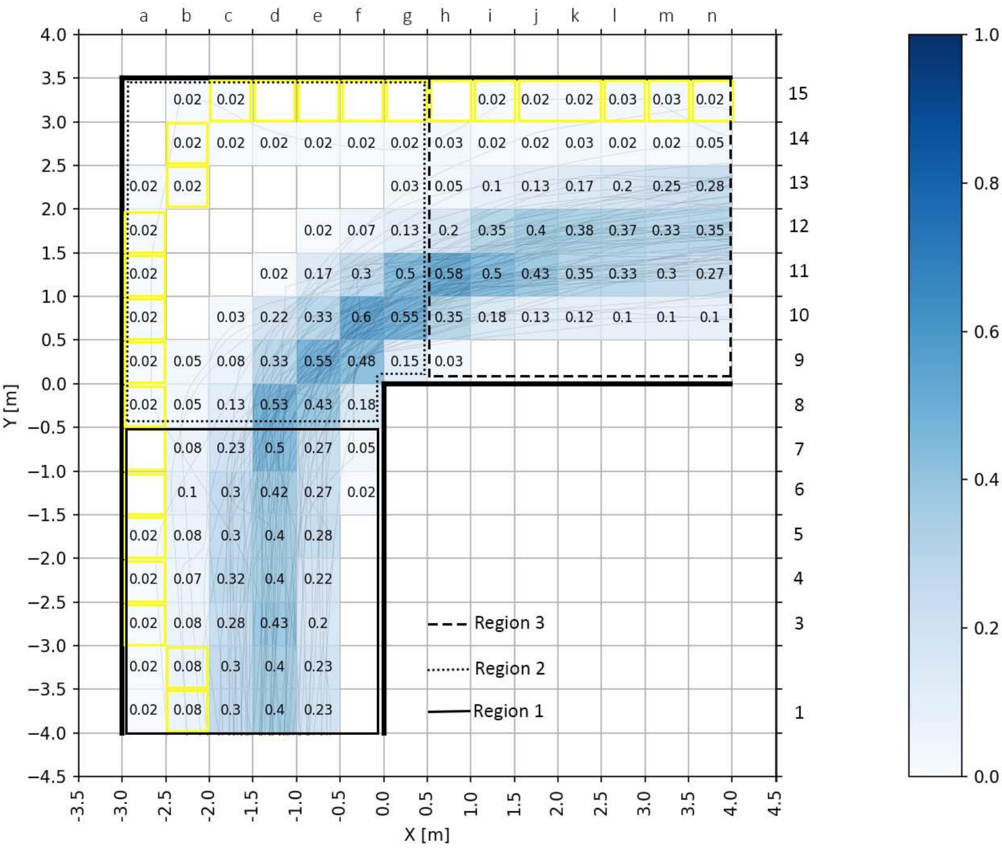


Figure 26. Multi VR experiment: Trajectories in corridor A. Virtual agents travel path in yellow

As shown in Figure 27, between 35% to 43% of participants navigated Region 1 through lane d, and between 30% to 42% of participants moved along column c. Both lanes represent the center part of the region. Hence, most of the participants kept a distance higher or equal to 0.75 m from the inner and outer walls of the corridor. Most of the participants did not moved through the grid cells that the virtual agents used.

Participants did not approach the outer corner of the wall in Region 2. They tended to move closer to the inner corner, as reflected in the grid cell f9, where 53% of participants moved through it. In Region 3, participants were more prone to move through the inner rows and kept a distance from the walls. Between 30% to 57% moved through row 11 and between 17% to 45% row 12.

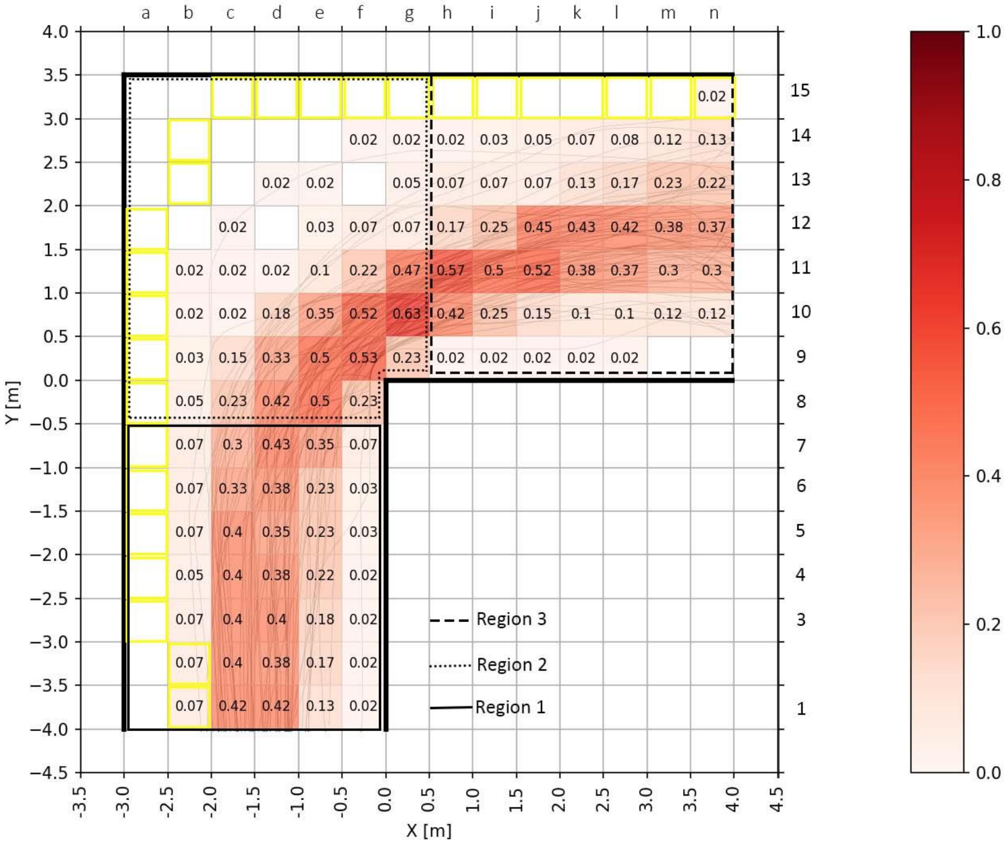


Figure 27. Multi VR experiment: Trajectories corridor B. Virtual agents travel path in yellow.

4.2.4 Comparison of trajectories between corridor A and corridor B

As shown in Figure 28, in Region 1, fewer people in corridor B tended to move close to the outer wall. Between 20% and 33% of participants moved less through lane b than the trajectories obtained in corridor A. In Region 3, the outer wall is avoided for participants in corridor B (row 15). More participants in corridor B moved through row 14 than in corridor A.

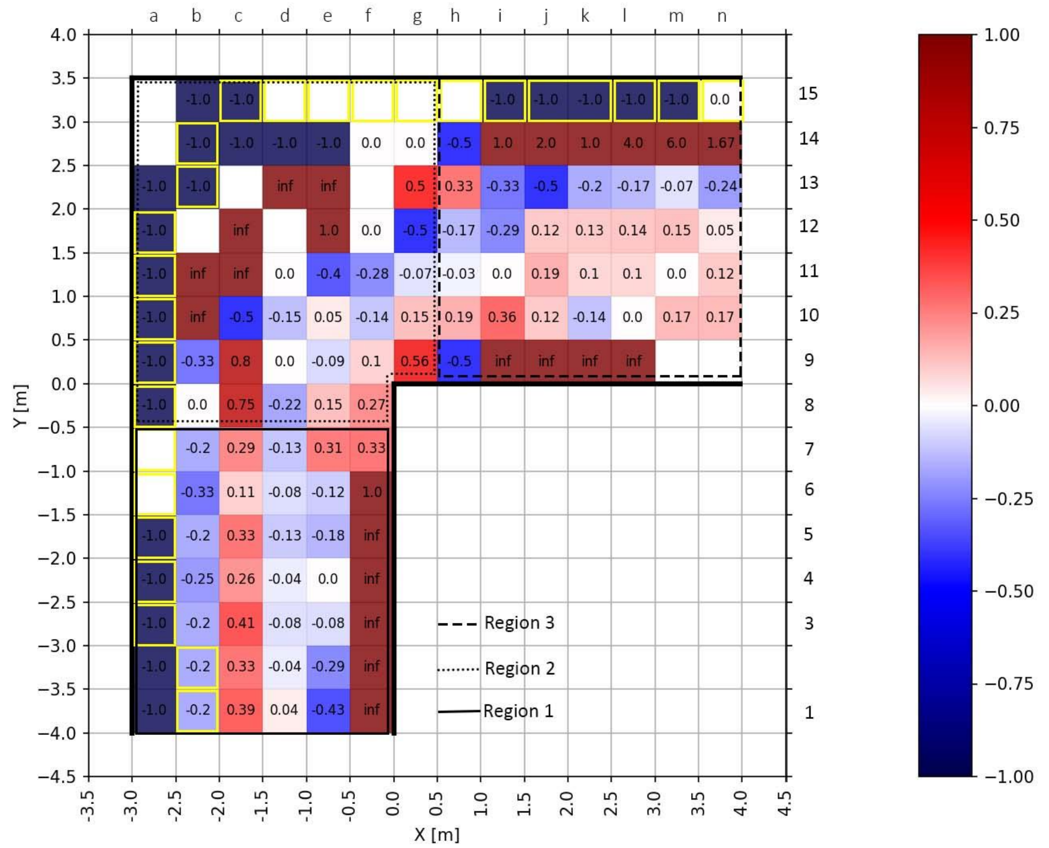


Figure 28. Multi VR experiment. Comparison of trajectories between corridor A and corridor B. Virtual agents travel path in yellow

4.2.5 Entrance and exit location.

As presented in Figure 29, participants were more prone to enter both corridors through the central lanes (c1 and d1). When pedestrians moved towards Region 2, they changed their path and went closer to the inner corner, illustrated by grid cells d8, e8, and f8. After they have navigated Region 2, they kept moving near the inner wall. When they completed their turning movement, they were prone to walk along the center of the corridor (most of them left the corridor through the grid cells n11, n12, n13).

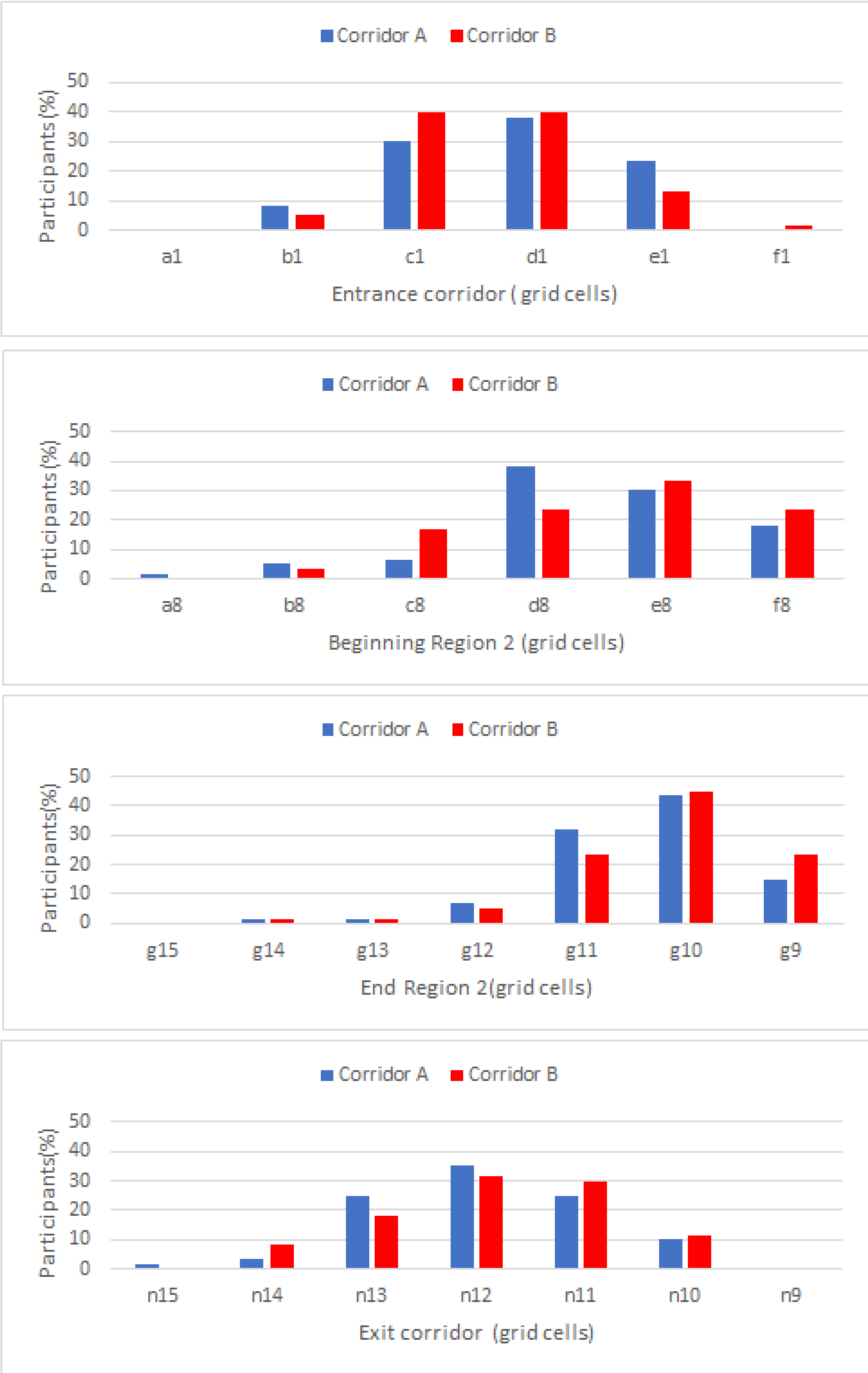


Figure 29. Multi VR experiment. Entrance corridor, Beginning Region 2, End Region 2, Exit corridor(grid cells).

4.2.6 Final questionnaire

Figure 30 shows the trajectories in corridor A based on the participants answers about how difficult it was to navigate within the scenario. 42 participants (70%) reported that they found it easy to walk through the corridors, 16 (27%) replied that the navigation was considered as moderate, and 2 participants (3%) stated that it was difficult to move around.

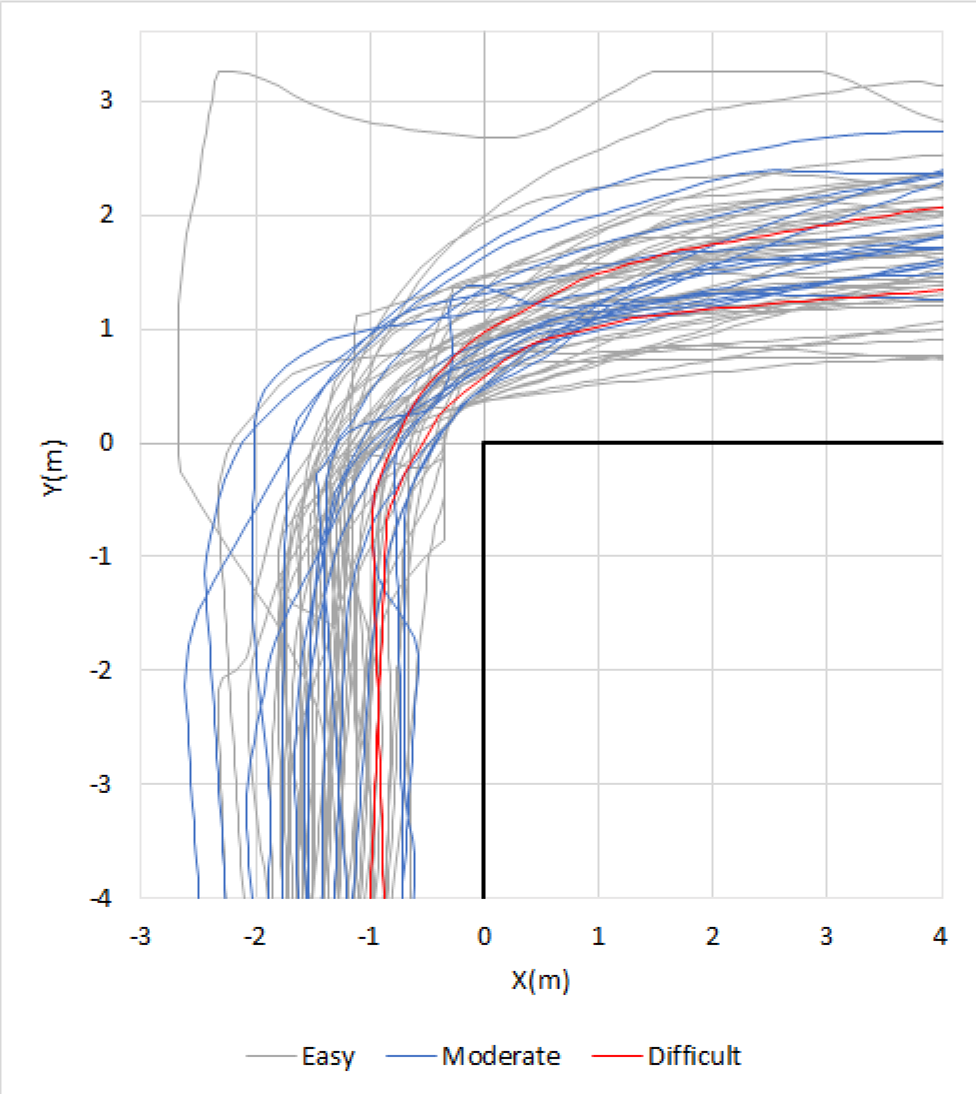


Figure 30.Multi VR experiment. Trajectories plotted according to how difficult participants considered it was to navigate the VE

Figure 31 shows the trajectories based on the participants' perception about been influenced by the virtual agents in their walking behavior. 47% mentioned that they were influenced, while 53% said that the virtual agents did not influence them.

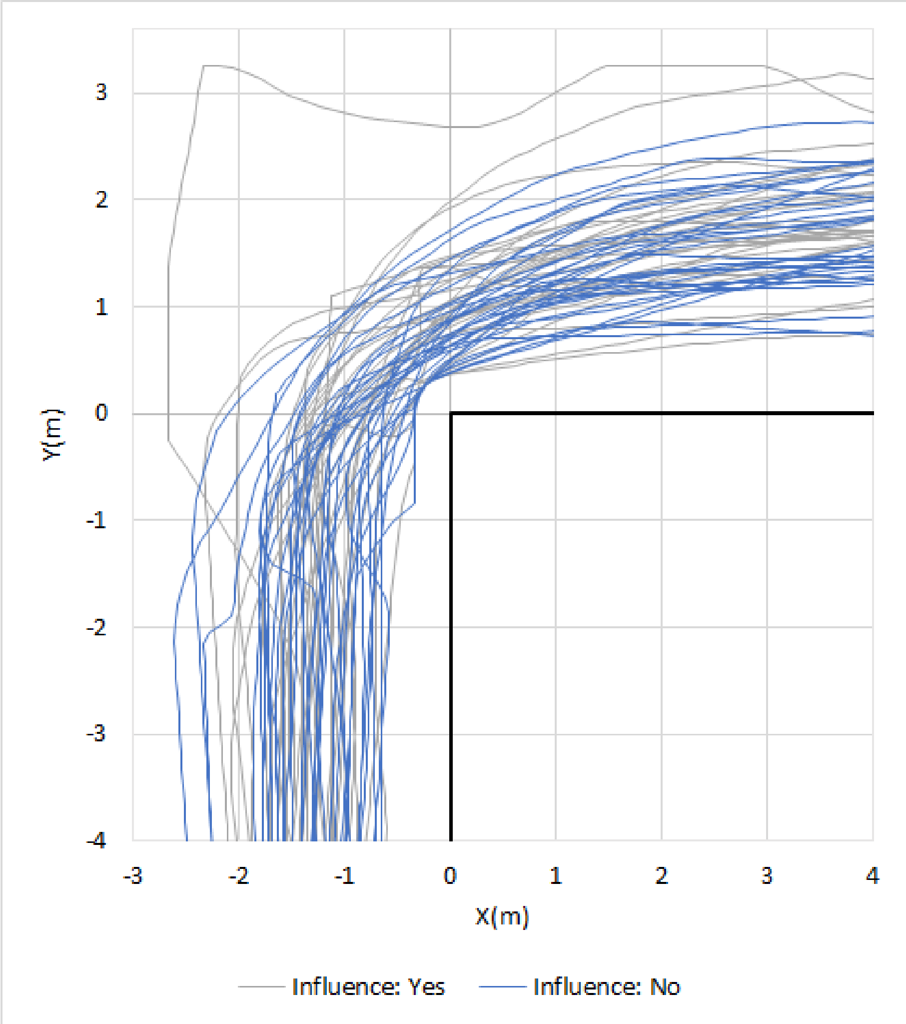


Figure 31.Multi VR experiment. Influence of virtual agents

Finally, 52% of participants stated that they believed the virtual agents were people playing at the same time as them. The rest said they did not believe there were people playing remotely.

4.3 Comparison between Single VR and Laboratory experiments.

In this section, the results obtained within the Single VR experiment are compared to the outputs collected in the Laboratory experiment (Keip & Ries, 2009).

4.3.1 Pedestrian trajectories

Figures 32 and 33 show the trajectories plotted. The orange lines represent the travel paths obtained within the laboratory experiment. The walking pattern in both experiments (VR-Laboratory) remains similar. In the beginning, people tend to walk in a straight manner followed by a curve path within the turning region, and finally, they come back to walk straight when reaching the exit of the corridor. However, it looks that the participants were more prone to walk closer to the interior wall within the laboratory experiment.

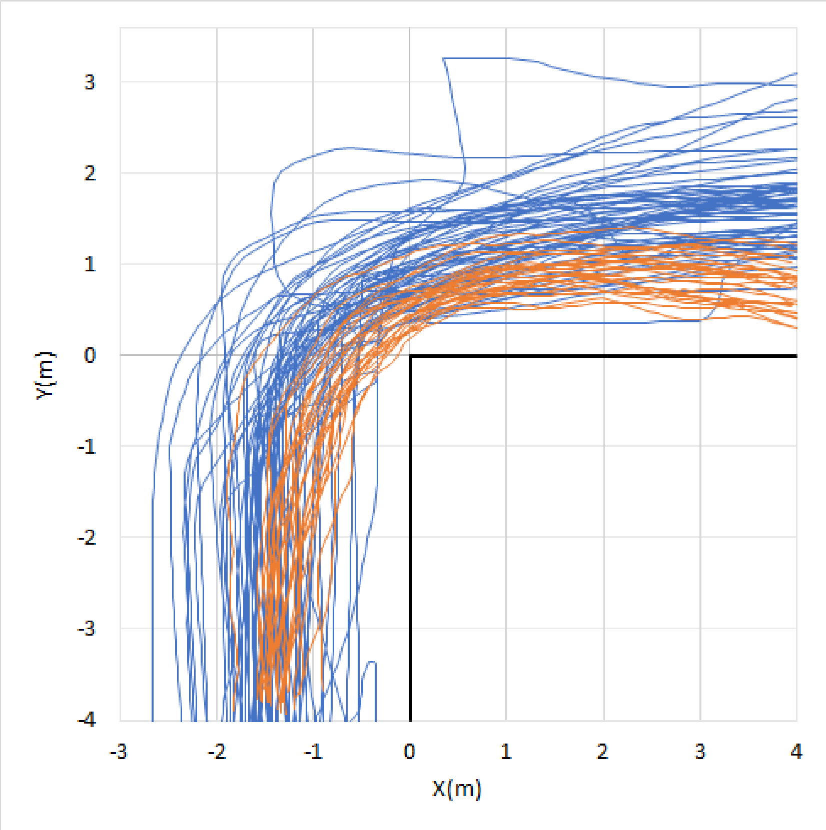


Figure 32. Single VR corridor A(blue) and Laboratory(orange)

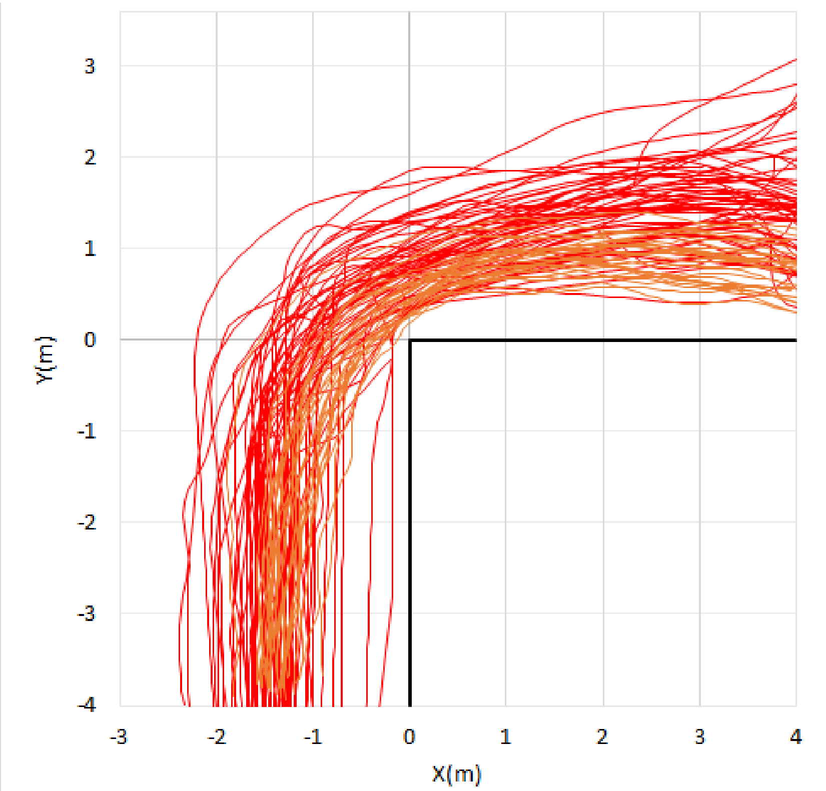


Figure 33. Single VR corridor B(red) and Laboratory(orange)

4.3.2 Walking path lengths

In Figure 34, the different walking path lengths walked by the participants within both experiments are shown. The purple bars represent the average of the trajectories obtained in corridor A and B. The walking path lengths in the Laboratory experiment were shorter than in the Single VR experiment. In the Laboratory experiment, there were lengths between a range of 8 m to 10 m, while for the Single VR experiment, the interval was between 8.5 m to 14 m.

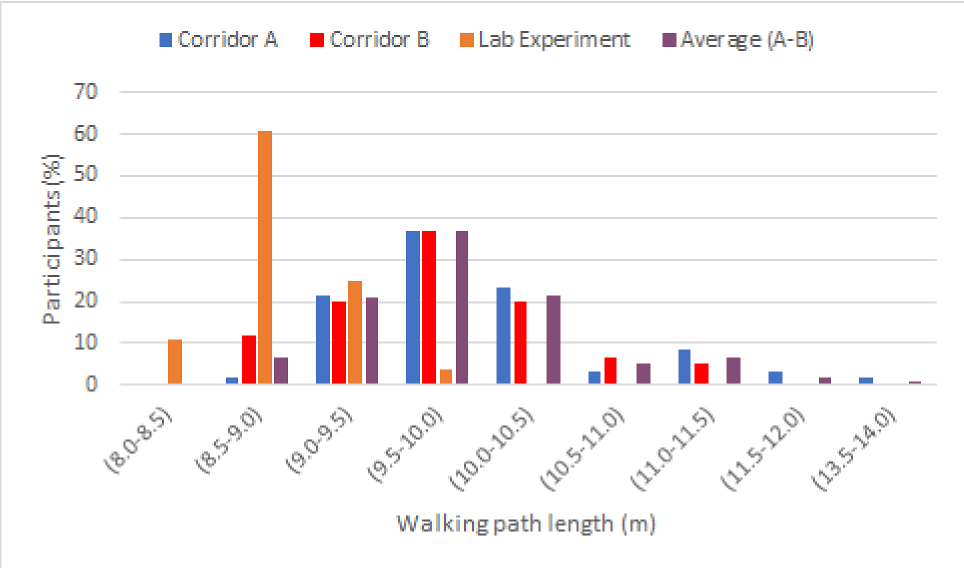


Figure 34.Single VR-Laboratory experiments. Walking path lengths

4.3.3 Comparison of trajectories

Since similar trends were found in corridor A and B in the Single VR experiment, the average was calculated to compare it to the Laboratory experiment. The quantification of the trajectories for the Laboratory experiment can be seen in section 8.5, and the comparison between corridor A and Corridor B taking as base the Laboratory experiment can be found in sections 8.6 and 8.7, respectively.

As it is illustrated in Figure 35, participants in the Laboratory experiment were prone to walk closer to the inner wall in the three regions. In region 1, it can be seen that nobody moved through lane a and b in the laboratory experiment, while some participants moved through those lanes in the Single VR experiment. In region 2, the same trend was kept. In region 3, participants moved on rows 9, 10, and 11 in the Laboratory experiment. In the Single VR experiment, they navigated within the whole corridor.

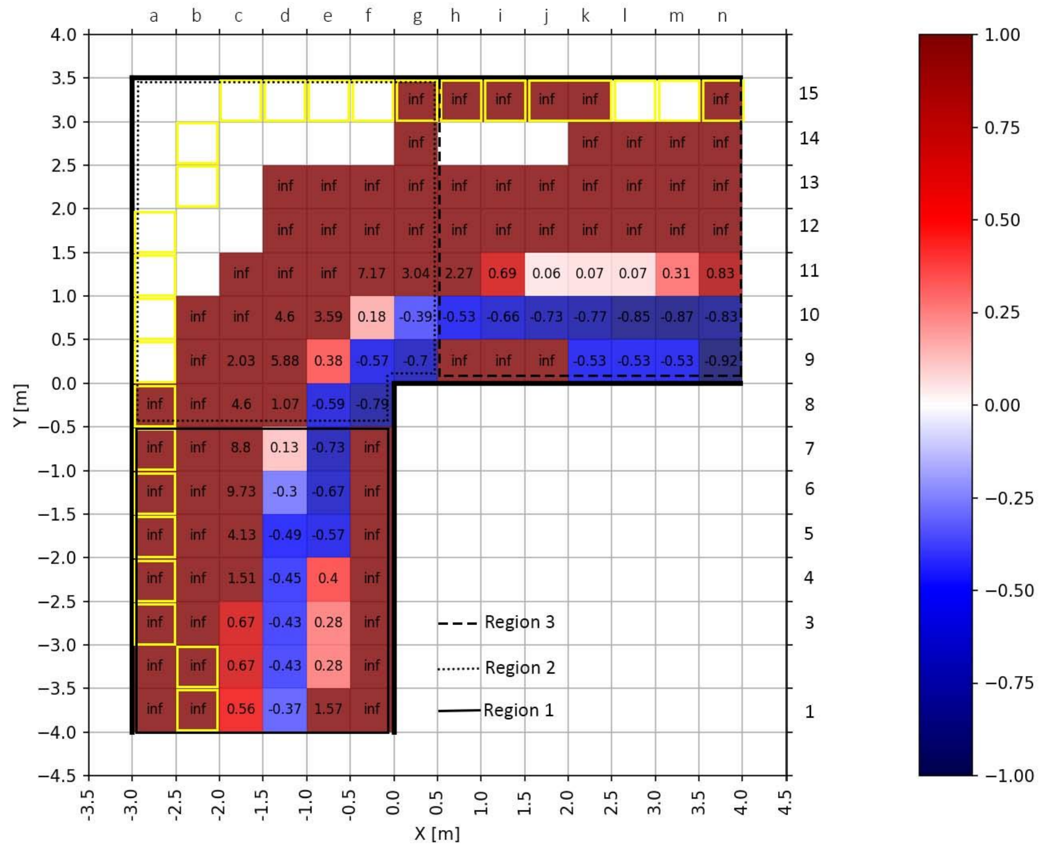


Figure 35. Comparison of trajectories between Average Single VR and Laboratory experiments

4.3.4 Entrance and exit location

As it is illustrated in Figure 36, most of the participants were prone to enter the corridor through the central lanes (c1 and d1) in both experiments. When participants moved towards Region 2 both in the Laboratory and the Single VR experiments, they changed their path and went closer to the inner corner (grid cells d8, e8, and f8). After Region 2, they kept moving near the inner wall in both experiments. Once their turning movement was completed in Region 2, participants in the Single VR experiment were prone to walk along the center of the corridor (most of them leave the corridor through the grid cells n11 and n12). In the Laboratory experiment, most participants left the corridor through the grid cells n11, n10, and n9, which are the grid cells closer to the inner wall.

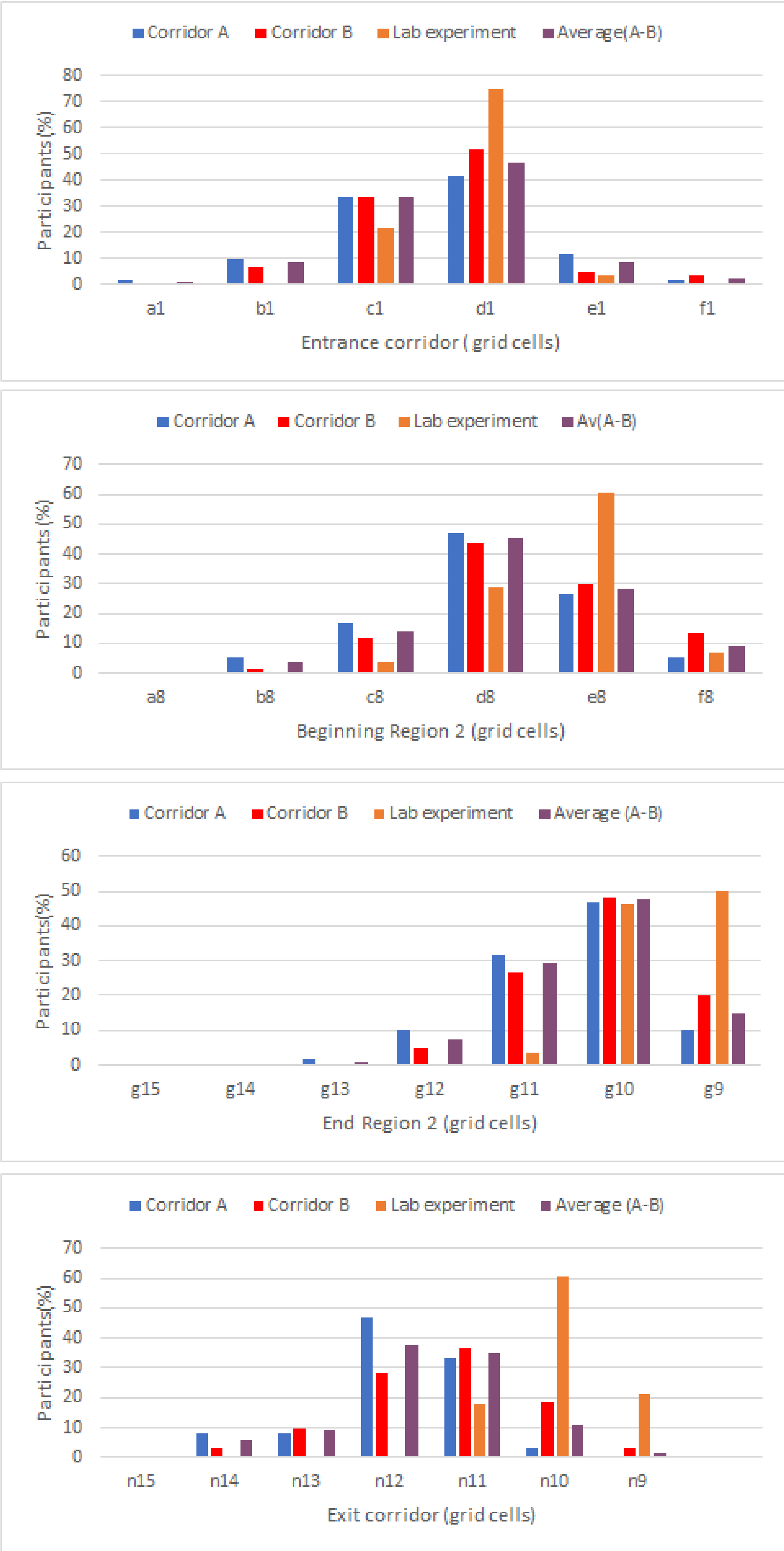


Figure 36. Single VR -Laboratory experiment. Entrance corridor, Beginning Region 2, End Region 2, Exit corridor(grid cells).

4.4 Comparison between Single VR and Multi VR experiments.

One of the goals of this project is to observe how social influence may affect individuals' walking paths in a virtual environment. Then, it is necessary to compare the results of the VR experiments (Single-Multi) considering as base the Single VR experiment where virtual agents were not present.

4.4.1 Pedestrain trajectories

As shown in Figure 37 and 38, the travel paths that the participants followed in both VR experiments followed a similar trend. The description of the trajectories can be found in sections 4.1.1 for the Single VR experiment and 4.2.2 for the Multi VR expemerint.

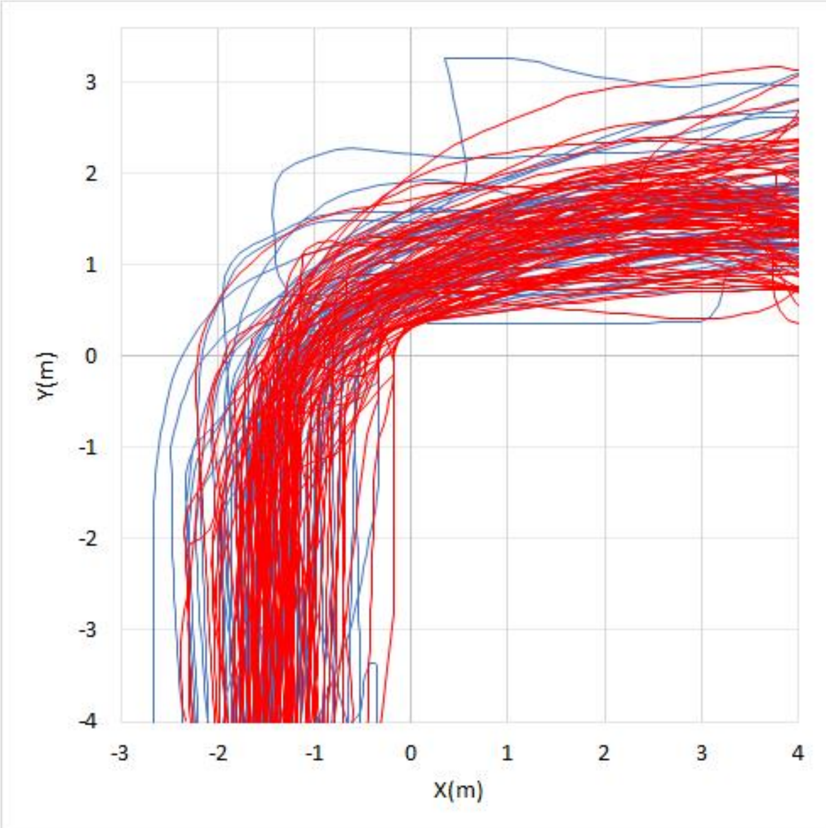


Figure 37. Single VR corridor A(blue) and Mult VR corridor A(red)

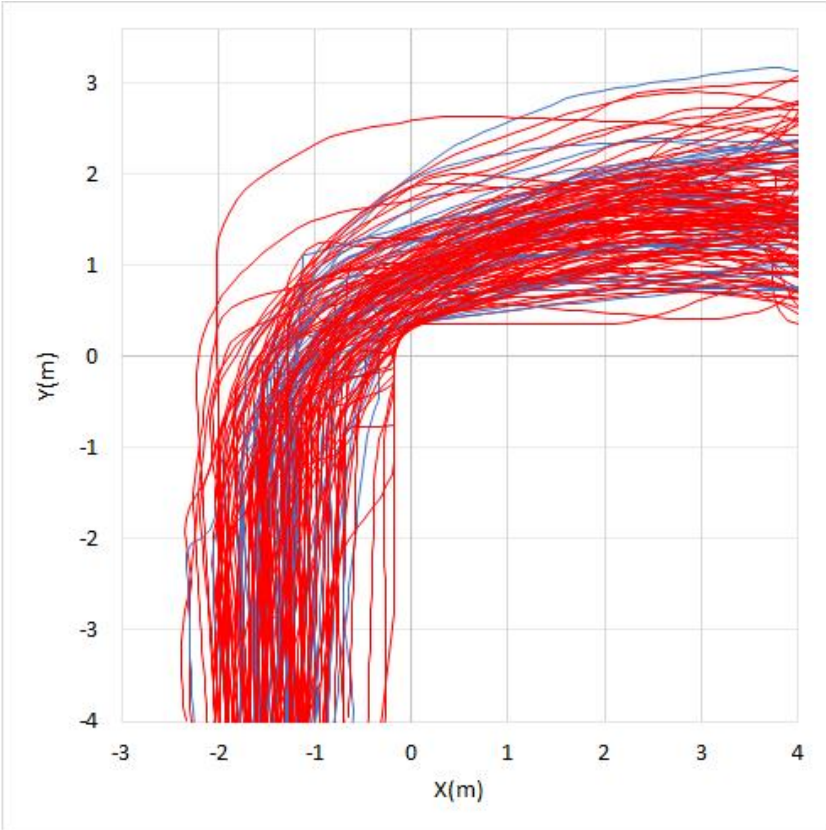


Figure 38. Single VR corridor B(blue) and Mult VR corridor B(red)

4.4.2 Walking path lengths

Figure 39 shows the walking path lengths collected in both experiments. The graph represents the walking path lengths in corridors A and B obtained in both VR experiments. The shortest walking path length was between 8.5 and 9 m found in both VR experiments. The longest was between 14.0 and 14.5 m, collected from one participant in corridor A in the Multi VR experiment.

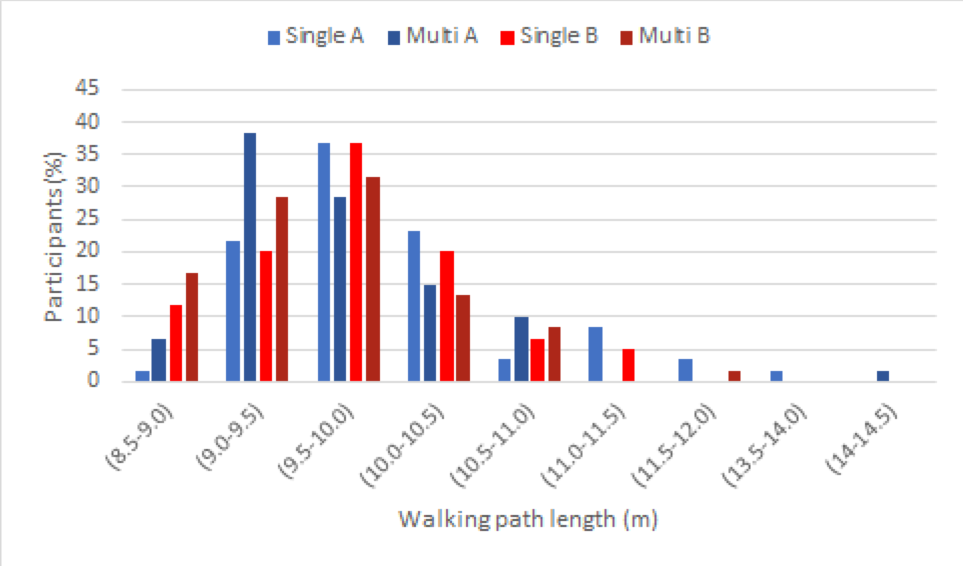


Figure 39.Single-Multi VR experiments. Walking path lengths

4.4.3 Comparison of the trajectories.

The comparison of the trajectories between Single corridor A and Multi corridor A, and between Single corridor B and Multi corridor B can be found on sections 8.8 and 8.9, respectively. Figure 40 below presents the comparison between the average obtained for the trajectories in the Multi VR(corridor A and B) experiment and the Single VR experiment(corridor A and B).

By looking at Region 1, more people in the Multi VR experiment moved through lane e than participants in the Single VR experiment. It may seem like participants in the Multi VR experiment followed the path of the virtual agents and were more prone to walk closer to the outer wall in Region 2 as some grids are marked as “inf”. This means that no participant moved through those grid cells in the Single VR experiment. However, it is essential to highlight that just between 1% and 3% of the participants in the Multi VR experiment moved on those grid cells (see sections 8.10 and 8.11, where the averages are presented separately for the Multi VR and Single VR experiment, respectively). In region 3, it is observed that participants are more prone to move through row 13 in the Multi VR experiment, which means closer to the virtual agents’ path.

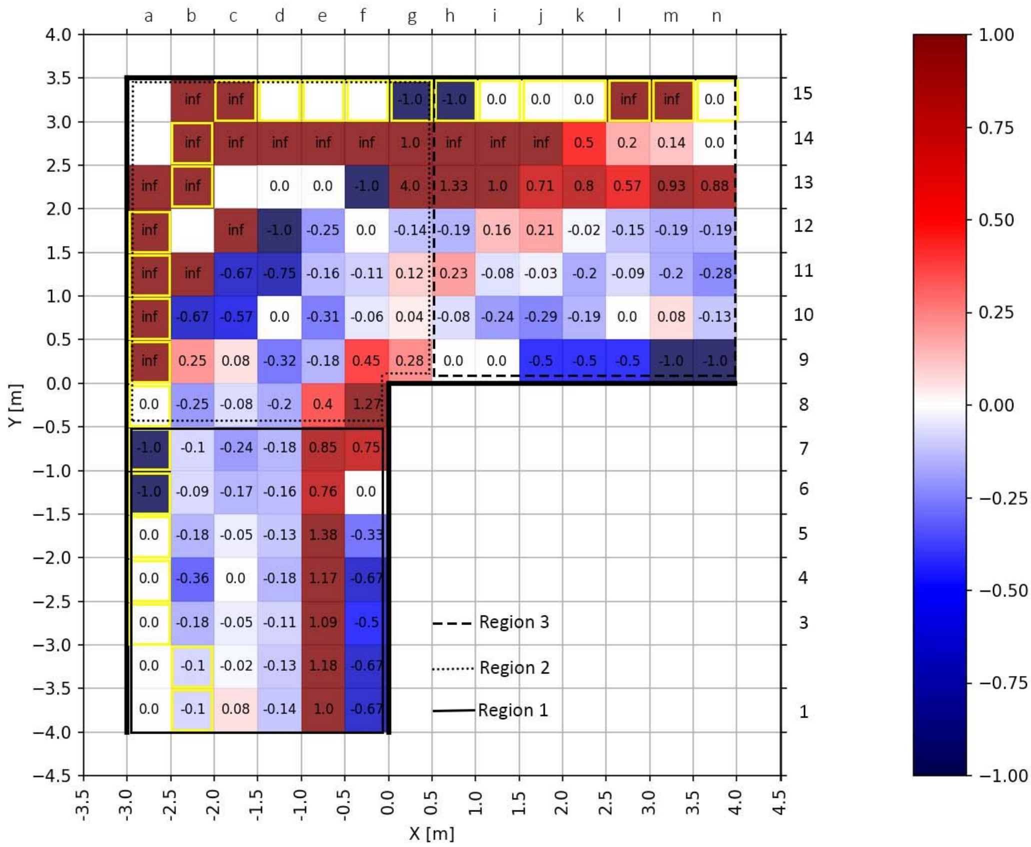


Figure 40. Comparison of trajectories between Average Multi VR and Average Single VR experiments. Yellow squares represent the virtual agents' travel paths.

4.4.4 Entrance and exit location

In Figure 41, the average of the trajectories obtained within Multi VR corridor A and Multi VR corridor B is compared to the average of the trajectories obtained in Single VR corridor A and Single VR corridor B. The comparisons separately by corridors can be found in sections 8.11 and 8.12. The same trend described below it is also found in those comparisons.

As it is illustrated in Figure 41, in both VR experiments, most of the people enter the corridor through the center lanes (c1,d1). However, more people in the Multi VR experiment enter through the grid cell e1, closer to the inner wall. It differs entirely from the travel path left by the virtual agents where they enter to the corridor along the outer wall. Then, when participants approach the corner, the tendency to move closer to the inner wall is kept, as it has been already mentioned in previous sections. The same happens when they finish navigating Region 2. Finally, in both experiments, most of the participants go out through the central grid. However, in the Multi VR experiment, 21% of people leave through grid cell n13 while 10% do it in the Single VR experiment. It is the moment where participants were closer to the path of the virtual agents. Virtual agents leave through grid cell n15.

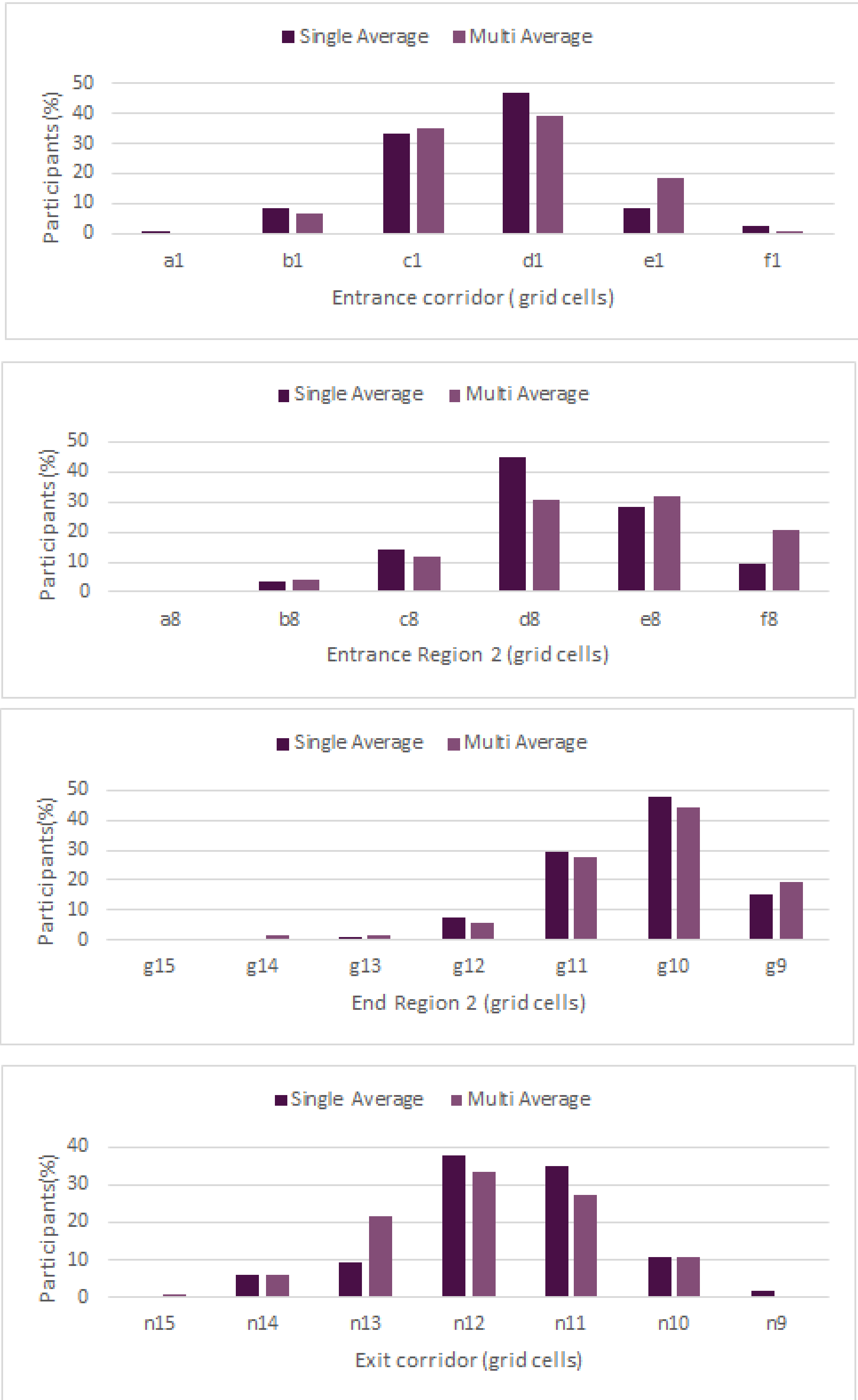


Figure 41. Multi Average-Single Average. Entrance and exit location.

5 Discussion

In this section, the results found are discussed by VR experiment. First, the outputs found for the Single VR experiment are compared to the results obtained in the laboratory experiment (Keip & Ries, 2009), making a cross-comparison validation between them. Then, the Multi VR experiment results were compared to the Single VR experiment outputs to identify if social influence was observed.

5.1 Single VR experiment

The results show that the trajectories obtained in the Single VR experiment had similarities to the travel paths found in the laboratory experiment (Keip & Ries, 2009). However, some differences were observed between the different travel paths obtained.

When comparing the trajectories in both the Laboratory experiment and the Single VR experiment, the walking path trend was similar. Participants walked on a straight path before the corner, keeping a certain distance from the inner wall. When they approached the 90° turn, they did not change their direction abruptly. Instead, they changed it gradually following a curved path, and the distance to the inner wall was reduced. After the turning region, participants tended to regain distance to the inner wall and walked in a straight manner again. The same walking pattern was also found in other studies(Dias et al., 2014a) and (Steffen & Seyfried, 2009).

Before the corner, in both experiments, most participants kept a distance higher or equal to 0.75 m to the inner wall, which suggests that most participants entered the corridor through the central lanes. After the corner, when participants tend to regain the distance from the inner wall, a difference was observed. In the Single VR experiment, the distance was the same as before the corner, while in the Laboratory experiment, the distance was reduced, and they moved closer to the inner wall. Most participants kept a distance equal to or higher than 0.25 m to the inner wall. This implies that participants were prone to walk closer to the inner wall in the Laboratory experiment after the curve path than in the Single VR experiment. Additionally, it was noticed that in the Laboratory experiment, participants did not approach the exterior wall, while in the Single VR experiment, some participants navigated within the whole corridor.

A possible explanation for this difference could be related to the controlling devices (keyboard-mouse) offered to navigate the virtual environment. Perhaps participants wanted to move closer to the inner wall after completing the turning movement, but they did not because they could not operate the equipment comfortably. Therefore, they did not move as naturally as they would in reality. This can be supported by the analysis performed by Kobes (2010), which recommended a joystick as a controlling device in non-immersive VR experiments. As explained before, in this VR experiment, no joystick could be provided. The joystick considered for the experiments by Kobes(2010) can be seen in Figure 5.

Additionally, participants knew that they were not being observed during the Single VR experiment. They could have felt free to navigate within the VE and move around the corridor. The opposite happened in the Laboratory experiment, where researchers were always present to give instructions and to observe how the participants behave within the Lab experiment.

Regarding the difficulty that the participants expressed to navigate the virtual corridors, no large difference was found in the trajectories concerning their answers. Although some of them assessed the navigation as difficult, when comparing those travel paths to the trajectories obtained from the participants who assessed it as easy, the travel path trends remained similar. Perhaps some participants found the task more challenging than others because they did not have previous experience navigating a virtual environment. Therefore, they could complete the task, but they still considered it difficult. There were some participants whose trajectories deviated from the pattern observed in the study. Perhaps they did not consider the experiment seriously, and they decided to explore the VE instead of finishing the task as requested.

5.2 Multi VR experiment

Participants were not prone to follow the virtual agents' paths, and they did not walk close to the outer wall. This behavior contrasts with the findings in previous studies that showed that participants followed somehow VA in VR experiments (Kinateder et al., 2014a; Kinateder et al., 2014b). Both studies took place in VR smoke-filled tunnels, and participants needed to find a way to evacuate. Perhaps as in the Multi VR experiment, participants were not facing an emergency, and there were not ambiguous cues, then participants could complete the task without following the VA. Additionally, they did not have to decide between different options as they just needed to walk through the corridor as they would do it in normal situations. Then, they were not influenced by the VA because VA's navigation behavior was other than what they would do alone. While evacuating from a fire in a tunnel required quick decision-making, participants may have felt that they did not know what to do. Then, they were influenced by how the VA were moving. Additionally, VA were moving towards the exit of the tunnel; then, in this context, social influence was a reinforcement to the expected behavior when evacuating.

In a general way, similar paths were obtained in the Single VR experiment where the virtual agents were not present. When the paths of the Multi and Single VR experiments were compared in detail, it was observed that before the corner, some people in the Multi VR experiment moved farther from the virtual agents but closer to the virtual agents after the corner. It seems that before the corner, participants avoided the virtual agents, but after the corner, they were more prone to follow them. Although 47% of participants replied that they were influenced in their walking behavior by the virtual agents, when their trajectories were analyzed, they were akin to the trajectories of the participants who replied that the VA did not influence them. Then, it was difficult to observe in which way they felt influenced by the virtual agents.

Social influence was difficult to observe clearly in the Multi VR experiment. A possible explanation for this is that virtual agents were approximately 4 m away. Experimental studies have shown that social influence is stronger when people are closer (Nilsson & Johansson, 2009). Additionally, the same study suggests that social influence is more notorious when there is a limitation of information, for instance, ambiguous fire cues in a fire evacuation. Putting this statement into the context of the Multi VR experiment, participants knew what they had to do, the instructions were clear, and they just needed to move through the corridors. Therefore, there was no need to observe what others did, and they could just complete their task on their own.

Finally, 52% of participants stated that they believed the three virtual agents were people playing at the same time as them. Therefore, telling participants that other players/participants are present in a VE, and tagged the virtual agents with common names may be a strategy to consider for future research. Research where there could be a need to make believe participants that virtual agents are people who are also part of the VR experiment.

5.3 Learning effect

It was intended to analyze whether making the participants walk through the 90° turning corridor twice a learning effect could be achieved. Then, it is necessary to assess how the trajectories in corridor B differ from those in corridor A. The results did not show a large difference between the trajectories obtained in both corridors for the Single and Multi VR experiments. The trajectories lengths remain similar, and the travel path patterns were closely akin. A possible explanation for the similarities found could be the simplicity of the task given. Perhaps participants did not need to change their trajectories as they completed the task successfully when moving through corridor A. Therefore, when passing through corridor B, participants could repeat the movement as they knew that they would not face any problems if they maintained the same behaviour. Similar results were found in Dias et al (2014 b) where participants also walked through a 90° turning corridor three times and their trajectories remained similar in the trials.

5.4 Conclusion

The Single VR experiment presented some similarities with the laboratory experiment concerning the travel paths. However, some differences were observed as the people in the Laboratory experiment were more prone to walk closer to the inner wall after the turning region in comparison to the Single VR experiment. Perhaps, the devices used to navigate within the VE may have affected the results. Therefore, future research could use a joystick as the one described by Kobes (2010) to navigate within the VE and observe if more accurate results could be obtained. Additionally, it would be interesting to perform an immersive virtual reality experiment, where participants could move in the VE using their feet, which is more akin to reality than navigating the VE with a mouse and keyboard.

Social influence was difficult to observe in the multi-VR experiment. This may be due to the simplicity of the task given to the participants. Future research could include the presence of virtual agents closer to the participants and give ambiguous cues to make the participants hesitate and feel the need to follow or avoid what others do.

More research is needed to apply the findings of this project to represent realistically the pedestrians walking behavior through 90° turning corridors in simulations or use them to calibrate evacuation models.

6 Acknowledgments

I would like to express my gratitude to the following people, without whom I would not have been able to complete this thesis and made it through the International Master of Science in Fire Safety Engineering (IMFSE).

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8 Appendices

8.1 Informed consent-Single VR experiment.

No seguro | solo.vrlab-vhuset.net

Informed consent

1. About
This online non-immersive virtual reality serious game will allow participants to walk around a virtual scenario with the presence of corridors.The purpose of the study is to analyze how people interact in the virtual scenario given.

2. Call for participants
You have had access to this non-immersive virtual reality serious game through a link posted in different platforms. Your participation is completely voluntary.

3. How does it work?
You will write down your age, nationality, and gender. You don't have to write your name; therefore, you can pick any nickname-username as you desire. Consequently, you will receive instructions in how to move in the game and a description about what you need to do.

4. Handling the data
The data to be presented in reports and articles will be encoded and it will not be possible to identify you in it. We will not have access to your contact information. Sensitive information as data about your gender will be shared in an aggregated form (e.g total number of participants of each gender)

5. How do I get information about the experiment results?
The results of the experiment will be published at Lund University's home page (http://lup.lub.lu.se/search/). We expect to publish the results during 2021.

6. Voluntary participation
Participation in the experiment is fully voluntary. You can stop the participation at any point of the experiment by closing the browser window on your computer.

7. Who is responsible for the experiment?
The responsible researcher is Jonathan Wahlqvist from the Department of Building and Environmental Technology. You can reach him by phone (+46 46 222 15 58).

By clicking "Start experiment" below you confirm that have accurately read out the informed consent and agree to participate on the experiment.

Start experiment

Consentimiento informado

1. Objetivo
Este juego serio en linea de realidad virtual no inmersiva permitira a los participantes caminar alrededor de un escenario virtual que contiene corredores. El objetivo de este estudio es analizar como las personas interactuan en el escenario virtual dado.

2. Llamado a participantes
Usted ha tenido acceso a este escenario virtual a traves de un enlace publicado en diferentes plataformas sociales. Su participacion es completamente voluntaria.

3. Como funciona?
Usted escribira su edad, nacionalidad y genero. Ud. no tiene que escribir su nombre, por lo tanto, puede escoger un nickname como lo desee. Posteriormente recibira mas instrucciones para saber como moverse en el juego y una descripcion de lo que necesita hacer.

4. Manejo de informacion
La informacion que estara presente en los reportes y articulos estara codificada y no sera posible identificarlo. No se tendra acceso a su informacion de contacto. Informacion sensible como el genero sera compartida en una manera general (ej.: Numero total de participantes de cada genero)

5. Como recibir informacion de los resultados?
Los resultados seran publicados en la pagina de la Universidad de (http://lup.lub.lu.se/search/). Se espera que sean publicados en el 2021.

6. Participacion voluntaria
La participacion en el experimento es completamente voluntaria. Usted puede parar su participacion cerrando la ventana del navegador.

7. Responsable del experimento
El investigador responsable es Jonathan Wahlqvist del Department of Building and Environmental Technology. Ud. puede contactarlo al telefono (+46 46 222 15 58).

Al hacer clic en "Iniciar experimento" a continuacion, confirma que ha leido con precision el consentimiento informado y acepta participar en el experimento.

Iniciar experimento

8.2 Informed consent-Multi VR experiment.

No seguro | multi.vrlab-vhuset.net

Informed consent

1. About
This online non-immersive virtual reality serious game will allow participants to walk around a virtual scenario with the presence of corridors.The purpose of the study is to analyze how people interact in the virtual scenario given.

2. Call for participants
You have had access to this non-immersive virtual reality serious game through a link posted in different platforms. Your participation is completely voluntary.

3. How does it work?
You will write down your age, nationality, and gender. You don't have to write your name; therefore, you can pick any nickname-username as you desire. Consequently, you will receive instructions in how to move in the game and a description about what you need to do.

4. Handling the data
The data to be presented in reports and articles will be encoded and it will not be possible to identify you in it. We will not have access to your contact information. Sensitive information as data about your gender will be shared in an aggregated form (e.g total number of participants of each gender)

5. How do I get information about the experiment results?
The results of the experiment will be published at Lund University's home page (http://lup.lub.lu.se/search/). We expect to publish the results during 2021.

6. Voluntary participation
Participation in the experiment is fully voluntary. You can stop the participation at any point of the experiment by closing the browser window on your computer.

7. Who is responsible for the experiment?
The responsible researcher is Jonathan Wahlqvist from the Department of Building and Environmental Technology. You can reach him by phone (+46 46 222 15 58).

By clicking "Start experiment" below you confirm that have accurately read out the informed consent and agree to participate on the experiment.

Start experiment

Consentimiento informado

1. Objetivo
Este juego serio en linea de realidad virtual no inmersiva permitira a los participantes caminar alrededor de un escenario virtual que contiene corredores. El objetivo de este estudio es analizar como las personas interactuan en el escenario virtual dado.

2. Llamado a participantes
Usted ha tenido acceso a este escenario virtual a traves de un enlace publicado en diferentes plataformas sociales. Su participacion es completamente voluntaria.

3. Como funciona?
Usted escribira su edad, nacionalidad y genero. Ud. no tiene que escribir su nombre, por lo tanto, puede escoger un nickname como lo desee. Posteriormente recibira mas instrucciones para saber como moverse en el juego y una descripcion de lo que necesita hacer.

4. Manejo de informacion
La informacion que estara presente en los reportes y articulos estara codificada y no sera posible identificarlo. No se tendra acceso a su informacion de contacto. Informacion sensible como el genero sera compartida en una manera general (ej.: Numero total de participantes de cada genero)

5. Como recibir informacion de los resultados?
Los resultados seran publicados en la pagina de la Universidad de (http://lup.lub.lu.se/search/). Se espera que sean publicados en el 2021.

6. Participacion voluntaria
La participacion en el experimento es completamente voluntaria. Usted puede parar su participacion cerrando la ventana del navegador.

7. Responsable del experimento
El investigador responsable es Jonathan Wahlqvist del Department of Building and Environmental Technology. Ud. puede contactarlo al telefono (+46 46 222 15 58).

Al hacer clic en "Iniciar experimento" a continuacion, confirma que ha leido con precision el consentimiento informado y acepta participar en el experimento.

Iniciar experimento

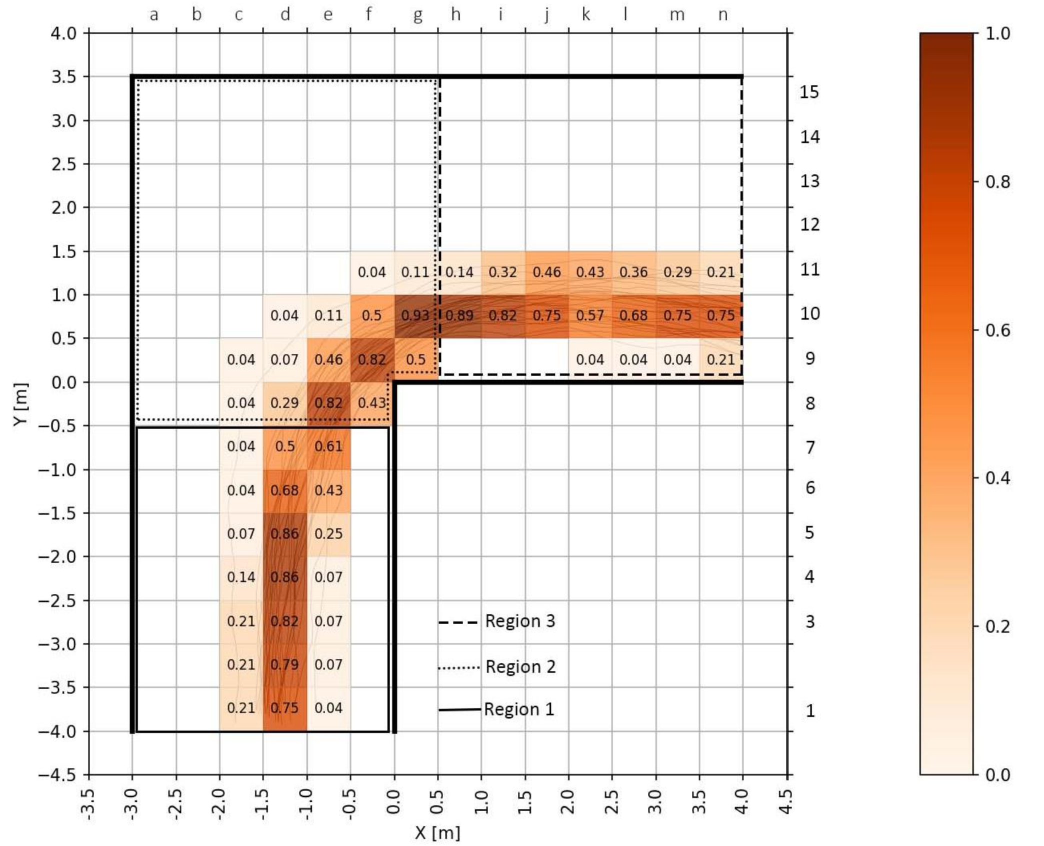
8.3 Single VR experiment data collected (one participant)

Movement: 1				
UserName	Age	Gender	Nationality	Country
Alisson Ricardo	44	Male	Brazilian	Brazil
Time	X	Y	Rotation	Zone
0	-1.632859	-4.201835	271.0793	A
0.1093063	-1.629774	-4.038056	271.0793	A
0.226387	-1.626687	-3.874181	271.0793	A
0.3429108	-1.623614	-3.711075	271.0793	A
0.4593658	-1.620543	-3.548066	271.0793	A
0.5758972	-1.61747	-3.384947	271.0793	A
0.6765442	-1.614816	-3.244068	271.0793	A
0.7921066	-1.611769	-3.082306	271.0793	A
0.8927155	-1.609116	-2.941484	271.0793	A
1.009956	-1.606024	-2.777377	271.0793	A
1.125816	-1.602969	-2.615195	271.0793	A
1.225937	-1.600329	-2.475052	271.0793	A
1.325981	-1.597691	-2.335021	271.0793	A
1.426033	-1.595052	-2.194969	271.0793	A
1.542557	-1.59198	-2.031863	271.0793	A
1.659286	-1.588902	-1.868477	271.0793	A
1.759377	-1.586262	-1.728376	271.0793	A
…	…	…	…	A
7.652641	4.163994	1.632384	1.279269	A
21.12348	-1.360265	-4.127033	358.8793	B
21.22683	-1.357435	-3.982378	358.8793	B
21.34251	-1.354267	-3.820465	358.8793	B
21.45859	-1.351089	-3.657976	358.8793	B
21.55868	-1.348348	-3.517885	358.8793	B
21.65925	-1.345594	-3.377106	358.8793	B
21.76356	-1.342738	-3.2311	358.8793	B
21.86782	-1.339883	-3.085163	358.8793	B
21.96935	-1.337102	-2.943048	358.8793	B
22.07312	-1.334261	-2.797798	358.8793	B
22.17587	-1.331448	-2.653984	358.8793	B
22.29221	-1.328261	-2.491125	358.8793	B
22.39231	-1.325521	-2.351011	358.8793	B
22.49259	-1.322775	-2.210653	358.8793	B
22.59293	-1.320027	-2.070211	358.8793	B
22.70956	-1.316833	-1.906954	358.8793	B
…	…	…	…	B
28.67735	4.167461	1.195805	230.2793	B

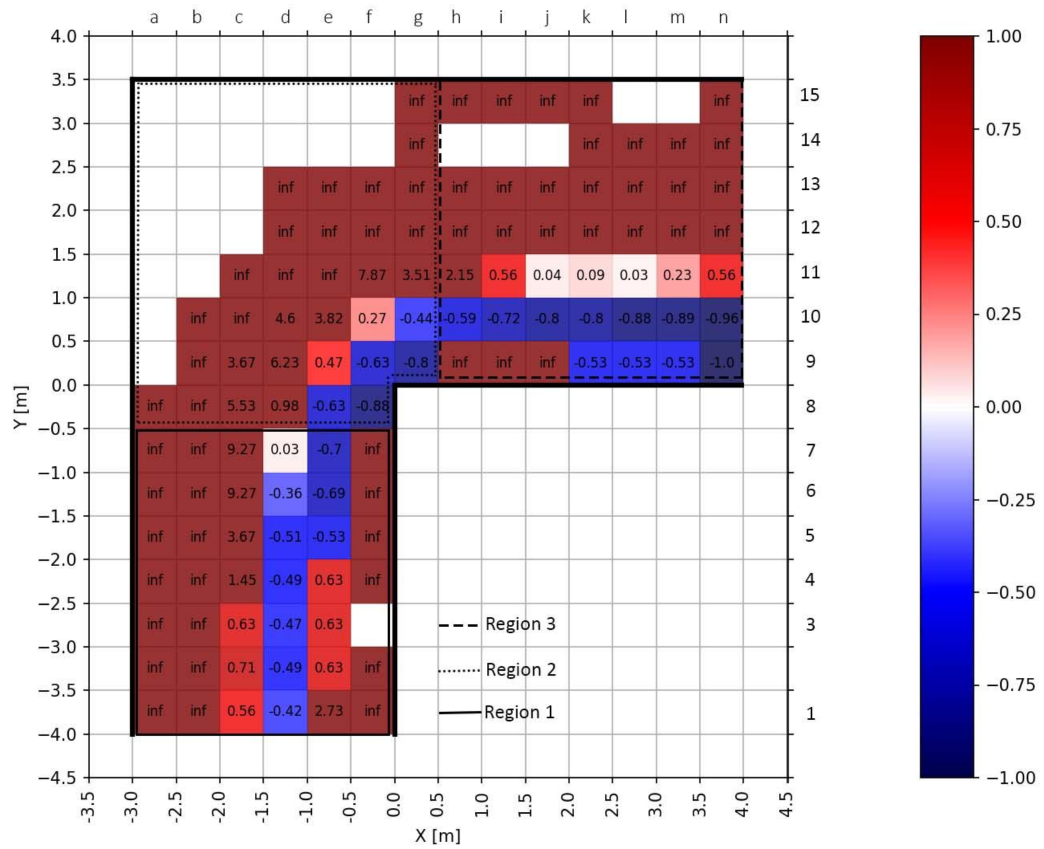
8.4 Multi VR experiment data collected (one participant)

Movement: 1	Agent: No	Influnce:No		
UserName	Age	Gender	Nationality	Country
Alexis	30	Masculino	Colombiano	Colombia
Time	X	Y	Rotation	Zone
0	-0.6226814	-4.158553	273.0792	A
0.1742249	-0.6076405	-3.878958	273.0792	A
0.2742233	-0.6094997	-3.739049	268.2792	A
0.3742218	-0.6175296	-3.599329	266.0792	A
0.4742203	-0.6357305	-3.460621	261.4792	A
0.5742188	-0.6559656	-3.322116	261.4792	A
0.6742249	-0.6746719	-3.183378	262.4792	A
0.7742233	-0.6911323	-3.044355	263.4792	A
0.8742218	-0.6958334	-2.90456	269.2792	A
0.9742203	-0.6970093	-2.764601	269.8792	A
1.074219	-0.6974809	-2.624609	269.8792	A
1.174225	-0.6978114	-2.484611	269.8792	A
1.274223	-0.6981137	-2.344612	269.8792	A
1.374222	-0.6984098	-2.204612	269.8792	A
1.47422	-0.6983144	-2.064612	270.0792	A
1.574219	-0.6981404	-1.924612	270.0792	A
1.674225	-0.6979511	-1.784612	270.0792	A
…	…	…	…	A
6.774223	4.32677	1.74062	354.6792	A
20.27422	-1.234433	-3.953022	0.6792159	B
20.37422	-1.236093	-3.81303	0.6792159	B
20.47422	-1.237753	-3.67304	0.6792159	B
20.57422	-1.239412	-3.533051	0.6792159	B
20.67422	-1.241072	-3.393061	0.6792159	B
20.77422	-1.242731	-3.253071	0.6792159	B
20.87422	-1.244391	-3.113081	0.6792159	B
20.97422	-1.246051	-2.973089	0.6792159	B
21.07422	-1.24771	-2.833099	0.6792159	B
21.17422	-1.24937	-2.69311	0.6792159	B
21.27422	-1.251029	-2.55312	0.6792159	B
21.37422	-1.252689	-2.41313	0.6792159	B
21.47422	-1.253567	-2.273132	0.2792159	B
21.57422	-1.252724	-2.133139	359.4792	B
21.67422	-1.241392	-1.993696	354.2792	B
21.77422	-1.208027	-1.858213	343.8792	B
…	…	…	…	B
27.17422	4.335469	1.891554	253.0792	B

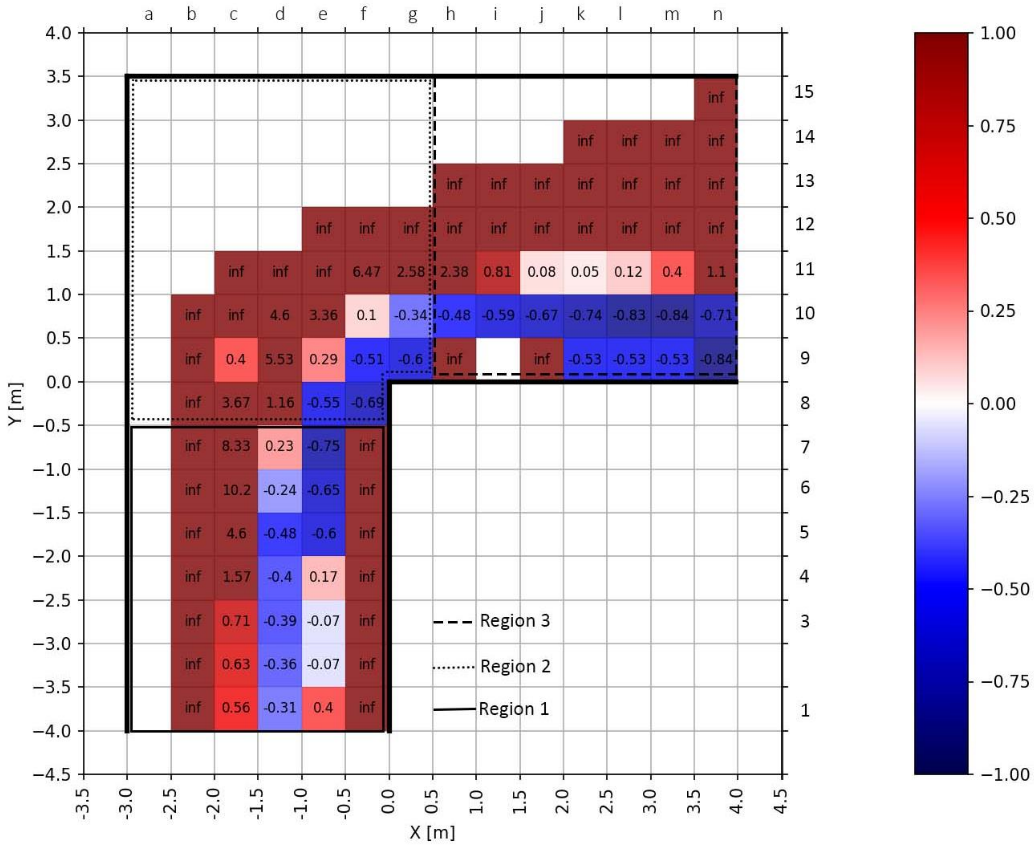
8.5 Quantification of the trajectories in the Laboratory experiment



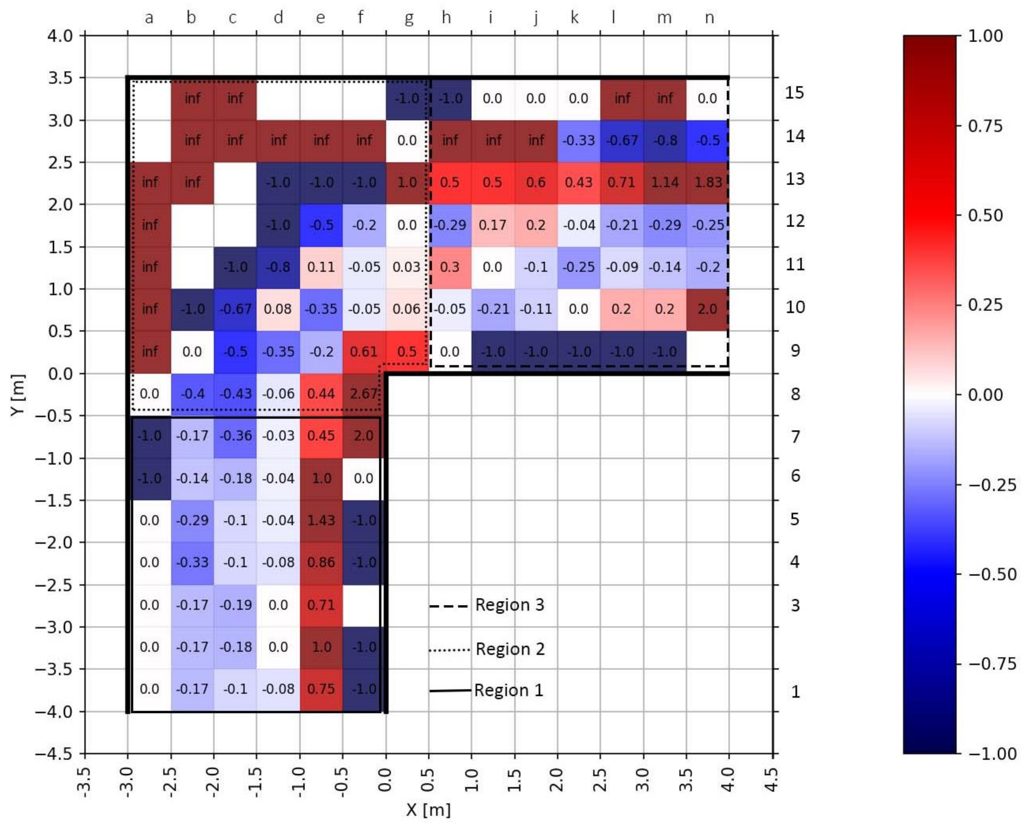
8.6 Comparison of the trajectories: Single VR: corridor A -Laboratory experiment



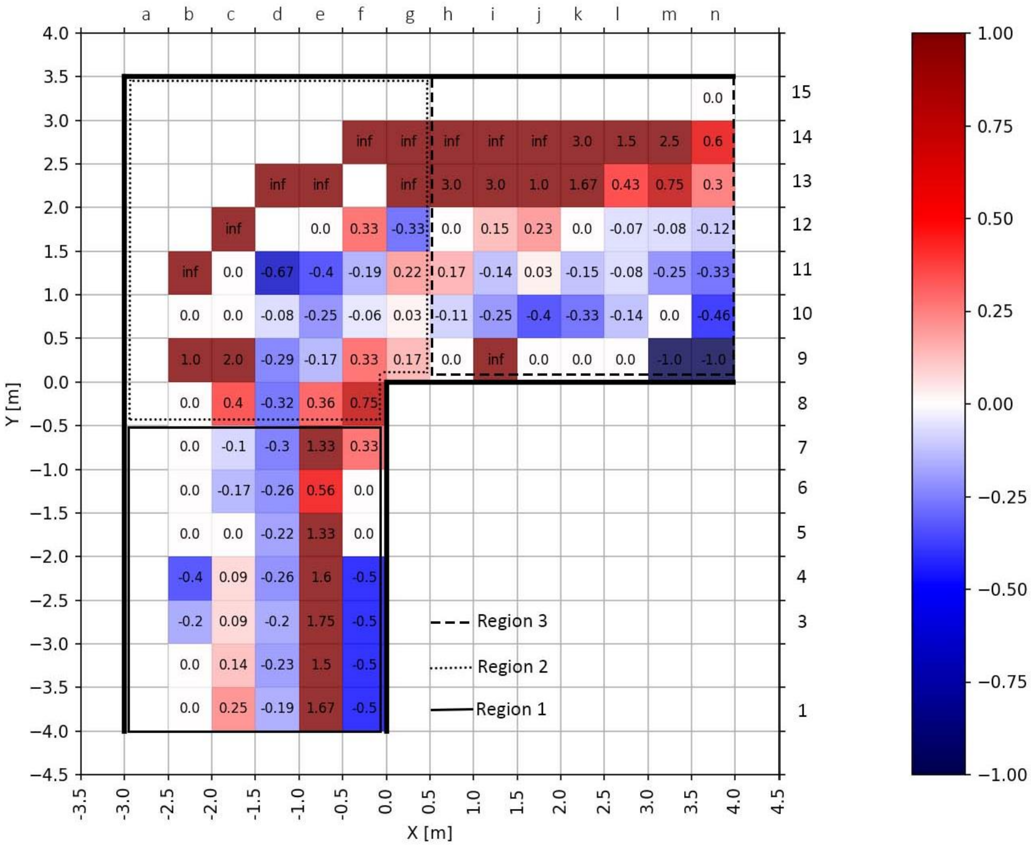
8.7 Comparison of the trajectories: Single VR: corridor B - Laboratory experiment



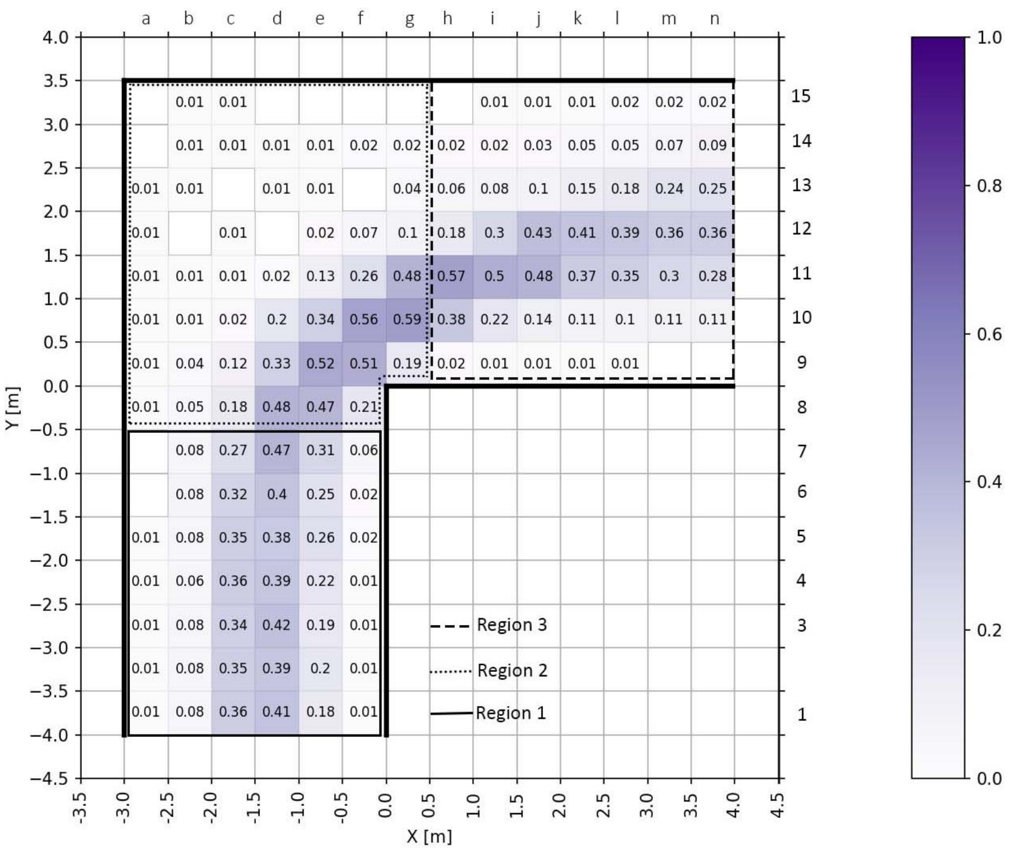
8.8 Comparison of the trajectories: Multi VR: corridor A - Single VR: corridor A



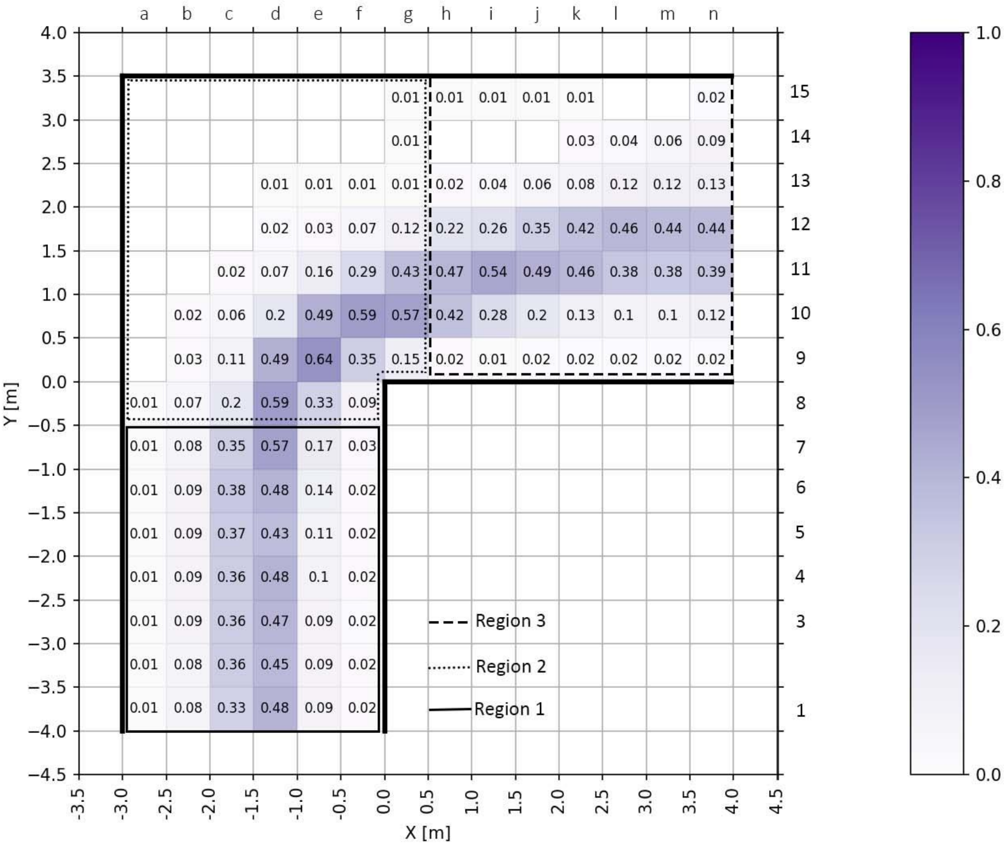
8.9 Comparison of the trajectories: Multi VR: corridor B - Single VR : corridor B.



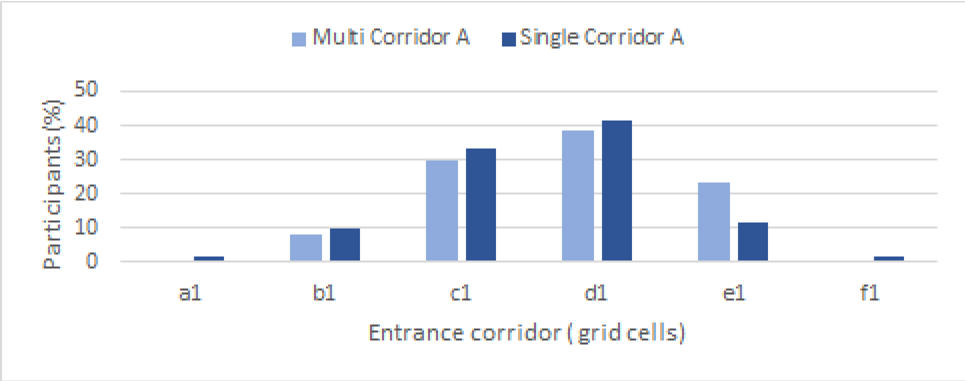
8.10 Multi VR experiment: Average of the trajectories corridor A and corridor B

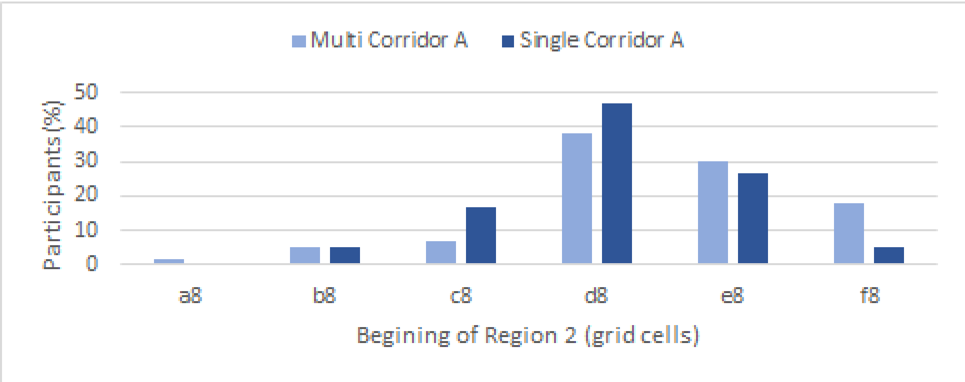


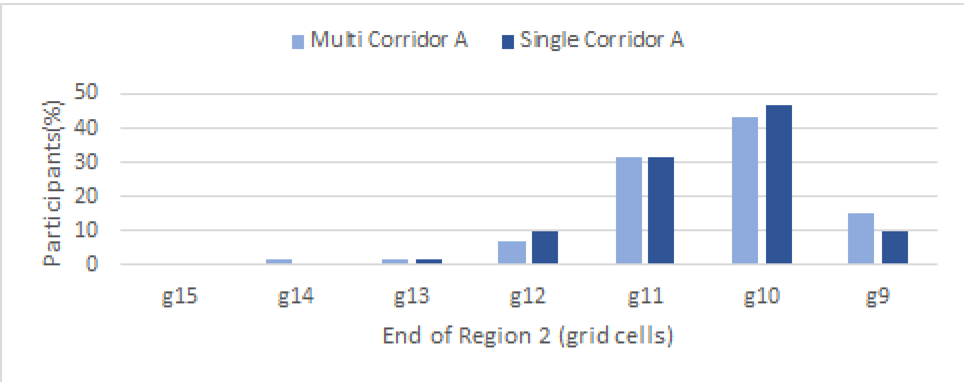
8.11 Single VR: Average of the trajectories corridor A and corridor B.

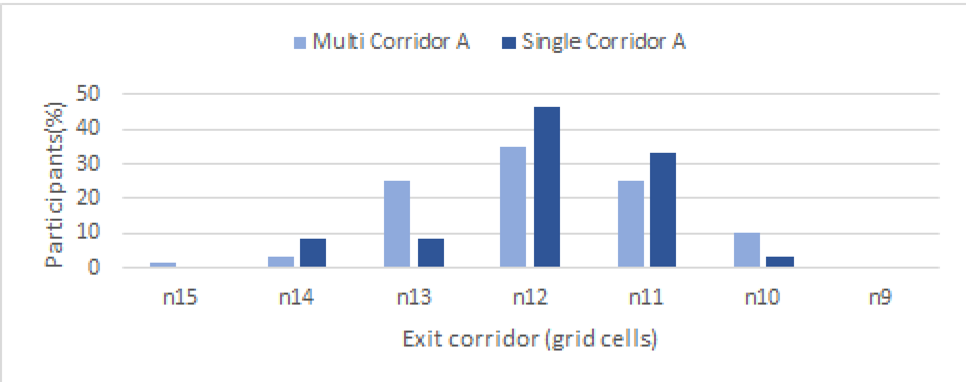


8.12 Entrance and exit location: Multi VR corridor A-Single VR corridor A









8.13 Entrance and exit location: Multi corridor B-Single Corridor B