Pedestrian Wayfinding and Evacuation in Virtual Reality

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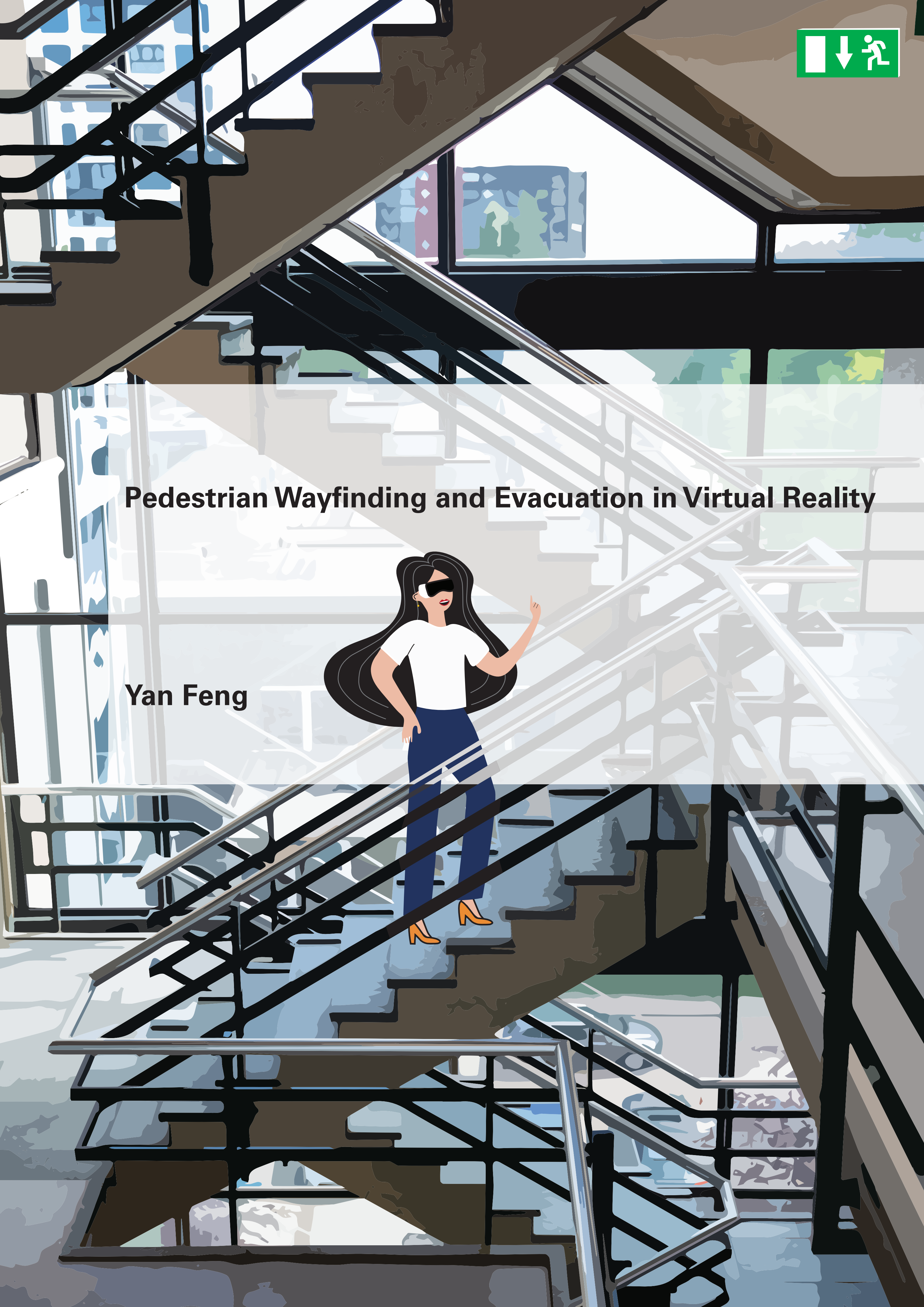

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Yan Feng

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Delft University of Technology

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Pedestrian Wayfinding and Evacuation in Virtual Reality

Dissertation

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Nothing in life is to be feared, it is only to be understood.
Now is the time to understand more, so that we may fear less.

— *Maria Skłodowska*-Curie

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Five years ago, I was sitting in the audience of PED conference 2016. At that time, I was a master student wondering where the future leads. Shall I continue my research and start PhD? Or shall I choose what was typically expected for a female: find a stable job, get married, and life goes on. Then I heard all the pedestrian researchers passionately talk about their research; their enthusiasm, passion, and expertise moved me deeply. That is when my decision was made. One year later, I started my PhD journey at Delft University of Technology, the Netherlands. A country I had never visited but I was sure an exciting journey is ahead.

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Yan

Germany, December 2021

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Chapter 1

Introduction

How did you, the reader, find the place where you are reading this thesis? Every day people find their way through buildings while moving from one location to another. Data collection featuring pedestrian wayfinding behaviour are needed in order to understand this behaviour process to ensure pedestrian safety. Collecting accurate data is not a simple task, in particular in situations where subjects are potentially at risk. Virtual Reality (VR) provides the possibility to study pedestrian wayfinding choice behaviour with high experimental control in various situations, such as complex buildings and dangerous scenarios. This thesis explores the usage of VR to study pedestrian wayfinding behaviour under normal and emergency conditions, from simple buildings to complex buildings.

This chapter outlines the objective, research questions, approach, and contributions of this thesis. Section 1.1 sketches how researchers are currently studying pedestrian behaviour. In particular, it introduces the background of existing data collection endeavours for pedestrian wayfinding behaviour and identifies the current research gap regarding using VR to study pedestrian wayfinding behaviour. Section 1.2 presents the research objective, scope, and research questions that will be pursued in this thesis. Section 1.3 describes the research approach was adopted through the research in order to address the research questions. Section 1.4 discusses the scientific and practical contributions of this thesis. Finally, the outline of the thesis is presented in section 1.5.

1.1 Research background and problem statement

Walking is an essential active mode of transportation and remains a main component of people's daily physical activity. Pedestrians perceive their environment while walking. Their behaviour is the result of interacting continuously with the surrounding environment and people within a dynamic process (Feng et al., 2021a).

Walking through buildings is a daily activity for pedestrians. This behavioural process may be as easy as moving from one room to another or as difficult as trying to evacuate from a complex building due to an emergency (Dogu & Erkip, 2000). A thorough understanding of pedestrian wayfinding behaviour in buildings is essential in order to ensure pedestrian safety and design efficient buildings. In order to understand the decision-making process and movement behaviour of pedestrians in buildings, it is vital to collect pedestrian behaviour data. Essential to analyse and understand pedestrian behaviour are data collection efforts featuring pedestrian behaviour using data collection methods. Previous studies used a variety of data collection methods to collect data regarding pedestrian behaviour (Feng et al., 2021a), including field observations (e.g., Moussaïd et al., 2010), controlled experiments (e.g., Hoogendoorn & Daamen, 2004) and survey methods (e.g., Duives & Mahmassani, 2012).

Despite the usefulness of contemporary data collection methods, they have restrictions concerning the pedestrian behaviours that can be studied using these methods. To name a few, there are privacy-related restrictions regarding the recording of pedestrians in public space via field observations, ethical constraints concerning the creation of real, stressful and dangerous experiments to collect behaviour data via traditional controlled experiments, and the recall accuracy of participants is limited via survey methods (Feng et al., 2021a). All these restrictions lead to a lack of some behavioural data with respect to pedestrian wayfinding behaviour. In particular, data featuring pedestrian behaviour in dangerous or futuristic environments, highly complex large-scale environments and complex interaction scenarios.

These restrictions might be overcome by the usage of Virtual Reality (hereafter named VR) technologies to study pedestrian behaviours. With advances in high-quality simulations technology and computer processing power, realism and validity of VR have been enhanced quickly. Thus, VR is becoming an interesting research approach, also for the study of pedestrian behaviour as this new technology allows researchers to have complete experimental control and collect accurate behavioural data (e.g., trajectory, speed, gaze points). Compared with traditional laboratory experiments or survey methods, VR also allows participants to be immersed in virtual environments that they are either not likely to encounter in real-life or which are too dangerous to expose a participant to voluntarily due to the potential health risks (Feng et al., 2021a).

Given this potential, researchers have begun to explore VR as a relatively novel technique to investigate pedestrian wayfinding behaviour during evacuations, which showed promising results. The literature pertaining the use of VR for pedestrian research mainly features the impact of social behaviours (e.g., Kinateder et al., 2014a; Bode et al., 2015; Cao et al., 2019) and the impact of information on wayfinding behaviour of pedestrians during evacuations (e.g., Tang et al., 2009; Kobes et al., 2010b; Kinateder et al., 2019). The application of VR technologies is therefore expected to be a valuable complement to the current experimental method toolbox to study pedestrian behaviour.

Yet, it is currently unclear to what extent VR technologies can enhance a researcher's toolbox to study pedestrian wayfinding behaviour. Through literature studies, the following research gaps were identified. First of all, the lack of validation data is a major concern to existing research endeavours, as without validation, it is unknown whether the results from any VR experiments align with the actual behaviours of pedestrians in the real world (Kinateder & Warren, 2016). Secondly, existing research have predominantly studied simplified virtual environments, mostly in a single level of a building. Pedestrian wayfinding behaviour is affected by the layout of the architectural setting and the quality of the environmental information (Dogu & Erkip, 2000). Since the complexity and difficulty of pedestrian movements in complex environments are very different (Jeffery et al., 2013), findings pertaining to simplified environments cannot be directly generalised to complex buildings. Moreover, some VR studies recorded issues such as lack of natural movements, missing details of real-life situations, which might lead to the unrealistic perception of the virtual environment. Consequently, studies that use VR to study pedestrian wayfinding behaviour in complex buildings are rare. Third, another unresolved issue is that the suitability of different VR technologies for pedestrian behaviour research is still undetermined. Different VR technologies have different characteristics and may cause people to interact and perceive the virtual environment differently (Santos et al., 2009). To date, only a few studies have directly compared the presentation of the same virtual environment using different VR technologies on pedestrian behaviour (e.g., Hsieh et al., 2018; Ronchi et al., 2019; Ruddle et al., 1999). Consequently, the knowledge regarding the effectiveness of different VR technologies is still limited. Thus, in order to provide a complete picture of the possible differences between different VR devices and explore the possibilities of using VR technologies for the study of pedestrian wayfinding behaviour, there is a strong need for studies that test the behavioural differences and perceptual differences using different VR devices.

1.2 Research objective, questions, and scope

This thesis aims to determine the capability of using VR technologies in collecting valid data featuring pedestrian wayfinding behaviour and thereby allow us to better understand pedestrian wayfinding behaviour in buildings. Thus, the main research objective of this thesis is formulated as:

'To understand to what extent VR technologies can be used to study pedestrian wayfinding behaviour in buildings.'

In order to achieve the research objective, four research questions will be answered:

1. What are the most essential gaps of contemporary data collection methods for collecting pedestrian behavioural data and what are the possibilities and challenges of using VR to (partly) fill in these gaps?

The outcomes of the above-mentioned research question provide insights for identifying the possibilities and challenges while applying VR for pedestrian behaviour research. Based on these insights and the identified research gaps in section 1.1, namely lack of (1) validation studies, (2) pedestrian wayfinding behaviour studies in complex environments and (3) comparison between different VR technologies, the following research questions were formulated:

2. How valid are the behavioural results generated by VR for use in pedestrian wayfinding behaviour study?

According to the identified research gaps, one of the main concerns of using VR to study pedestrian wayfinding behaviour is the lack of validation study, namely studies investigate whether the behavioural data collected through VR is valid. This research question focuses on the validation of behavioural data collected through VR from several aspects, namely ecological validity, construct validity, content validity and face validity (Deb et al., 2017).

3. What are the requirements and procedures of designing and developing a VR research tool to study pedestrian wayfinding behaviour in multi-story buildings?

A VR research tool is a VR application that is capable to perform wayfinding experiments and collect sufficient behavioural data. One of the research gaps is that few studies have investigated pedestrian wayfinding behaviour in multi-story and complex buildings. To do so, it is necessary to develop a VR research tool that supports researchers to systemically study pedestrian wayfinding behaviour in a complex building. This research question focuses on identifying the key functional requirements and design procedures of such a VR application.

4. What are the behavioural and perceptual similarities and differences of using different VR technologies to study pedestrian wayfinding behaviour?

Another identified research gap is that studies that compare the usage of different VR technologies to study pedestrian wayfinding behaviour are still rare. Different VR technologies have different characteristics, it may cause people to interact and perceive the virtual environment differently (Santos et al., 2009). This research question focuses on investigating the similarities and differences of pedestrian wayfinding behaviour (e.g., route choice, exit choice, wayfinding performance) and perception of the virtual environment (e.g., realism, simulation sickness, presence, usability) among different VR technologies.

The scope of this thesis is pedestrian wayfinding behaviour in buildings, considering decision making (e.g., route and exit choice), wayfinding task performance (e.g., time, speed, distance), and observation behaviour (e.g., head rotation, gaze point, hesitation) (Ruddle and Lessels, 2006). From a traffic engineering point of view, pedestrian behaviour can be classified using a hierarchical structure consisting of three levels, being strategic, tactical and operational levels (Hoogendoorn & Bovy, 2004). This thesis focuses on pedestrian wayfinding behaviour at the tactical level (e.g., route choice, exit choice) of the behavioural taxonomy. Additionally, pedestrian behaviour at the strategic level (e.g., wayfinding strategy) and pedestrian's observation behaviour (e.g., hesitation, head rotation) are also analysed. However, detailed analyses of pedestrian behaviour at the operational level is out of the scope of this thesis. Meanwhile, the research conducted in this thesis is principally empirical. Data collection of data featuring pedestrian wayfinding behaviour under normal and emergency conditions, from simple buildings to complex buildings are both taken into account. This means that the computational modelling perspective of understanding pedestrian behaviour is not included in the thesis. Moreover, this thesis only considers individual wayfinding behaviour rather than collective behaviour. Furthermore, three different types of VR are employed in this thesis, namely Mobile VR, Desktop VR and HMD VR. Relatively, these VR technologies are more easily accessible and affordable for most researchers. Thus, the use of Cave Automatic Virtual Environment (CAVE) is not considered in this thesis.

1.3 Research approach

The methodology for this research involves literature study, setup and performance of empirical experiments, and data analysis of pedestrian behaviour. To accomplish the above research objective, first of all, it is important to review the use of contemporary data collection methods to study pedestrian behaviour in order to identify research gaps and potential opportunities for using VR. Secondly, data collection of pedestrian wayfinding behaviour in buildings is necessary in order to gain empirical insights. Empirical data were collected and analysed both via VR experiments and field experiments in order to validate the results. Moreover, different VR technologies were employed in order to compare and understand the impact of technological differences on pedestrian behaviour and their perception. To be more specific, the following approaches were applied in order to achieve the research objective and address the research questions:

In order to identify the research gaps in the current data collection method toolbox and determine the potential of VR technology as part of this toolbox to address these gaps, a systematic review was first conducted. It reviews the empirical studies that use traditional and emerging data collection methods to collect and investigate pedestrian behaviour. Meanwhile, in order to establish the potential of a data collection method, one needs to determine the different types of pedestrian behaviour and whether a data collection method is able to study certain types of behaviour. A taxonomy was developed which represents the decision-making process of pedestrian behaviour. Together with the literature review and the taxonomy, the following research question are answered: *1. What are the most essential gaps of contemporary data collection methods for collecting pedestrian behavioural data and what are the possibilities and challenges of using VR to (partly) fill in these gaps?*

As a first step of the empirical study, a VR experiment was conducted, in which mobile-based HMD VR is employed in order to determine whether simple VR devices could be used to study pedestrian exit choice behaviour. The aim of this study was to investigate whether VR can be used to study pedestrian exit choice behaviour during an evacuation. The study compares exit choice behaviour during a real-life evacuation drill and a VR experiment that covers exactly the same situation. Based on the validation results, the impact of different guidance information on pedestrian exit choice was further investigated. It answers the research questions: *2. How valid are the behavioural results generated by VR for use in pedestrian wayfinding behaviour study?*

Based on the promising results from the first VR experiment, the possibility of using more advanced VR devices to investigate pedestrian and exit choice behaviour in a more complex environment is explored. A VR research tool was designed in order to investigate pedestrian wayfinding behaviour in a complex building, which supports free movement in any directions, collects pedestrian position, head movement and gaze points automatically in the virtual environment. It answers the research question: *3. What are the requirements and procedures of designing and developing a VR tool to study pedestrian wayfinding behaviour?*

Applying this VR research tool, pedestrian wayfinding behaviour using a HMD VR and a Desktop VR was investigated, which aims to understand the possible behavioural differences and perceptual differences by applying different VR technologies to study pedestrian behaviour. It answers the research question: *4. What are the behavioural and perceptual similarities and differences of using different VR technologies to study pedestrian wayfinding behaviour?*

1.4 Main contributions

In this section, the main scientific and societal contributions of this thesis are briefly highlighted in section 1.4.1 and 1.4.2.

1.4.1 Scientific contributions

This thesis provides both theoretical and methodological contributions related to pedestrian wayfinding behaviour, pedestrian evacuation behaviour, usage of VR in pedestrian behaviour research and human-computer interaction. They are presented below in the order-of-appearance in the thesis and the details can be found in the corresponding chapters.

Inventory of research gaps in current data collection methods for pedestrian behaviour studies and pinpoint opportunities for new technologies to bridge these gaps (Chapter 2).

A systematic review was conducted which aims to identify the gaps in current data collection methods for pedestrian behaviour studies and pinpoints opportunities for new technologies (i.e., VR, crowd monitoring and Internet of Things) to bridge these gaps. In order to achieve this aim, this chapter determines the capabilities of contemporary data collection methods regarding the study of pedestrian behaviour using a new taxonomy. This study contributes to the existing literature in four ways: (1) it develops a pedestrian behaviour taxonomy that can be used to classify the broad range of pedestrian behaviour; (2) it presents a comprehensive review of experimental pedestrian behaviour studies with a specific focus on the capabilities of the adopted data collection methods to study pedestrian behaviour; (3) it identifies the most essential gaps of the contemporary data collection methods for pedestrian behaviour research; and (4) it discusses how new technologies can potentially bridge these gaps.

Validation of the usage of mobile-based VR to study pedestrian exit choice during evacuations (Chapter 3).

The validation study contributes to the literature by providing proof of the ecological validity of the mobile-based VR simulator using the results from a field experiment and a VR experiment. This study compares pedestrian exit choice behaviour during a real-life evacuation drill and a VR experiment that covers exactly the same situation. It is one of the first studies that validates using mobile-based VR to study pedestrian exit choice during evacuations. The results demonstrated that the combination of smartphone-based HMD and 360◦ videos can be used to conduct evacuation experiments under controlled experimental conditions, which allows researchers to control specific variables of interest systematically and to test pedestrian exit choice behaviour in well-specified scenarios.

Insights into the influence of the different types of information on pedestrian exit choice during evacuations (Chapter 3).

Based on the validation results, the mobile-based VR simulator is used to determine to what extent different types of information (i.e., visibility of exit signs, directional information, and the presence of other people) influence pedestrian exit choice behaviour. In particular, four different information strategies were realised in the VR experiment and the effects of these strategies on pedestrian exit choice behaviour were examined with VR experiments. The result shows that the presence of other pedestrians and directional signs have a significant influence on the participants' exit choice. Meanwhile, it helps researchers understand the potential of using cost-efficient smartphone-based HMD to investigate pedestrian evacuation choice behaviour.

A new VR research tool that with high detail, realism, and immersion (Chapter 4).

A VR research tool is developed which aims to study pedestrian wayfinding behaviour in a complex multi-story building. To the best knowledge of the author, this is the first VR tool that features a real-life multi-story building at a high level of detail, realism, and immersion. It supports free navigation in all directions, collects pedestrian walking trajectory, head movement and gaze point automatically. Meanwhile, five main functional requirements were identified regarding the development of a VR research tool in order to study pedestrian wayfinding behaviour in complex buildings. Moreover, the development process of the VR tool was detailed which including (1) choice of the virtual environment, (2) construction of the virtual environment, and (3) implementation of the interactive elements in the virtual environment. Together, it provides guidance for researchers who are interested in building their own VR applications.

A method to compare pedestrian choice behaviour and user experience for various types of VR (Chapter 5).

This thesis determines the impact of the technological difference of VR technology impact participant’s wayfinding behaviour in a complex multi-level building and the user experience of the VR technology. Pedestrian behavioural data (i.e., pedestrian route and exit choice, task performance, gazing behaviour) and questionnaire data (i.e., realism, simulation sickness, presence, usability) were compared between two groups of participants, where one group used the HMD VR and another group used the Desktop VR. This study provides the first direct comparison of VR technologies regarding the differences in pedestrian wayfinding behaviour and user experience in a complex multilevel building. Recommendations are made regarding the choice of VR when investigating pedestrian wayfinding behaviour in complex buildings.

Exemplars of investigating pedestrian behaviour using various types of VR (Chapter 3 & 4 & 5).

In this thesis, VR experiments were conducted with different types of VR technology (i.e., Mobile VR, HMD VR and Desktop VR) and several questionnaires (i.e., face validity, usability, presence, simulation sickness). The experimental method is evaluated through collected pedestrian behaviour data and user experience data. This combination allows us to gain insights into pedestrian wayfinding and human-computer interaction. The thesis demonstrates the developed experimental set-up is useful, valid, and reliable for investigating pedestrian wayfinding behaviour. Meanwhile, it provides researchers the evidence of using different types of VR technology to investigate pedestrian wayfinding behaviour in both normal and emergency situations.

Empirical data sets pertaining to pedestrian wayfinding behaviour during normal and evacuation conditions.

This thesis contributes new empirical data sets featuring pedestrian wayfinding behaviour from simple scenarios to complex scenarios, and from normal conditions to evacuation conditions. In combination with personal characteristics, the user experience results from the questionnaire and detailed behavioural data collected through VR (i.e., movement trajectory, head movement, gaze points), more detailed information is available with respect to the available aspects to investigate pedestrian wayfinding behaviour. It contributes new findings based on systematically collected data, especially pedestrian wayfinding strategies in complex buildings, pedestrian gazing behaviour, and human behaviour and its relationship to technology.

1.4.2 Societal contributions

Besides the scientific contributions, the results from this thesis also provide contributions to practice and society. The main implications are discussed in this section.

Insights about impacts of guidance information for evacuation management.

First, this thesis provides valuable insights for fire and security officers. The findings regarding pedestrian evacuation behaviour provide insights to evacuation managers to develop (better) strategies to facilitate efficient evacuation, for instance, what kind of guidance information is beneficial in order to use exits evenly and avoid crowds in front of exits.

A VR tool for practitioners testing new infrastructure design and information strategies.

Second, this thesis provides a ready-to-use VR research tool that can simulate a variety of contexts which is able to facilitate designing comfortable buildings and ensure pedestrian safety. Practitioners may test how hypothetical or planned environmental change might affect pedestrian behaviour by manipulating the virtual building. It can be used to test new infrastructure design and information strategies before they are implemented in the field. For instance, it could be potential used to test the effect of COVID-related measures (e.g., signs on the floor) on pedestrian wayfinding behaviour in the building in order to choose the most effective measures to distribute pedestrian flow evenly. Meanwhile, this tool provides the opportunity to create dangerous situations, such as building fires, earthquakes. It could be used to train evacuation management personnel or to test evacuation planning before it is implemented.

Guidance for practitioners using VR experiment method to evaluate pedestrian-related design.

Last but not least, the experimental setup in this thesis can be used for designers, architects and urban planners through their design process. VR has been rapidly applied in the designing process in the field of building design, sign design and infrastructure design. This thesis provides valuable guidance for testing interaction between pedestrians and hypothetic scenarios (e.g., new building designs and new transportation infrastructure). The experimental setup helps to evaluate the design which can be used to improve the design in an early stage of the design process before it is finally implemented.

1.5 Outline

The thesis outline is illustrated in Figure 1.1. The research questions posed in Section 1.2 are addressed in Chapter 2-5, which are either published articles or are currently under review. The text is completely identical to the published or submitted articles. The chapters in this thesis are structured as follows:

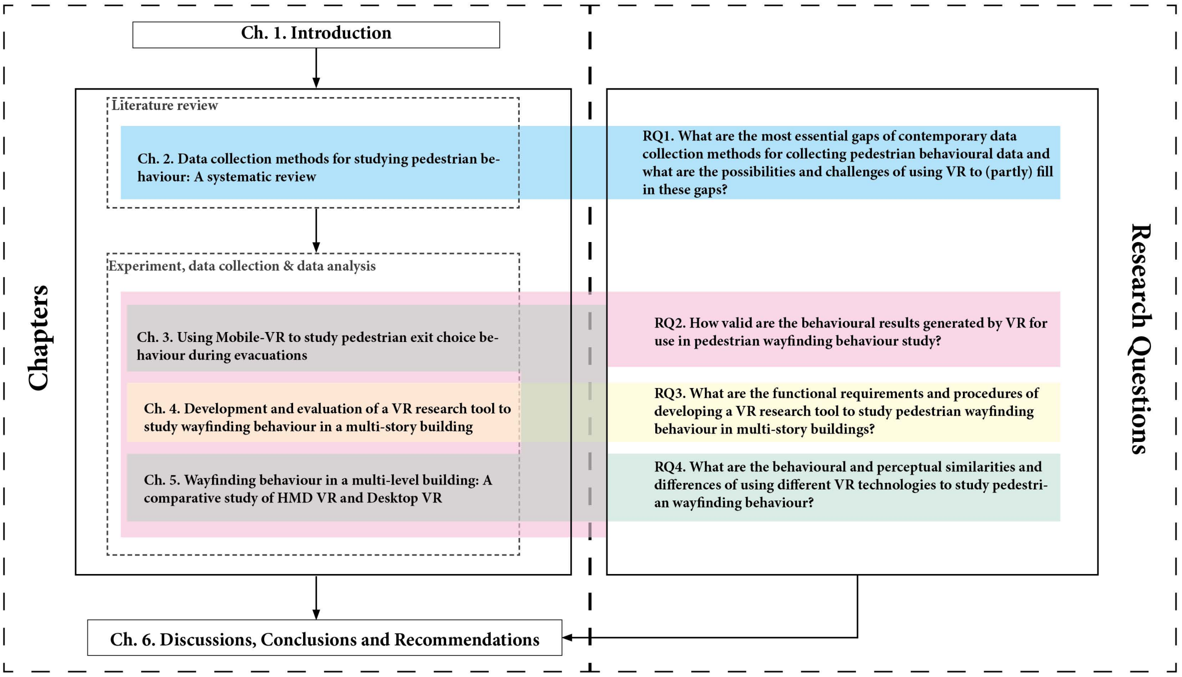


Figure 1.1: The structure of the thesis

Chapter 2 provides a comprehensive review of studies featuring pedestrian behaviour with respect to using different experimental methods, in order to identify the research gaps and opportunities for new technologies to complement the current data collection toolbox. It determines the capability of contemporary data collection methods in collecting different pedestrian behavioural data, identifies research gaps and discusses the possibilities of using new technologies to study pedestrian behaviour.

Chapter 3 presents the results of comparing pedestrian exit choice behaviour with a VR experiment and a field experiment. It determines the ecological validity of a particular VR simulator (smartphone-based HMD and 360° video) as a research tool to study pedestrian exit choice behaviour.

Chapter 4 presents an innovative VR research tool that was designed to investigate pedestrian wayfinding in a multi-story building. Meanwhile, it contains the evaluation results of applying this VR tool to collect pedestrian behaviour data in a multi-story building. The validity and usability of the VR research tool are evaluated from objective measures (i.e., route choice, evacuation exit choice, wayfinding performance, observation behaviour) and subjective measures (i.e., realism, feeling of presence, system usability, simulation sickness).

Chapter 5 investigates the impact of the technological differences between two VR techniques (i.e., HMD VR vs. Desktop VR) on pedestrian's behaviour and user experience, using the newly developed VR tool. Experiments were performed with participants using a Desktop VR or a HMD VR to perform four different wayfinding tasks.

Finally, **Chapter 6** discusses the key findings, draws the conclusion, and indicates the implications of this thesis, as well as the directions of future research.

Chapter 2

Data collection methods for studying pedestrian behaviour: A systematic review

This chapter provides a review of data collection methods for researching pedestrian behaviour. The review focuses on data collection methods that can be used to study pedestrian behaviour at three levels (i.e., strategic, tactical and operational), being field observations, controlled experiments, and survey methods. Our review notes that there is a clear imbalance in studying various aspects of pedestrian behaviour using contemporary data collection methods. VR offer opportunities to overcome some of these limitations. Yet, it is not clear what perspectives regarding pedestrian behaviour study are missing and to what extent VR can help bridge these gaps. This review aims to determine the capability of contemporary data collection methods in collecting different pedestrian behavioural data, identifies research gaps and discuss the possibilities of using new technologies to study pedestrian behaviour.

This chapter is organized as follows. Section 2.2 describes the review methodology and introduces the behavioural taxonomy and assessment framework that are used to assess the literature. Section 2.3 applies this framework to the literature using data collection methods for pedestrian behaviour research. Based on the review of 145 studies, section 2.4 discusses the research gaps and opportunities of using technologies to enhance the data collection toolbox. The last section details the conclusions of this review.

This chapter is based on the journal publication: **Feng, Y.**, Duives, D., Daamen, W., Hoogendoorn, S., 2021. Data collection methods for studying pedestrian behaviour: A systematic review. *Building and Environment, 187*, 107329.

2.1 Introduction

Walking is an essential mode of transportation and movement of pedestrian remains the major component of today’s urban transportation networks. Pedestrian behaviour is complex and multi-dimensional because while walking pedestrians interact continuously with the surrounding environment and people within a dynamic process. For walking as a mode of transport, environments are required in which pedestrians feel safe, empowered, and invited. A thorough understanding of pedestrian behaviour is of great significance for ensuring pedestrian safety and providing implications for crowd management, building design, urban development, evacuation management, etc.

In order to understand the decision-making process and movement dynamics of pedestrians, pedestrian behaviour has been extensively studied over the last decades. Essential to understanding pedestrian behaviour are data collection efforts featuring pedestrian behaviour under different circumstances, from daily trips, mass gatherings and even disasters. This had led to abundant studies which used a variety of data collection methods to investigate pedestrian behaviour, including field observations (e.g., Duives, 2012; Moussaïd et al., 2010; Nilsson & Johansson, 2009; Shields & Boyce, 2000), controlled experiments (e.g., Hoogendoorn & Daamen, 2004; Moussaïd et al., 2009; Shahhoseini et al., 2017; Zhang & Seyfried, 2014), and survey methods (e.g., Do et al., 2016; Duives & Mahmassani, 2012; Haghani & Sarvi, 2016a; Lovreglio et al., 2014).

Even though studies have illustrated the usefulness of contemporary data collection methods, they also showed that there are restrictions concerning the types of pedestrian behaviour that can be studied by means of these methods. For instance, there are privacy-related restrictions regarding the recording of crowds in public spaces, difficulty of building temporary experimental setups that realistically represent real-life scenarios, and ethical constraints concerning the creation of stressful experimental environments. We suspect that the restrictions of the contemporary data collection methods (partially) induce a lack of these specific types of studies, data and insights featuring various types of particular pedestrian behaviour, for instance, pedestrian movement and choice behaviour during disasters, inside complex (multi-level) buildings, and in vast street networks. These gaps signal that it is apparently difficult to perform research featuring these specific types of movement and choice behaviours which are not covered in the existing literature.

The abovementioned restrictions highlight the need for developing researcher’s data collection toolbox to collect pedestrian behaviour data. Various new technologies have gained increasing attention in pedestrian behaviour field in recent years, amongst which, Virtual Reality, smartphone sensing, etc. They offer the possibility of collecting new types of pedestrian behaviour data due to their special features (e.g., high experimental control, minimal ethical concerns or lower cost). These technologies might allow us to overcome contemporary restrictions and partially cover the current research gaps. Yet, it is currently unclear to what extent, and in particular, under which circumstances these technologies enhance a researcher’s toolbox to study pedestrian behaviour.

In order to address this, a comprehensive review of the use of contemporary data collection methods to study pedestrian behaviour is needed. Several reviews provided a partial overview of the use of various new technologies to study several stereotypical pedestrian behaviours. For instance, Feng et al. (2018), Kinateder et al. (2018b), Lovreglio & Kinateder (2020) and Moussaïd et al. (2018) focused on reviewing studies used VR or AR to study pedestrian evacuation and crowd behaviour. Some reviews discussed a broad range of empirical studies featuring pedestrian behaviour, for instance, Haghani & Sarvi (2018), Haghani (2020a, 2020b), Shi et al. (2018), Schweiker et al. (2020), and Zhu et al. (2020a). However, to our knowledge, there are no reviews that classify pedestrian behaviour systematically, cover a wide range of data collection methods and techniques for featuring pedestrian behaviour, and determine new opportunities to enhance the research toolbox with new technologies. Thus, this review is a complement to the current body of review studies, which helps clarify the contemporary technical and methodological challenges, and indicates the potential contribution of new technologies.

This study aims to identify the gaps in current data collection methods for pedestrian behaviour studies and pinpoints opportunities for new technologies to bridge these gaps. In order to achieve this aim, this study determines the capabilities of contemporary data collection methods regarding the study of pedestrian behaviour using a new taxonomy. This study contributes to the existing literature in four ways, namely (1) it develops a pedestrian behaviour taxonomy that can be used to classify the broad range of pedestrian behaviour, (2) it presents a comprehensive review of experimental pedestrian behaviour studies with a specific focus on the capabilities of the adopted data collection methods to study pedestrian behaviour, (3) it identifies the most essential gaps of the contemporary data collection methods for pedestrian behaviour research, and (4) it discusses how new technologies can potentially bridge these gaps.

This paper is organised as follows. Section 2.2 describes the review methodology and introduces the behavioural taxonomy that is used to assess the literature. Section 2.3 applies this taxonomy to review the literature using data collection methods for pedestrian behaviour research. Based on a review of 145 studies, section 2.4 discusses the research gaps and opportunities for new technologies to study pedestrian behaviour. The last section summarises the main conclusions of this review.

2.2 Review methodology

This section details the review methodology. First, the scope of the study is introduced in section 2.2.1. Secondly, a taxonomy to classify the range of pedestrian behaviour is presented in section 2.2.2.

2.2.1 Scope of the literature review

A systematic literature search was conducted using the PRISMA Statement (Preferred Reporting Items for Systematic Reviews and Meta-Analysis) (Moher et al., 2009). In the following, we describe the process of scoping the literature in detail. The literature was firstly identified using “Scopus” and “Web of Science” databases in January 2020. A limited set of keywords was used to search through the databases and, in particular, applied to article title, abstract and keywords. No limitation pertaining to the publication date of the articles was applied. Only articles published in English were included in the list of potential articles. The list of keywords included the combination of terms of ‘pedestrian behaviour’ and terms of ‘data collection method’. Therefore, the following keywords were used for searching: “pedestrian behaviour”, “pedestrian dynamics”; and “experiment”, “controlled experiment”, “laboratory experiment”, “field experiment”, “survey”, “virtual reality”, “augmented reality”, “Wi-Fi”, “Bluetooth”, “GPS”, “GMS”, “social media”, “IoT”. This set of references was enhanced by means of forward and backward snowballing (Wee & Banister, 2016).

To be included in the review, eligible literature should be empirical studies which include: (i) a description of the applied data collection method; and (ii) the application of this method to study particular types of pedestrian behaviour. Pure theoretical studies, modelling studies and simulation applications without relation to data collection endeavours were disregarded. Besides that, studies focusing on the perception or psychological perspective of pedestrian behaviour were excluded.

The scoping procedure and results are presented in Figure 2.1 The first search yielded a total of 720 records (including duplicates). After removing duplicates, the abstracts were reviewed by authors to confirm the inclusion of studies meeting the search criteria. 203 articles were screened for full-text review to check their eligibility. After we evaluated the eligibility of identified articles by reviewing the full text, 145 papers remained on the list. In total, 145 articles were identified that use data collection methods to study pedestrian behaviour between 1971 to 2020.

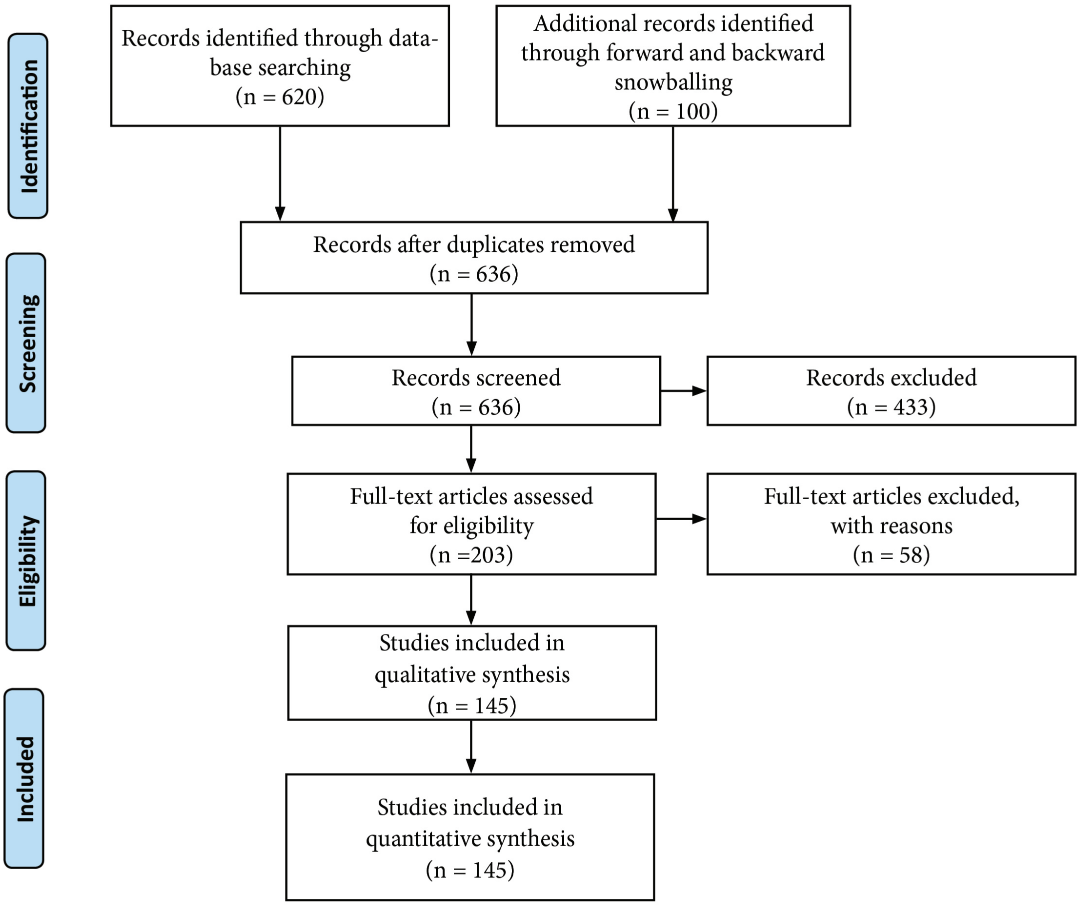


Figure 2. 1: The scoping procedure and results of literature.

2.2.2 Taxonomy of pedestrian behaviours

In order to establish the potential of a data collection method, one needs to determine the different types of pedestrian behaviour and whether a data collection method is able to study certain types of behaviour. This section introduces a taxonomy to structure pedestrian behaviours. The taxonomy explicitly represents the decision-making process of pedestrian behaviour (Figure 2.2). It includes a hierarchical structure of pedestrian behaviour and the including pedestrian behaviours, which together represent a broad range of pedestrian behaviours. This taxonomy will be used to assess literature in section 2.3.

2.2.2.1 The global layout of the taxonomy

From a traffic engineering point of view, pedestrian behaviour can be classified using a hierarchical structure consisting of three levels, being strategic, tactical and operational level (Hoogendoorn & Bovy, 2004). These levels feature three distinct temporal scales pertaining to choices that pedestrians make, and have served as an umbrella concept in the pedestrian research community to categorise pedestrian behaviours for at least two decades. This categorisation shapes the first layer of our taxonomy of pedestrian behaviours. The second to fourth layer detail specific pedestrian behaviours we identified in the first layer. Here, the second layer distinguishes between the choice dimensions. The third and fourth layer further disentangle the various interactions that jointly determine the overarching choice behaviour. Underneath, the taxonomy is further elaborated upon in sections 2.2.2.2-2.2.2.4.

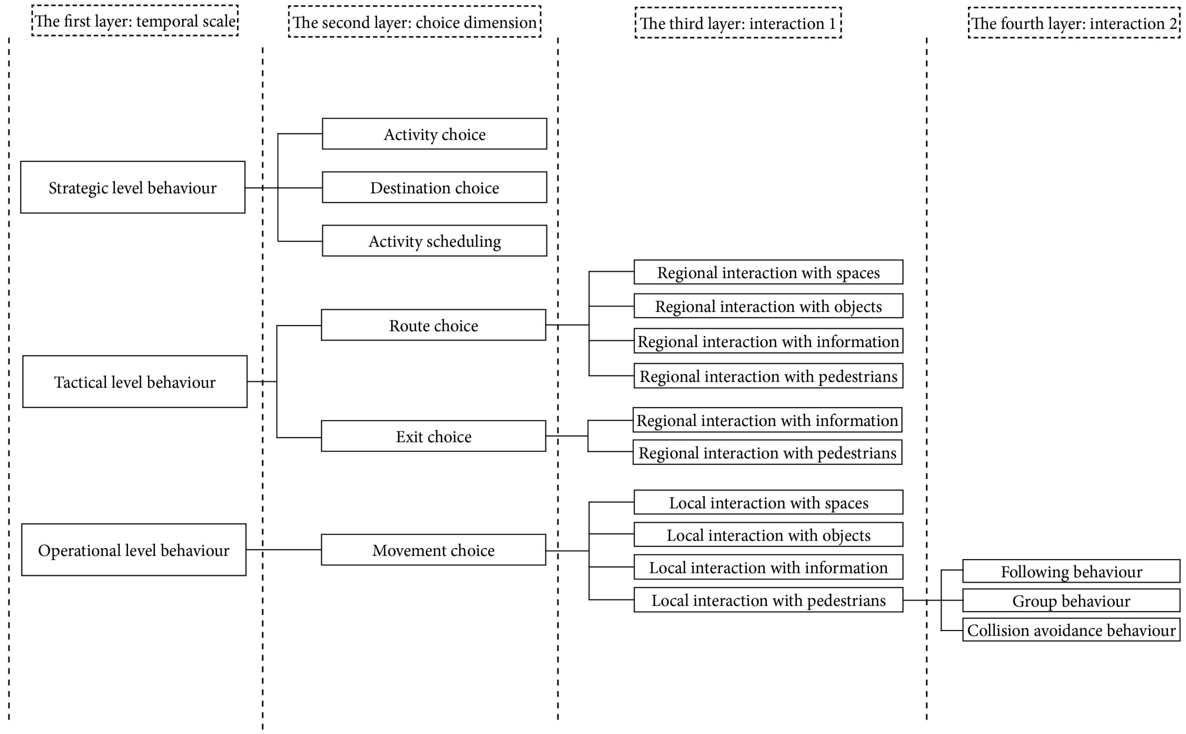


Figure 2. 2: A conceptual taxonomy of pedestrian behaviour.

2.2.2.2 Strategic level behaviour

Strategic level behaviour considers pedestrian behaviours which take place prior to their trip. At the highest level, pedestrians make decisions featuring their activity, corresponding destination and activity schedule. These choice behaviours are generic, have a very long-term impact on a pedestrian’s movement and choice behaviour (i.e., up to 24 hours) and reflect the purpose of the trip (Hoogendoorn & Bovy, 2004). From the set of activities, pedestrians choose (a subset of) *activities* to achieve the purpose of travelling. Accordingly, pedestrians choose a *destination* at which they would like to perform the activity (Duives, 2012). Last of all, pedestrians decide on the *scheduling of their intended activities*, which is called activities scheduling (Hoogendoorn & Bovy, 2004). Once the activity set, destination and activity schedule are decided, the basis for movement is formed.

2.2.2.3 Tactical level behaviour

The tactical level describes the decision of choosing a specific route in order to move from one location to the next (Li et al., 2019). The tactical level includes a range of pedestrian behaviours on a medium time scale, featuring *route and exit choice behaviour*. Here, *route choice* defines the process during which pedestrians choose between a number of routes to reach the destination (Schadschneider et al., 2009). *Exit choice* behaviour features the choice of one exit within a set of alternative exits to enter or leave a room and/or a building (Prato, 2009).

Pedestrian route choice behaviours are determined by four types of interactions. First, pedestrian route choice behaviour can be the result of *interactions with the types of space*. Daamen & Hoogendoorn (2003a) distinguished between functional, physical and specialised spaces (e.g., stairs and waiting areas). Moreover, *objects in the environment can attract, distract, hinder, or repulse* pedestrians during walking. For example, pedestrians might change their route in order to watch a storefront or avoid a dirty pathway. Additionally, pedestrians tend to *interact with information* (e.g., signs, lights, sounds and mobile phones) (Mwakalonge et al., 2015; Sime, 1995). Lastly, pedestrian route choice behaviour can be impacted by the *movements and choices of other pedestrians in a pedestrian's vicinity* (e.g., van den Berg, 2016). Here, *exit choice* behaviour can be seen as a special type of route choice behaviour. The literature illustrates that pedestrians *interact with information and other pedestrians* in order to establish their exit choice (e.g., Duives, 2012; Kobes et al., 2010b; Feng et al., 2020a).

2.2.2.4 Operational level behaviour

At the operational level, pedestrians continuously make short-term movement decisions on their route to respond to their immediate environment (Daamen, 2004). It entails the *operational walking dynamics* of individual pedestrians within a demarcated space and a demarcated period of time (Duives, 2016). Literature featuring pedestrian behaviour identifies at least four distinct types of behaviour, namely the *movement through certain types of space*, *the local interaction with objects*, *interaction with information,* and the *interaction with other pedestrians* (e.g., Daamen & Hoogendoorn, 2003b; Jeon et al., 2011; Moussaïd et al., 2009; Paris et al., 2007).

The first two types of interactions at this level feature the pedestrian *interaction with a certain type of space*, and the *interaction with information*, the demarcation of both types is similar to the tactical level. The third type of interaction is the *interaction with objects*, where four types of objects can be distinguished, namely objects that attract, repulse, obstruct and distract. For example, in a classroom, students try to avoid colliding with tables to the exits. The fourth type of interaction is *the interaction between pedestrians* (Wolff, 1973). Here, three typical types of interaction are described. Firstly, *following behaviour*, which entails the tendency of an individual to follow another individual, in order to benefit from the space they create. Secondly, *group behaviour*, which describes group members that share some collective behaviour, share a salient social identity and act according to the social norms of that group (Ando et al., 1988). Thirdly, *collision avoidance behaviour,* where pedestrians adjust their movements to avoid potential future collisions of two or more pedestrians occupying the same area at the same time (Goffman, 1971).

2.3 The capabilities of contemporary data collection methods concerning pedestrian behaviour research

This section presents a comprehensive review of studies that feature data collection methods that are frequently used to study pedestrian behaviour. There are three frequently adopted data collection methods, namely: field observations, controlled experiments, and survey methods. The literature concerning all three categories is detailed in subsections 2.3.1 – 2.3.3.

In each subsection, one of the three data collection methods is briefly defined, after which a summary is provided of the studies that have used this method to study pedestrian behaviour. For each study, the data collection set up is detailed and summarised in a table based on the taxonomy defined in section 2.2.2. The outcomes of the first three sections are used in section 4 to identify the research gaps in the current data collection toolbox.

2.3.1 Field observations

The first data collection method, namely field observations, involves the study of humans who move and make choices in realistic, natural environments, which include normal and emergency conditions. Here, the goal is to study pedestrian behaviour as unobtrusively as possible. This data collection method usually requires researchers to record pedestrian behaviour in specific situations and/or particular locations, either using manual labour (e.g., manual counting), digital recording equipment (e.g., camera), or sophisticated sensor system (e.g., GPS, Wi-Fi, Bluetooth). In general, one can distinguish between the traditional techniques (section 2.3.1.1) and newer digital technologies (section 2.3.1.2). The reader is referred to Appendix A, Table A.1 for an assessment of the studies discussed underneath.

2.3.1.1 Field observations using traditional techniques

The literature illustrates that studies, which use field observations are predominantly centred around four themes, namely the study of evacuation behaviour, pedestrian walking dynamics, group behaviour and pedestrian behaviour during large-scale events.

The first major research theme was the study of *pedestrian behaviour during evacuations* in real venues and unannounced emergencies. One of the early studies was performed by Shields and Boyce (2000), who used in-house closed-circuit television cameras to study pedestrian route and exit choice behaviour during unannounced evacuations at retail stores. Several other studies followed, which predominantly researched unannounced evacuation drills. For instance, Kobes et al. (2010b) investigated the influence of smoke and exit signs on pedestrian exit behaviour, and Yang et al. (2012) used video recordings of staircases to investigate pedestrian speed difference under emergency conditions. Galea et al. (2017) and Nilsson & Johansson (2009) determined the effect of the social relationship on pedestrian evacuation behaviour in a theatre.

The second theme focused predominantly on *pedestrian flow characteristics* at different spaces and, in particular, the relationships between speed, flow and density. One early study was conducted by Fruin (1971), who collected pedestrian flow data on the walkway and analysed the relationships of density-speed and density-flow volumes. A large number of studies followed his example and used time-lapse photography and video recordings to investigate pedestrian walking dynamics at walkways (e.g., Corbetta et al., 2016; Lam et al., 1995; Virkler & Elayadath, 1992), sidewalks (e.g., Al-azzawi & Raeside, 2007; Tanaboriboon et al., 1986) and stairways (e.g., Shah et al., 2013; Tanaboriboon & Guyano, 1991).

The third theme featured the *movement dynamics of pedestrian groups*. Moussaïd et al. (2010) and Duives et al. (2014), for instance, collected video recordings to study the impact of group behaviour on crowd dynamics. Gorrini et al. (2015) and Do et al. (2016) focused on the spatial movement behaviour of social groups. Lastly, Feng & Li (2016, 2017) observed the movement of groups consisting of family members or friends. Most of the studies featuring this theme analysed the walking velocity, interpersonal distance, step frequency and walking patterns of pedestrians in relation to group size.

The last group of field observations studied *pedestrian movements at mass events using video recordings*. Duives (2012) and Zhang et al. (2013) were the first to record crowd movement dynamics using an unmanned aerial vehicle (UAV), infrared counters and video recordings. In contrast to the relatively safe crowd movements, studies of Helbing et al. (2007), Johansson et al. (2008), Ma et al. (2013) and Larsson et al. (2020) investigated crowd dynamics under high densities at religious events, festivals and public events. More recently, Wang et al. (2019) used recorded videos to analyse crowd movement in a terrorist-attack event. All five studies only used material captured by unrelated third parties and had no control over the location or vantage point of the videos.

2.3.1.2 Field observations using monitoring techniques

Recently, sophisticated digital sensor systems that are able to monitor pedestrian movements and choice behaviours have also been adopted to study pedestrian movements in crowded spaces, such as transfer hubs, city centres and mass events. In comparison to traditional video recording techniques, these new monitoring techniques can actively cover pedestrian behaviour with larger spatial and time scale, and can be operational for a very long time (potentially multiple years). In particular, five distinctive types of digital sensors are mentioned in the literature that can be part of a crowd monitoring system, namely camera-based monitoring systems, Bluetooth/Wi-Fi sensors, GPS trackers, mobile phone data and social media crawlers. The studies applying these techniques mostly focused on pedestrian activity location choice and pedestrian movements at large-scale events. Underneath, the latest developments pertaining to each technology are mentioned separately.

The first group of studies featured the use of camera-based monitoring systems to study *pedestrian crowd movements on multiple occasions*, which generally feature a combination of a camera, a stand-alone mini-computer and a set of AI or computer vision algorithms. Earlier versions of these systems predominantly counted people or moving objects within the field of view (e.g., Yang et al., 2003). More recent studies automatically derived crowd speed and density information from video images (e.g., Favaretto et al., 2017; Wang et al., 2012). Duives (2016) combined video systems and computer vision algorithms to study pedestrian walking dynamics at five mass events, and Li et al. (2020) determined the pedestrian Level of Service using multiple overlapping cameras.

The second group of studies featured Wi-Fi and Bluetooth sensors (e.g., Centorrino et al., 2019; Danalet et al., 2016; Ton et al., 2015; Versichele et al., 2012; Yoshimura et al., 2017, 2014). These researchers adopted this type of sensor to study *pedestrian activity location and route choice behaviour* in, respectively, a museum, a university campus, a train station, a festival, and a museum. Other studies researched the *operational walking behaviour of crowds* (e.g., Bonne et al., 2013; Duives et al., 2018; Gioia et al., 2019). Besides that, some studies combined Wi-Fi sensors with other digital sensor types to *monitor pedestrian crowd conditions*. For instance, Wirz et al. (2012) collected pedestrians' location traces and information through GPS and Wi-Fi to infer real-time crowd conditions. Farooq et al. (2015) applied Wi-Fi sensors and infrared to monitor a large-scale crowd at a festival; and Daamen et al. (2016) monitored crowd movements using a combination of Wi-Fi, counting cameras and GPS trackers.

The third group of studies featured the use of *GPS* traces to study *pedestrian movements at public space or large-scale events*. For example, van der Spek (2008) and Galama (2015) used GPS trackers to monitor pedestrian movements in city centres and a public event. Daamen et al. (2017) used the same technique to study the activity choice and route choice behaviour of visitors at a music event. Blanke et al. (2014) studied the dynamics of crowd and activity location choice by means of GPS traces from smartphones. Similarly, Duives et al. (2019) adopted GPS-traces from smartphones to analyse tactical and operational crowd movements at mass events in real-time.

The fourth type of analysis made use of GSM data obtained from mobile-cellular networks to capture *pedestrian crowd information*. This type of mobile phone data was used by Gao (2015) and Keij (2014) to explore human mobility patterns. Calabrese et al. (2011) and Zhang et al. (2017) used GSM data to identify the locations of large pedestrian flow and crowd density.

The last group of studies featured the use of social media to *determine the crowd's characteristics at large events*. Botta et al. (2015) and Yang et al. (2019), for instance, used Twitter to determine the global movement patterns of pedestrians through an urban context. Gong et al. (2020, 2018) used similar social media platforms to derive information on the crowd itself, for instance, crowd distribution, age and country of origin. More recently, Yang et al. (2019) used social media to determine pedestrian activity patterns, and Alkhatib et al. (2019) determined incidents at pedestrian gathering events using social media messages.

2.3.1.3 Pros and cons of field observations to study pedestrian behaviour

In summary, field observations have been often applied to gather pedestrian behavioural data related to pedestrian evacuation behaviour, pedestrian movement dynamics at different spaces, group behaviour, and pedestrian movements at mass events. The captured data pertains to strategic level behaviour, tactical, and operational choices of pedestrians moving in crowds, groups and as individuals. The content of the studies mentioned above is used to discuss the pros and cons of field observations, which are discussed underneath from perspectives of controllability, data richness and quality, validity, representativeness and cost.

Controllability. The factors influencing pedestrian behaviour cannot be controlled during field observations, and the conditions under which data are collected cannot be influenced by the researcher directly (Hoogendoorn, 2004). Besides that, acquiring permissions for collecting such data in public and some restricted areas can be difficult because of safety, security and privacy issues. In particular, in relation to (new) digital monitoring techniques, this often hampers their adoption in the public domain. Moreover, in some contexts, such as evacuation and panic situations, video recordings are rarely accessible to researchers. Furthermore, individual characteristics of the pedestrians are hard to capture during field observations.

Data richness and quality. One advantage of field observations is that one can track the movements of many pedestrians over a long-term period. Consequently, the collected pedestrian behavioural data contains rich information considering the fundamental quantities of pedestrian behaviour (Vanumu et al., 2017). However, the accuracy of behavioural data is highly influenced by the sensor setup and techniques, for instance, camera position and angel, satellite signal strength, granularity of the data and distribution density of the beacons. As a result, collected pedestrian behaviour data is often not accurate and reliable enough for a detailed analysis (e.g., Love Parade 2010).

Validity. Pedestrians usually walk in a real-life environment with no or little knowledge of being tracked and are thus more likely to behave in a more natural fashion. This results in unbiased behavioural data, which in turn ensures a relatively high degree of validity.

Representativeness. Data collection during field observation usually occurs coincidentally during the time and at the location of the study (Hoogendoorn, 2004). It means that only the behaviour of a sample of the pedestrian population during a certain period or at a specific location is collected. Therefore, the sample of observed pedestrians in a field observation may not be representative of the population, or the observed behaviours may not be representative of the individual (Millonig et al., 2009).

Cost. It is time-consuming and challenging to obtain approval to perform a field observation. Contracts, approval to install sensors, and access to existing recordings from video surveillance systems are difficult to arrange. Furthermore, the raw data captured during a field observation experiment often still needs to be identified and interpreted through software or manual operation, which requires an enormous investment in labour.

2.3.2 Controlled experiments

Contrary to field observations, controlled experiments entail the participants' movements in a controlled condition and a temporary experimental setup designed by the researchers (Haghani & Sarvi, 2018). The literature considering controlled experiments can be split into three parts, namely studies featuring normal conditions (section 2.3.2.1), studies featuring evacuation conditions (section 2.3.2.2), and Virtual Reality experiments (section 2.3.2.3). Table A.2 and Table A.3 in Appendix A provide a summary of the studies that feature controlled experiment (both in normal and evacuation conditions), and VR experiments.

2.3.2.1 Traditional controlled experiments featuring normal condition in real life

The controlled experiments featuring pedestrian behaviour under normal conditions mainly cover two topics, namely walking dynamics of pedestrians in a particular type of spaces (e.g., bottlenecks, intersections and corridors) and collision avoidance behaviour.

A large number of studies have used laboratory experiments to study *pedestrian's operational walking dynamics in various settings*. Many studies conducted experiments to investigate the impact of bottleneck width on pedestrian movement dynamics (e.g., Bukáček et al., 2018; Daamen & Hoogendoorn, 2003a; Helbing et al., 2005; Hoogendoorn & Daamen, 2005; Kretz et al., 2006; Liao et al., 2014a; Seyfried et al., 2010, 2009; Zhang & Seyfried, 2014). Numerous studies investigated *other pedestrian movement base cases* (e.g., corridors, intersections). Seyfried et al. (2005), Chattaraj et al. (2009) and Liu et al. (2009), for instance, conducted experiments to investigate the movement dynamics of single-file pedestrians at corridors. Boltes et al. (2011) and Zhang & Seyfried (2013) conducted experiments to study uni- and bidirectional flow experiments in straight and T-junctions corridors. Wong et al. (2010) and Zhang & Seyfried (2014) studied pedestrian movement behaviour at intersections with different angles. Shiwakoti et al. (2015) and Lian et al. (2017) studied pedestrian merging movements under various angles and flow rates. While Gorrini et al. (2013), Dias et al. (2014) and Rahman et al. (2019) examined the effect of turning angled corridors on pedestrian movement dynamics. Recently, more experiments have been performed in diverse experimental settings. For instance, Ziemer et al. (2016) experimented in a high-density ring corridor to study pedestrian dynamics in crowded situations. Huang et al. (2018) investigated individual and single-file pedestrian walking behaviour in a narrow seat aisle. Cao et al. (2019b) investigated pedestrian movement by single-file experiments under different visibilities in a ring-shaped corridor. Hu et al. (2019) and Xiao et al. (2019) conducted multidirectional flows experiments in a circle setup to study pedestrian movement choice.

Another set of studies thoroughly researched *collision avoidance behaviour*. In the experiment conducted by Paris et al. (2007), pedestrian collision avoidance behaviour was observed via a motion capture system. Also, Moussaïd et al. (2009) and Versluis (2010) conducted experiments with pedestrians performing avoidance tasks in a corridor with various interaction distances and angles. In another study by Moussaïd et al. (2012) studied collision avoidance behaviour in a ring-shaped corridor. Huber et al. (2014) investigated path and speed adjustments when participants avoid another person at different angles and walking speeds. In the study of Parisi et al. (2016), collision avoidance behaviour was investigated individually and collectively in crossing and head-on encounters. In contrast, Liu et al. (2016) investigated another type of collision avoidance, namely the effect of inactive pedestrians on the pedestrian walking dynamics on other pedestrians, and Li et al. (2019) investigated the influence of obstacles in the travel path on pedestrian route choice behaviour.

2.3.2.2 Traditional controlled experiments featuring evacuation conditions in real life

Compared to normal-condition controlled experiments, the focus of controlled evacuation experiments is to study pedestrian behaviour under evacuation or more stressful conditions (e.g., participants are asked to hurry, environments change appearance due to varying smoke and lighting conditions). In general, three types of evacuation behaviour were investigated, namely pedestrians' operational movement dynamics, route and exit choice behaviour, and the impact of information and social behaviour on the choices of evacuees.

The first type of pedestrian behaviour, namely *pedestrians' operational movement dynamics* during evacuations, has first been studied by Daamen & Hoogendoorn (2010), who captured pedestrian movements through emergency doorways under stressful conditions. Tian et al. (2012) studied pedestrian movements when participants entered a bottleneck during an evacuation. Another study by Jo et al. (2014) researched the change of crowd speed around doors as a result of the change of corridor density. Huo et al. (2016) conducted evacuation experiments in a high-rise building and investigated pedestrian movements on stairs. Shahhoseini et al. (2017) investigated the movement of merging crowds under emergency egress, and Cao et al. (2018) studied pedestrian movement characteristics under low visibility conditions. Various studies, amongst which Zhao et al. (2020) and Ding et al. (2020), studied the impact of various types of obstacles on pedestrian evacuation efficiency.

The second type of studies researched *pedestrian route and exit choice behaviour* in evacuation situations. Most of these studies focused on exit and route choice behaviour for a specific type of infrastructure. For example, Fang et al. (2010) carried out an evacuation experiment in a teaching building and investigated the exit choice of pedestrians. Jeon et al. (2011) investigated the effect of different visibility condition at a transfer hub. Guo et al. (2012) and Zhu & Shi (2016) performed classroom evacuation experiments to contrast route choice behaviour under varying visibility conditions, occupant distributions and alarm information.

Other researchers studied how the *information provided by evacuation installations (e.g., signs, sounds, lights) influences pedestrian evacuation decisions*. Fridolf et al. (2013) and Galea et al. (2017) studied the impact of evacuation installations on pedestrian exit choice and movement speed. D'Orazio et al. (2016) compared pedestrian movement speed and evacuation time between continuous wayfinding system and punctual signs in a theatre. Ronchi et al. (2018) and Porzycki et al. (2018) conducted a series of experiments to study pedestrian evacuation behaviour during a road tunnel with artificial smoke. Cao et al. (2019a) conducted evacuation experiments to compare pedestrian evacuation behaviour under varying visibility.

The fourth group of studies featured the *impact of social behaviours*. Heliövaara et al., (2012), for example, conducted an evacuation experiment to study the effect of selfish and cooperative behaviour on evacuation performance. The study of Krüchten & Schadschneider (2017) investigated the impact of social groups and intergroup interactions on pedestrian movement during evacuations. Haghani & Sarvi (2017) and Xie et al. (2020) investigated the effect of social interaction on pedestrian route and exit choice in a room during an evacuation.

2.3.2.3 Controlled experiments using Virtual Reality (VR)

In VR experiments, participants experience an immersive virtual world through a continuous stream of highly realistic images and soundscapes. Individuals experience a feeling of immersion via VR equipment and are provided with the ability to interact with the virtual environment through a human-machine interface (e.g., joystick, gloves) (Reid, 2003). Overall, the VR studies pertaining to pedestrian behaviour mainly featured the effect of various factors on pedestrian choice behaviour under normal and evacuation conditions. Here, the latter category can be split into the impact of other pedestrians' behaviours and the impact of information on pedestrian evacuation behaviour.

VR has been used to analyse the *influence of various factors on pedestrian behaviour* under normal conditions in immersive and controllable environments. Tan et al. (2006), for example, collected pedestrian responses to hypothetical changes in virtual urban environments, namely activity choices and scheduling. Natapov & Fisher-Gewirtzman (2016) captured pedestrian movement trajectories walking through a virtual environment to investigate the impact of the distributions of urban attractors and the urban street network on pedestrian route choices. Feng et al. (2020a) investigated pedestrian route and exit choice behaviour in a multi-level building.

Another set of studies featured *pedestrian obstacle avoidance behaviour and collision avoidance behaviour*. Fink et al. (2007) and Sanz et al. (2015) investigated pedestrian movement and walking trajectory when they need to avoid obstacles in a virtual environment. Li et al. (2019) studied pedestrian route choice behaviour in a top-down view virtual environment with obstacles. Bruneau et al. (2015) used a VR simulator for a different application, namely to investigate how pedestrians avoid collision with a group of pedestrians.

Also, the *impact of other pedestrian's activities on pedestrian choice behaviours* during evacuation situations was widely investigated using VR. For instance, Kinateder et al. (2014a, 2014b) and Kinateder & Warren (2016) studied the effect of social influence on pedestrian exit choice. Bode et al. (2015), moreover, investigated the impact of queues in front of the exits on pedestrian evacuation exit and route choice behaviour. van den Berg (2016) used a 3D multi-user virtual game to study herding behaviour during an evacuation, and Moussaïd et al. (2016b) adopted a VR platform to investigate high-stress evacuation scenarios. More recently, Kinateder et al. (2018a) investigated the influence of exit familiarity and neighbour behaviour on pedestrian exit choice in a virtual museum. Lin et al. (2020a) examined the influence of crowd movements on pedestrian evacuation route choice.

The last group of studies investigated the *impact of information on pedestrian behaviour* in evacuations. Tang et al. (2009) created a VR game to determine the effect of emergency signs containing different information on pedestrian way-finding behaviour. Kobes et al. (2010a) investigated the influence of smoke and location of exit signs on pedestrian exit and route choice in a virtual hotel. Ahn & Han (2012, 2011) investigated building evacuations using AR-assisted guidance on smartphones. Silva et al. (2013) used a serious game to investigate pedestrian evacuation time and exit choice in a hospital while the game system provided continuous information about the evacuation's progress. More recently, Duarte et al. (2014) examined how dynamic features in exit signs affect pedestrian exit behaviour. Cosma et al. (2016) studied pedestrian behaviour in a virtual tunnel evacuation with different lighting situations. Furthermore, Kinateder et al. (2019), Cao et al. (2019a) and Zhu et al. (2020b) studied the impact of coloured signs, virtual fire and visual access on pedestrian exit and route choice behaviour.

Several above-mentioned studies also *compared pedestrian behaviour in VR and real life*. For example, one of the earliest validation studies was conducted by Kobes et al. (2010a), which compared pedestrian evacuation behaviour in a real-life hotel and a virtual hotel. Kinateder & Warren (2016) compared the impact of social influence on pedestrian exit choice behaviour in a real and virtual environment. More recently, Feng et al. (2019) compared pedestrian exit choice behaviour in a real-life evacuation drill and a virtual environment using mobile-based HMD. Besides pedestrian evacuation behaviour, several studies also compared obstacle avoidance behaviour. In the study of Fink et al. (2007) and Sanz et al. (2015) compared participants' collision avoidance behaviour surrounding static obstacles in matching physical and virtual environments. In a recent study, Li et al. (2019) compared pedestrian route choice behaviour in a virtual environment with obstacles to similar real-life conditions.

2.3.2.4 Pros and cons of controlled experiments to study pedestrian behaviour

In this section, the pros and cons of traditional controlled experiments and VR experiments are discussed separately, as the applied techniques have distinguished differences. Five main perspectives are discussed, namely controllability, data richness, validity, representativeness and cost.

2.3.2.4.1 Pros and cons of traditional controlled experiments

In summary, traditional controlled experiments in normal conditions are predominantly used to study the operational movement behaviour of pedestrians, in particular, walking dynamics and collision avoidance behaviour. Concerning emergency conditions, most controlled experiments aim to capture tactical level behaviour, and a limited number of studies feature operational movement behaviour.

Controllability. The review illustrates that a major advantage of laboratory experiments is that experimental conditions can be controlled well. That is, researchers can take tight control of the scenarios that participants experience and the moments in time at which participants make decisions (Haghani et al., 2016). However, controlled experiments are also restricted by ethical considerations and need to ensure a reasonable balance between the realism and level of invasiveness of their design at all times (Haghani & Sarvi, 2018).

Data richness and quality. Due to high controllability, controlled experiments provide the opportunity to easily observe and analyse the effect of very specific factors (Falk & Heckman, 2009). Meanwhile, the control of the data collection devices also assures a higher level of data accuracy, considering the detection and extraction of pedestrian behavioural data.

Validity and representativeness. In controlled experiments, pedestrian behavioural data is usually collected in a specific context. Therefore, it is questioned if collected data can either represent pedestrian behaviour in real life or it can be generalised to different situations. Meanwhile, students are over-represented in many controlled experiments, which limits the overall validity and representativeness of most controlled experiments (Falk & Heckman, 2009).

Cost. In order to conduct controlled experiments to collect data, it is essential to create an artificial experiment environment, install data collection devices and gather a large number of participants, which often proves costly and labour intensive. Meanwhile, the built environment is mostly in a simple setup and missing architectural features (e.g., colour, texture).

Furthermore, once the environment is built, it can hardly be changed during experiments (Daamen & Hoogendoorn, 2003b).

2.3.2.4.2 Pros and cons of using VR in controlled experiments to study pedestrian behaviour

In summary, VR experiments mainly have been focused on investigating the impact of various factors on pedestrian behaviour under normal and evacuation conditions (i.e., the impact of other pedestrians and the impact of information on evacuation behaviour of pedestrians).

Controllability. The studies presented in section 2.3.2.3. identify that one of the main advantages of VR is high experimental control. It means that the virtual scenes can be quickly built, modified, and a number of possible factors that potentially influence pedestrian behaviour can be controlled in the virtual environment. Compared with traditional controlled experiments, VR allows participants to be immersed in virtual environments that they are either not likely to encounter in real-life or which are too dangerous to expose. Thus, participants can be fully immersed in a VR environment without exposing them to risk of injury (Schwebel et al., 2008).

Data richness and quality. Compared to other data collection methods, using VR is more likely to collect pedestrian behavioural data more accurately and automatically. It means that VR may provide easier and quicker access to the collected behavioural data (Haghani & Sarvi, 2018). Besides, researchers can design and develop virtual environments which are complicated, stressful and even dangerous, in which they can still collect sufficient behavioural data (Cohen et al., 2012; Kinateder et al., 2014a).

Validity. One often recorded concern is whether participants' behaviour in VR environments is consistent with their behaviour during real-life situations. In particular, because participants know they move and act within the virtual environment, and they face no real danger (Feldstein et al., 2016).

Representativeness. VR experiments using some VR devices (i.e., HMDs, desktop displays) can be conducted at different locations and different times (Cosma et al., 2016), which increase the heterogeneity of sampling. However, the potential pre-selection effects might influence the representativeness the results, for instance, elder or people who have issues with dizziness might not be included in the sample, participants are more familiar with new technologies might perform more smoothly (e.g., Bode & Codling, 2013).

Cost. Another significant advantage of VR simulators is its cost-effectiveness (Deb et al., 2017). That is, both the operational and logistics costs of VR experiments are lower than those of comparable lab experiments (Haghani et al., 2016). Furthermore, once the VR simulator system is set up, it can be used repeatedly.

2.3.3 Survey methods

Research featuring survey methods collects and analyses data using a list of predetermined questions. There are two main types of surveys, namely stated preference surveys (SP) and revealed preference surveys (RP). The first type is based on the participants' response or answers to hypothetical scenarios, while the latter is based on experienced scenarios with a given set of questions. Table A.4 in Appendix A provides a summary of the studies discussed in this section.

2.3.3.1. Pedestrian behaviour study using surveys

Several studies used surveys to understand *pedestrian route and exit choice behaviour*. Duives & Mahmassani (2012) used a web SP-questionnaire to investigate pedestrian evacuation decisions, including pre-evacuation behaviour, route and exit choice. Lovreglio et al. (2014) also used SP survey to study the effect of nearness to the exit, the density of near exits, herding behaviour and cooperative or selfish behaviour on pedestrian exit choice. Haghani & Sarvi (2016b) used an SP questionnaire to investigate pedestrian exit choice behaviour during evacuations. Olander et al. (2017) performed a questionnaire study to evaluate the design of dissuasive emergency signage, and Chen et al. (2018) used a questionnaire-based experiment to study children route choice behaviour in an evacuation scene in a classroom. Aleksandrov et al. (2018) used an online questionnaire and designed multiple scenarios to investigate pedestrian route choice during evacuations.

Next to the use of standalone surveys, survey data is also often combined with field observations or controlled experiments, during which people, who have been involved in an experiment and have personal experiences in the (real-life) scenarios are questioned. Do et al. (2016), for instance, combined RP survey data with field observations to understand groups and single pedestrian behaviour at a train station and Haghani & Sarvi (2016a) collected RP data regarding pedestrian exit decision in a train station. D’Orazio et al. (2016) used the survey another way, namely to collect qualitative data regarding pedestrian pre-movement time activities and evacuation route choice after an evacuation experiment. Daamen et al. (2017), similarly, combined GPS trajectory data with a survey regarding pedestrian experiences and personal characteristics to identify the factors influencing route choice.

2.3.3.2. Pros and cons of survey methods

To summarise, survey methods have predominantly been used to study pedestrian behaviour at the tactical level (during evacuations), to enhance datasets gathered using other data collection methods, and to determine the influence of personal characteristics and external factors on pedestrian behaviour. Underneath the pros and cons of survey methods concerning controllability, data richness, validity, representativeness, and costs are discussed.

Controllability. Researchers have high experimental control to design predetermined questions in a survey. Questions can be related to past events or futuristic situations. In particular, SP surveys provide the opportunity to gather insights regarding pedestrian behaviours that rarely happen or have not presented itself in real-life situations.

Data richness and quality. In addition to field observations or controlled experiments, surveys provide the opportunity to acquire complementary (qualitative) information concerning, for instance, personal characteristics and psychological insights (e.g., preferences, attitudes, motivations, and intentions). However, not all pedestrian behaviours, for example, pedestrian walking dynamics, can be studied using survey methods because individuals do not consciously make these decisions.

Validity. Different from real observations, the answers from respondents may differ from their actions in a real situation, which limits the generalizability and validity of most survey results. This is especially the case when participants are required to answer questions regarding unfamiliar situations (SP survey) or when they need to recall past events or experiences (RP survey).

Representativeness. Surveys can be distributed among pedestrians through different media, for instance, on the street, via mail, email or web forms. Compare to controlled experiments, it allows researchers to collect relatively comprehensive data samples to represent the pedestrian population well.

Costs. One of the main benefits of surveys is that the time to develop and perform a survey study is, in general, limited. That is, questionnaires can be quickly and repeatedly distributed. As such, it allows researchers to collect large data samples at low costs (Millonig et al., 2009). However, a full orthogonal survey requires a vast number of respondents which have proven costly to achieve.

Table 2. 1: An overview of the number of studies featuring different types of pedestrian behaviour.

Data collection methods		**Strategic level behaviour**			**Tactical level behaviour**						**Operational level**					
					Route choice				Exit choice					Interaction with pedestrians		
		Activity choice	Destination choice	Activity scheduling	Interaction with spaces	Interaction with information	Interaction with objects	Interaction with pedestrians	Interaction with information	Interaction with pedestrians	Movement through spaces	Interaction with objects	Interaction with information	Following behaviour	Group behaviour	Collision avoidance behaviour
Field observations	Using traditional techniques	0	0	3	0	1	0	0	2	0	18	0	0	0	7	0
	Using monitoring techniques	8	19	8	5	2	2	2	0	0	9	0	0	0	0	0
Controlled experiments	Normal conditions in real life	0	0	0	0	0	1	0	1	0	24	1	0	0	1	9
	Evacuations in real life	0	0	0	1	3	1	6	4	5	10	2	4	2	1	0
	VR experiments	3	5	6	1	8	0	5	9	2	0	2	0	1	0	2
Survey methods		0	0	0	1	4	1	5	3	5	0	0	0	1	2	0
Summary		**11**	**24**	**17**	**8**	**18**	**5**	**18**	**19**	**12**	**61**	**5**	**4**	**4**	**11**	**11**

Low High

Note: colour scale (from low to high)

Table 2. 2: A comparison of the pros and cons of different data collection methods

Data collection methods		**Controllability**	**Data richness and quality**	**Validity**	**Representativeness**	**Cost**
Field observations		• External factors cannot be controlled • Acquiring permissions for collecting such data in public and some restricted areas can be difficult	• Track the movements of many pedestrians over a long-term period • Accuracy of behavioural data is highly influenced by the experimental setup • Often not accurate and reliable enough for a detailed analysis	• A relatively high degree of validity	• May not be representative of the population, or the observed behaviours may not be representative of the individual	• Time-consuming and challenging to obtain approval to perform a field observation • Require a large investment in labour to extract the collected data
Controlled experiments	Traditional controlled experiments	• Experimental conditions can be controlled well	• Easily observe and analyse the effect of very specific factors • A higher level of data accuracy	• Questioned whether collected data can represent pedestrian behaviour in real life	• Questioned if collected data can be generalised to different situations • Overrepresented students limit the overall representativeness	• Install data collection devices and gather a large number of participants, which often proves costly and labour intensive • Once the environment is built, it can hardly be changed during experiments
	VR controlled experiments	• High experimental control	• More accurately and automatically collect data	• Questioned whether participants' behaviour in VR	• Can be conducted at different locations and different times	• Lower than those of comparable lab experiments

				environments is consistent with their behaviour during real-life situations	which increase the heterogeneity of sampling • Potential pre-selection effects might influence the representativeness	• Can be used repeatedly
Surveys		• High experimental control	• Acquire complementary (qualitative) information • Not all pedestrian behaviours can be collected, for example, pedestrian walking dynamics	• Answers from respondents may differ from their actions in a real situation	• Allow researchers to collect relatively comprehensive data samples to represent the pedestrian population well	• Questionnaires can be quickly and repeatedly distributed • A full orthogonal survey requires a vast number of respondents can be costly to achieve

2.4 Research gaps and opportunities

The review of contemporary data collection methods used to study pedestrian behaviour illustrates that there are certain imbalances using contemporary research toolbox. Table 2.1 shows an overview of reviewed studies featuring different types of pedestrian behaviour. Table 2.2 shows an overview of the pros and cons of different data collection methods for collecting pedestrian behaviour data. Moreover, the review also identifies there are new technologies that can potentially enhance our research capabilities. This section first identifies five research gaps pertaining to the contemporary research method toolbox for pedestrian behaviour research. These gaps are identified by using the reviewed empirical studies featuring pedestrian behaviour (Section 2.3) in combination with the taxonomy framework (Section 2.2). Section 2.4.2 accordingly determines three potential opportunities pertaining to new technologies to potentially bridge the research gaps identified in section 2.4.1. The process of identifying research gaps and opportunities for new technologies is conceptualised in Figure 2.3.

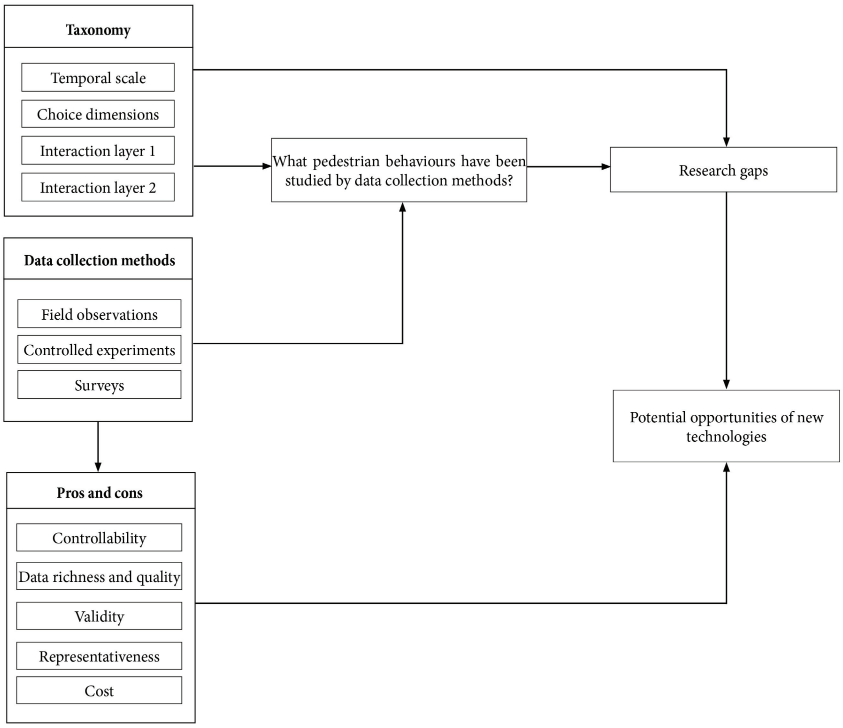


Figure 2. 3: A conceptual framework for identifying research gaps and opportunities

2.4.1 Research gaps

In the review, five research gaps are identified, namely: (1) studying pedestrian behaviour under vast complex scenarios, (2) capturing comprehensive behavioural data sets, (3) studying pedestrian behaviour in new types of high-risk scenarios, (4) comparing pedestrian behaviour data with different data collection methods and (5) high experimental costs.

Gap 1: studying pedestrian behaviour under vast complex scenarios

Although there have been many studies that use controlled experiments to investigate pedestrian behaviour in varying scenarios, more than half of the studies focused on pedestrian behaviour in simple experimental conditions (e.g., corridor, bottleneck, simple room). Apart from these, studies featuring strategic level behaviour were limited. The lack of studies of pedestrian behaviour under vast complex scenarios seems to be the result of three things. First, longitudinal data collection of pedestrian behaviour is difficult to arrange. Second, data collection methods (i.e., controlled experiments, surveys) have a limited scope, which makes it difficult to provide participants with a wide range of options. Third, the variability and complexity of pedestrian behaviour, the variety of contexts, and the variety of geometric and architecture features (Shahhoseini et al., 2017) are challenging to achieve from the contemporary research toolbox. Consequently, more complex scenarios cannot be represented entirely realistically, experiments featuring these complex situations are hardly controllable and repeatable (Bruneau et al., 2015). Thus, there is a need for data collection methods that can create and mimic realistic complex scenarios while retaining the capability of collecting pedestrian behaviour data.

Gap 2: capturing comprehensive behavioural data sets

Pedestrians perceive the environment while walking, and their behaviour is the result of decision-processes that range from the long-term strategic level to the short-term operational level (Chen et al., 2017; Duives, 2016). However, the internal relationship between different choice dimensions and the details considering each of the choice dimensions is, to a large extent, currently not yet understood.

The review illustrates that one of the underlying issues is a lack of valid behavioural data spanning multiple-choice dimensions or encompassing information on the individual and the crowd simultaneously. It is difficult to use traditional data collection methods to capture all the data that is necessary to improve our understanding of pedestrian choices. Consequently, realistic behavioural data about pedestrian choices is still lacking. Thus, there is a need for methods that allow researchers to capture sufficient behavioural data in a scenario simultaneously (i.e., personal characteristics, psychological data, movement data, experienced settings, crowd movements).

Gap 3: studying pedestrian behaviour in new types of high-risk scenarios

Furthermore, this review shows that while pedestrian behaviour has been extensively investigated in traditional emergency scenarios, such as fire, new types of high-risk scenarios (e.g., earthquakes, terrorist attacks, stampedes) have received far less attention. Examples of these newer types of high-risk scenarios include the crowd disaster during Hajj (Helbing et al., 2007), the Love Parade disaster (Ma et al., 2013) and the Kunming terrorist attack event in China (Wang et al., 2019). These studies show that pedestrian behaviour during those scenarios differs from pedestrian behaviour in traditional evacuation scenarios. There is a lack of research approaches that can study pedestrian behaviour during these newer risky situations while being in a relatively safe environment. For example, although studies of pedestrian behaviour during fire situations have been done on a number of field observations and lab controlled experiments, it generally suffers from a lack of controllability, precision, reality and replicability

(Shahhoseini et al., 2017). Meanwhile, the limited information provided to participants restricts their behavioural responses to the situation because of the physical dangers involved when they are walking (Shochet et al., 2010). Consequently, a data collection method is required that allows participants to experience and move through dangerous environments with comprehensive information, while they remain physically safe.

Gap 4: limited representativeness of the collected pedestrian behavioural data sets

It is known that pedestrian behaviour is highly dependent on the external environment and surrounding pedestrians, however, for controlled experiments and survey methods, pedestrian behaviour data are usually collected in a specific context (i.e., temporary experimental setup, participants need to follow certain instructions) with a single type of participants (e.g., university students). Therefore, it is questioned if collected data through these methods can either represent pedestrian behaviour in real life or it can be generalised to different situations. The review shows that there are only a few studies that have attempted to address this issue (e.g., Feng et al., 2019; Fink et al., 2007; Kobes et al., 2010a; Li et al., 2019). Thus, more studies are needed to be conducted repeatedly in various data collection methods or with various heterogeneity of participants.

Gap 5: alternative choices with low experimental costs

To study pedestrian behaviour at the operational level, predominantly field observations and controlled experiments are used due to the stringent data requirements. Finding the optimal place and obtain the access to perform a field observation takes time. Besides that, it is challenging and costly to install all necessary sensors. At the same time, it is also very costly to design, develop and conduct controlled experiments. And it is challenging, and often expensive to acquire participants. Consequently, researchers need to choose between two costly alternatives to study operational behaviour, which limits the amount of research being performed featuring pedestrian operational movement behaviour. Thus, there is a need for a data collection method that allows researchers to set up, alter or change between different experimental setup quickly at no or very limited costs.

2.4.2 Opportunities pertaining to the use of new technologies

In this section, three opportunities of applying new technologies to (partly) bring the identified research gaps are identified, namely: (1) applying VR experiments, (2) leveraging large-scale crowd monitoring and (3) utilising the Internet of Things (IoT).

Opportunity 1: conducting VR experiments

The last few years VR technologies have improved with incredible speed. This allows researchers to generate large complex, realistic scenarios while still ensuring that researchers can collect behavioural data with great experimental control. Meanwhile, VR provides the opportunity to study pedestrian behaviour with a variety of dangerous situations, such as building fires, earthquakes, or crowd motion during massive events (Haghani et al., 2016). At the same time, with the ability to simulate a variety of contexts, VR allows researchers to investigate pedestrian behaviour in hypothetic scenarios (e.g., new building designs and new transportation systems). It helps researchers understand the interaction between pedestrians and scenarios that do not exist today and also helps planners through dilemmas when designing future infrastructure (Maheshwari et al., 2016).

Secondly, once the VR system is set up, it allows researchers to conduct the same experiment repeatedly and even in a physically different location while the settings of the experiment remain the same. It ensures that experimental conditions are similar for all participants, which helps to gain insights on how various external factors or personal characteristics affect behaviour in certain conditions. At the same time, it allows researchers to collect a multitude of pedestrian data with much flexibility and heterogeneity.

Thirdly, precise tracking technology (e.g., full-body tracking, eye tracking), which is incorporated in most VR technologies, allows researchers to collect and accurately analyse various aspects of pedestrian behaviour in great detail. Brief actions can also be captured, such as small steps, hesitations, or glances, that would be difficult to observe in the real world (Vilar et al., 2014a). In combination with questionnaire data, VR also provides opportunities to acquire complementary information to further our understanding of the decision-making processes.

At the same time, the review highlights several challenges of using VR to study pedestrian behaviour. Firstly, to ensure VR technologies can be used as a valid research tool to study pedestrian behaviour, more thorough insights with respect to the comparison of pedestrian behaviour in virtual and real-world environments is needed. In particular, research should establish under which conditions and for which pedestrian behaviours, VR technologies can be a valid research tool. Secondly, currently researchers have to balance between the level of realism, the scale of the virtual environments and the computational load of VR simulations. Thirdly, researchers should continue to work on solving the ethical (i.e., mental and physical load of VR experiments for participants) and methodological (i.e., pre-selection effects) limitations of applying VR technologies.

Opportunity 2: leveraging large-scale crowd monitoring

Until recently, the widespread installation of static digital sensors, such as automatic counting systems and Wi-Fi sensors, for the monitoring of pedestrian movements was very difficult due to the high installation and maintenance costs, high data loads and ever-present privacy concerns. In the last few years, improvements pertaining to all three issues have allowed cities and pedestrian infrastructure operators to install vast 24/7 operational sensor networks in pedestrian infrastructures. This development will allow researchers to study the movements of pedestrian (crowds) in large complex environments and incident situations in more detail in the years to come. Besides that, these systems will capture new pedestrian behaviours in complex situations that have not yet been studied in detail, for instance, walking at night or accidents.

The main issue concerning large monitoring systems is their potential infringement of the fundamental right to be forgotten by the government, i.e., the right to privacy. Most crowd monitoring systems currently make use of camera or Wi-Fi data, which intrinsically feature privacy-sensitive data. Consequently, to further the installation and operation of large crowd monitoring networks in pedestrian infrastructures, it is essential to advance the development of digital sensors, which ‘by design’, protect the privacy of the individual. Some first developments are seen in practice, such as radar, heat and depth sensors.

At the same time, limited information is available regarding the validity of, in particular, these newer sensor types. Some studies, such as Duives et al. (2018), illustrate that derivation of crowd dynamics information from sensor networks is less trivial than one might think. Thus, in order to add these new sensors to the pedestrian research method toolbox, studies into the valid usage of crowd monitoring system data are essential.

Opportunity 3: utilising the Internet of Things (IoT)

The concept ‘Internet of Things’ has been introduced a few years ago, which identifies systems of interrelated digital devices that can autonomously communicate with the internet and other devices. With the establishment of the first IoT-like systems, also new opportunities to study and monitor pedestrian behaviours arose. The first opportunity of IoT for the pedestrian study is tracking of pedestrian dynamics via smartphones (e.g., running apps, event apps), wearables (e.g., sports watches) and social media (e.g., Twitter, Foursquare, Instagram). In these applications, IoT is used to monitor pedestrian dynamics in a conventional manner (e.g., identify walking speeds, flows and densities). Besides that, IoT also has the potential to unravel new information regarding pedestrian movement and choice behaviour, for instance by linking pedestrians’ thoughts to their route choice behaviour and their local operational behaviour to their strategic day-to-day activity choices. Please note that the latest IoT systems gather pedestrian data as a by-product of their normal operation procedures, such as studying route choice behaviour in buildings using data from intelligent lighting systems and identifying collision avoidance behaviour using data from the sensors of autonomous vehicles. Consequently, IoT can unravel new insights regarding movement types and (functional) locations that are difficult to study for now.

In order to leverage the potential of IoT systems to increase our knowledge regarding pedestrian behaviour, two main issues need to be tackled. First and foremost, when studying and linking ubiquitous data, it is essential to ensure the TADA principles (tada.city) are adhered to. Currently, to the author's knowledge, little standards exist regarding how to ensure the correct handling of IoT data for research purposes, in particular in the field of pedestrian science. Microscopic data pertaining to pedestrian movements can be very sensitive and infringe on the right to be forgotten (art. 17 GDPR). Thus, working with IoT data requires researchers to pro-actively develop standards featuring privacy-protections protocols featuring IoT technologies in the years to come. Besides that, similarly to VR technologies, most analytic methods that are currently using data derived from IoT systems have not been validated. Therefore, it is essential for researchers to determine the construct, content and predictive validity of analysis methods based on IoT system data.

2.5 Conclusion

Our objective in undertaking this review was to present a comprehensive review of studies featuring pedestrian behaviour with respect to using different experimental methods, in order to identify the research gaps and opportunities for new technologies to complement the current data collection toolbox. This review paper's contributions are: 1) an extensive taxonomy of pedestrian behaviour, 2) a comprehensive review of contemporary data collection methods regarding pedestrian behaviour, and 3) a gap-analysis and opportunities of applying new technologies to partly cover the gaps.

The developed taxonomy explicitly distinguishes the decision-making processes of pedestrian behaviour. This taxonomy includes a hierarchical structure of pedestrian behaviours, which was used to assess contemporary data collection methods (i.e., field observations, controlled experiments, survey methods and new technologies experiments) with respect to their capabilities of studying pedestrian behaviour. This literature review discerns five main gaps, namely: 1. the impossibility to study pedestrian behaviour under vast complex scenarios; 2. the lack of comprehensive methods to capture all essential behavioural data simultaneously; 3. the current difficulties to study new types of high-risk scenarios; 4. the lack of comparisons of pedestrian behaviour data among different data collection methods to represent pedestrian behaviour in real life; and 5. the relatively high costs of most experimental methods.

At the same time, the review showed that new technologies could potentially address these research gaps in three ways. One is applying VR experiments to (1) study pedestrian behaviour in the environments that are difficult or cannot be mimicked in real-life; (2) conduct the same experiments repeatedly to explore effects of various factors on pedestrian behaviour; (3) gain more accurate behavioural data and deep understanding of the decision-making process of pedestrian behaviour. The second opportunity is applying large-scale crowd monitoring to study pedestrian movements in large complex environments and incident situations in more detail. The third opportunity is utilising the Internet of Things to track pedestrian dynamics and unravel new insights regarding pedestrian movement types and locations that are difficult to investigate at the moment.

Chapter 3

Using Mobile-VR to study pedestrian exit choice behaviour during evacuations

The review in Chapter 2 showed that one of the opportunities of using VR to study pedestrian behaviour is studying pedestrian behaviour in high-risk scenarios. Moreover, to ensure VR technologies can collect valid pedestrian behavioural data, a more thorough insight with respect to the comparison of pedestrian behaviour in virtual and real-world environments is needed.

This chapter presents the results of a VR experiment and a field experiment to study pedestrian exit choice behaviour during evacuations. Primarily, we compared pedestrian exit choice behaviour with a VR experiment and a field experiment to validate the use of Mobile VR to study pedestrian exit choice behaviour. Furthermore, we investigated whether and to what extent different types of guidance information (i.e., exit signs, directional signs, presence of people) influence pedestrian exit choice during evacuations. Section 3.2 presents the research methodology for the field experiment and the VR experiments. Section 3.3 focuses on validation results obtained from field observation and VR experiments. Section 3.4 presents the results featuring the impact of guidance information on pedestrian exit behaviour during evacuations. This chapter ends with conclusions and suggestions for future research.

This chapter is based on the journal publication: **Feng, Y.**, Duives, D. C., & Hoogendoorn, S. P. (2021). Using virtual reality to study pedestrian exit choice behavior during evacuations. *Safety Science, 137*, 105158.

3.1 Introduction

When evacuating a building, pedestrians usually face multiple exits and need to choose which of the exits to use (Heliövaara et al., 2012). Choosing the right exit is crucial for survival; hence it is important to understand such so-called pedestrian exit choice behaviour (Kobes et al., 2010b). Thus, for many disciplines, such as architecture, fire safety, or civil engineering, it is vital to have a thorough understanding of pedestrian exit choice behaviour to ensure pedestrian safety and create safe building designs.

During building evacuations, the information provided in the environment is a key aspect to provide evacuees clues to find an exit. A number of prior studies have found that information provided by the signage features or other pedestrian's influence pedestrian exit choice behaviour. For instance, visibility of evacuation exit signs (Haghani & Sarvi, 2016b; Kobes et al., 2010; Wong & Lo, 2007), signage about exits' direction (Bode et al., 2014; Ronchi et al., 2016a; Vilar et al., 2013a), and the indirect information provided by the presence of other people (Haghani & Sarvi, 2016b; Helbing et al., 2000; Kinateder & Warren, 2016; Lovreglio et al., 2016; Moussaïd et al., 2016). Therefore, it is also crucial to understand to what extent different types of information influence pedestrian exit choice behaviour during evacuations.

In recent years, different experimental studies have been performed to study pedestrian exit choice behaviour during evacuations. These corresponding experimental methods predominantly included observations of real-life evacuation situations (e.g., Galea et al., 2017; Kobes et al., 2010b; Shields & Boyce, 2000), controlled experiments under conditions of stress (e.g., Fang et al., 2010; Fridolf et al., 2013; Zhu & Shi, 2016) and surveys (e.g., Duives & Mahmassani, 2012; Haghani & Sarvi, 2016b; Lovreglio et al., 2014). Although these experimental studies have provided valuable information regarding the understanding of pedestrian exit choice behaviour in emergency situations, there are stringent limits regarding the insights one can derive by means of field observations or controlled experiments. For instance, it is difficult to control external variables in field observations, and evacuation drills cannot be completely realistic because of ethical and financial constraints. In controlled experiments, there are ethical and financial constraints to create real and stressful situations. Meanwhile, it is hard to provide participants with a strong sense of presence to make them fully participate and keep focused on the task which constrains the generation of realistic evacuation behaviour. Besides that, the answers from participants in surveys may deviate from their actual actions in real situations, especially the case when respondents are required to answer questions regarding unfamiliar situations or are required to recall past experiences.

To overcome these constraints, Virtual Reality (VR) has gained increasing attention and popularity for investigating pedestrian behaviour during evacuations. With VR experiments, it is possible to study the behaviour of participants during emergencies safely, while maintaining experimental control to analyse the influence of different factors on pedestrian behaviour more precisely. A number of prior VR studies have shown promising results regarding the derivation of pedestrian behaviour during evacuations (e.g., Duarte et al., 2014; Kinateder et al., 2019; Kinateder & Warren, 2016; Kobes et al., 2010a; Tang et al., 2009). The application of VR technologies is, therefore expected to be a valuable complement to the current experimental method toolbox to study pedestrian evacuation behaviour.

However, before VR can be adopted as a methodology for evacuation research, its ecological validity must be established (Kinateder & Warren, 2016). Although some aspects of pedestrian behaviour during evacuations have been investigated using VR, there are very few studies that validate VR research methods (e.g., Kinateder & Warren, 2016; Kobes et al., 2010a). Thus, in order to develop VR method as a valid research approach to study pedestrian behaviour, empirical evidence is needed that compares pedestrian behavioural results collected in a virtual world with behavioural results collected in the real world.

This study has two objectives, namely (1) to validate whether Virtual Reality combing smartphone-based HMD and 360-degree video can be used to measure pedestrian exit choice behaviour during an evacuation, and (2) to identify the impact of information on pedestrian exit choice during evacuations. To validate this VR, this study compares pedestrian exit choice behaviour during a real-life evacuation drill and a VR experiment that covers exactly the same situation. Afterwards, the VR simulator is used to determine to what extent different types of information (i.e., visibility of exit signs, directional information and the presence of other people) influence pedestrian exit choice behaviour.

The outline of the chapter is as follows. Section 3.2 provides an overview of the state of the art of using different experimental methods to study pedestrian exit choice behaviour during evacuations. Section 3.3 presents the research methodology for the field experiment and the VR experiments. Section 3.4 focuses on validation results obtained from field observation and VR experiments. Section 3.5 presents the results featuring the impact of information on pedestrian exit behaviour during evacuations. Section 3.6 discusses the results of the validation study and the effect of different types of information on pedestrian exit choice behaviour. This paper ends with conclusions, limitations and suggestions for future research.

3.2 Background

Up to this moment, predominantly three experimental methods have been used to study pedestrian exit choice behaviour during evacuations, including traditional methods such as field observations in real life, traditional controlled experiments, VR experiments and surveys. This section provides a brief overview of the work featuring experimental methods that make use of revealed behavioural data to study pedestrian choice behaviour during evacuations with a focus of field observations, controlled experiments and VR experiments. Consequently, this section reviews research pertaining to field observations, traditional controlled experiments and VR experiments that have been used to specifically study pedestrian exit choice behaviour.

3.2.1 Using field observations to study pedestrian exit choice behaviour during evacuations

Field observations are the traditional method to study pedestrian (exit choice) behaviour in real life. The intention of field observations is to study pedestrian behaviour as unobtrusively as possible (Feng et al., 2021a). Usually, a space with multiple exits is chosen as the experimental area and digital devices (e.g., camera) are used to record the evacuation process. For instance, Proulx (1995), Shields & Boyce (2000) and Galea et al. (2017) used video recordings to study pedestrian exit choice behaviour in apartment buildings, retail stores and a theatre. More recently, Imanishi and Sano (2019) and Rahouti et al. (2020) analysed evacuees' movements during evacuation drills in a theatre and a hospital respectively, featuring pedestrian route and exit choice. These studies illustrate that field observations can be a valuable experimental method to understand exit choice behaviour in the real world because pedestrians are more likely to behave naturally. Nevertheless, the variables of field experiments are difficult to control and evacuation drills cannot be completely realistic due to ethical and financial constraints. Therefore, it would be difficult for researchers to set up field observations to investigate how external variables (e.g., signage) influence pedestrian exit choice behaviour during evacuations.

3.2.2 Using traditional controlled experiments to study pedestrian exit choice behaviour during evacuations

Compared to field observations, in traditional controlled experiments (i.e., laboratory experiments and field experiments), variables can be controlled and the effect of each separate factor can be observed and analysed. Traditional controlled experiments have been widely used to study pedestrian behaviour under stressed conditions (e.g., enforce participants to hurry). One group of studies focused on the analysis of pedestrian exit choice under various experimental settings. For instance, Fang et al., 2010; Heliövaara et al., 2012; Zhu & Shi, 2016 studied evacuees' exit selection in a hall, a corridor and a classroom respectively. Kobes et al. (2010b) observed pedestrian behaviour during an unannounced evacuation drill in a hotel and investigated the influence of exit signs on pedestrian exit behaviour. Fridolf et al. (2013) and Ronchi et al. (2018) investigated pedestrian movement and exit choice in tunnel evacuation experiments with smoke. Another group of studies focused on the study of the influence of signage on pedestrian exit choice behaviour during evacuations. For instance, Wong & Lo (2007) tested the visibility of different exit signs during emergencies and Galea et al. (2017) studied the effect of dynamic signage on pedestrian exit choice behaviour. Guo et al. (2012) and Zhu & Shi (2016) performed classroom evacuation experiments to contrast route and exit choice behaviour under varying visibility conditions, occupant distributions and alarm information. More recently, Cao et al. (2018) investigated exit behaviour of pedestrians during evacuation under good and limited visibility in a supermarket. These studies illustrated that controlled experiment is also a useful approach to improve our understanding of pedestrian evacuation behaviour and the effect of external variables (e.g. information and infrastructure) on the choice behaviour of pedestrian. Nevertheless, participants have prior knowledge of the experiment and might not act naturally during the experiment. Furthermore, it is often costly to set up and perform controlled experiments.

3.2.3 Using VR experiments to study pedestrian exit choice behaviour during evacuations

To (partially) overcome the constraints of traditional experiment methods, VR is becoming a promising experimental approach that can potentially be used to study evacuation choice behaviour. With VR, it is possible to safely study the behaviour of participants during emergencies in immersive virtual environments, without being exposed to health risks (e.g., fire and smoke). Meanwhile, VR allows researchers to easily build and change the virtual scenes, thus a number of possible factors that potentially influence pedestrian behaviour can be studied with high experimental control (Feng et al., 2021a). The development and the increasing availability of VR hardware (e.g., HTC Vive, Oculus Rift, Samsung Gear VR) and software (e.g., Unreal Engine 4, Unity) provide different techniques and applications for VR to study pedestrian behaviour. Generally, two types of VR simulators exist, namely non-immersive VR and immersive VR.

In non-immersive VR, the virtual environment is displayed on a device, for instance, desktop monitor, and individuals interact with the environment via a device that controls the simulator (e.g., mouse, keyboard, joystick). For instance, Tang et al. (2009) created a VR emergency escape game to determine if and how various emergency signs help pedestrian behaviours in way-finding. Bode et al. (2014) tested the influence of directional signs on pedestrian exit choice. Silva et al. (2013) used a serious game to investigate pedestrian evacuation time and exit choice in a hospital while the game system provided information regarding the evacuation. Bode et al. (2015) and Fang et al. (2020), moreover, investigated the impact of presence of other people on exit and route choice behaviour using a 2D simulated virtual environment.

Another type of VR simulator is the immersive simulator. In immersion VR simulators, the virtual world is presented in a way that the virtual environment surrounds the participants. The participant interacts with the virtual environment through specialist simulator control devices (e.g., joystick**,** gloves) and motion tracking hardware (e.g., eye, head and motion tracking devices).

The first commonly adopted immersive simulator is the Cave Automatic Virtual Environment (CAVE), which displays the environment on huge screen monitors or multiple television projection systems simultaneously (Mujber et al., 2004). For instance, Kobes et al. (2010a) studied pedestrian exit and route choice behaviour in a hotel. Kinateder et al. (2014a, 2014b) used a 3D CAVE system to investigate the effect of social influence on pedestrian route and exit choice during evacuation from a tunnel emergency. Ronchi et al. (2016) investigated the effect of different lighting conditions during a road tunnel evacuation. Another most often used immersive simulator is HMD (head-mounted display). One major research theme using HMD simulators focused on studying the influence of environmental variables on pedestrian exit choice behaviour. Amongst other studies, Duarte et al. (2014) examined how dynamic features in exit signs affect pedestrian exit behaviour during an emergency egress using HMD device and a joystick. Moreover, Cosma et al. (2016) studied the influence of varying lighting conditions on pedestrian behaviour in a virtual tunnel evacuation and Tucker et al. (2018) tested the influence of hazard level and obstacle information on evacuees' anxiety levels and exit choice in a fire evacuation. Kinateder et al. (2019) studied the impact of coloured signs on pedestrian exit choice behaviour. Cao et al. (2019) and Zhu et al. (2020b) studied the impact of visual cues on pedestrian wayfinding behaviour, where the first studied the impact of virtual fire and the latter studied the impact of visual access. In a more recent study, Zhao et al. (2020) analysed the effects of different crowd management strategies (e.g., remove fences and/or police cordons) on crowd behaviour for the 2010 Love Parade disaster. Another theme focused on the social influence on pedestrian exit choice behaviour. For instance, Kinateder & Warren (2016) studied the effect of social influence on pedestrian exit choice and Kinateder et al. (2018) used a wireless head-mounted display to investigate the influence of exit familiarity and neighbour’s behaviour on exit choice in a virtual ambulatory museum. More recently, Lin et al. (2020) examined the influence of crowd flow on pedestrian route and exit choice behaviour during evacuations.

These studies illustrate that, although some aspects of pedestrian behaviours during evacuation have been investigated, there are few studies that validated VR research methods. That is, very few studies have compared pedestrian behaviour in VR and real life. For instance, Kobes et al. (2010a) compared pedestrian evacuation behaviour in a real-life hotel and a virtual hotel. Subsequently, Kinateder & Warren (2016) compared pedestrian exit choice behaviour in a real and virtual environment to establish the ecological validity of VR. More recently, Li et al. (2019) investigated pedestrian route choice behaviour around obstacles in a field experiment and an identical 2D virtual environment. Given the little evidence pertaining to the validity of VR simulators to study pedestrian choice behaviour, there is a need for studies that determine whether VR is a valid and reliable technique to study pedestrian choice behaviour during evacuations.

Moreover, although above-mentioned PC-based and console-based HMD devices can provide participants with a rich immersive experience, the cost of a comprehensive immersive system can be relatively high. A potential low-cost solution is smartphone-based HMD which is the combination of an HMD device and a smartphone (Krevelen & Poelman, 2010). To the author’s knowledge, only one study has used smartphone-based HMD to investigate pedestrian evacuation behaviour (Ronchi et al., 2019). Their results showed the consistency between a low-cost HMD and a CAVE system, which is a first attempt at establishing the validity of this low-cost immersive solution. However, the feature of different VR devices (e.g., interaction function and immersion) and costs vary, thus more smartphone-based HMD studies are needed in order to help researchers understand the validity and the potential of using cost-efficient smartphone-based HMD to investigate pedestrian evacuation choice behaviour.

3.3 Experimental method

To achieve the first objective of this study, two experiments were carried out to study the exit choice behaviour of pedestrians during evacuation when they face either a real-life environment or a virtual environment. To achieve the second objective, we compared the commonalities and differences in exit choice between scenarios with different types of information in the VR experiments. Underneath these two experiments are further specified. First, the setup of the field experiment is described in section 3.3.1. Accordingly, the setup of the VR experiment is detailed in section 3.3.2.

3.3.1 Field evacuation experiment

The video recordings were captured during an unannounced evacuation drill conducted on November 23rd, 2017 as part of the safety training programme of the emergency response services of the faculty of Architecture of the Delft University of Technology. The subsequent analysis mentioned in this chapter was conducted as part of this training exercise to evaluate the student’s and safety officer’s response to the alarm. As such, no Human Research Ethics Committee (HREC) examination was required for the evacuation drill. The subsequent usage of the video for the VR experiment was assessed by the HREC as part of the evaluation of the VR experiment protocols. See section 3.3.2 for the details pertaining to this assessment. Underneath the experimental layout, experiment setup and procedures of this field evacuation experiment are further elaborated upon.

3.3.1.1 Experiment area layout

A workshop area with multiple exits was chosen as the location of the field experiment. This area was used by students to work on their graduation assignments for the study of architecture. The size of the workshop area was approximately 50 x 30 meters. Both the workshop area and exits were located on the ground floor of the Architecture Faculty (Figure3.1). The workshop area had eight exits. Exits A1 and A2 were located at the front middle of the area and exits B, C&D, E&F and G were located at the four corners of the area. Exit signs were equipped above the exits with a green-coloured background. All eight exits are emergency exits.

At the time of the evacuation drill, twenty-four students were present. Students were standing/sitting next to the tables doing their assignments individually, their locations are identified by the black circles in Figure 3.1. While working in this space, students could see all exits from their current location. We do not know the used entrance of each student, but most students generally walk in via Exit A and C, as these exits are the major exits of the workshop space.

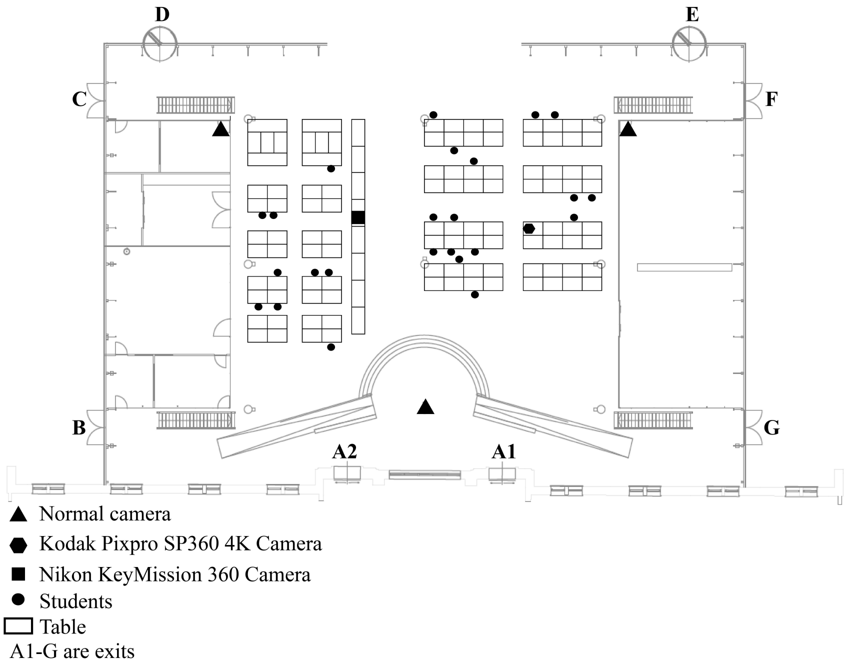


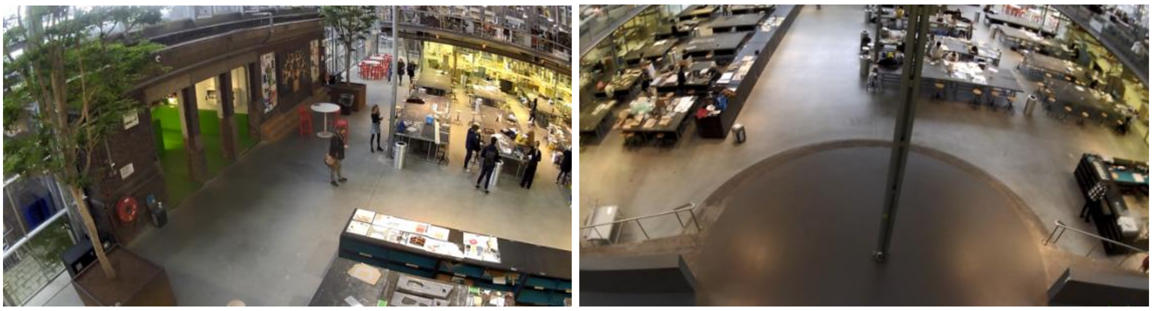
Figure 3. 1: A schematic illustration of the experimental area.

3.3.1.2 Experiment setup

The evacuation behaviour of the students working in the workshop was observed and recorded for two purposes. First and foremost, 360-degree videos were needed as the material to create the evacuation scenario for VR experiment. Second, the students' behaviour provided the benchmark for the comparison between the 'real' choice behaviour and the choice behaviour of the participants in the VR experiment.

A combination of normal cameras and 360 cameras was used, namely two 360-degree cameras (i.e., Nikon KeyMission 360 Camera and Kodak Pixpro SP360 4K Camera) and three normal cameras (i.e., CarCamDoo camera). Their positions in the workshop space are identified by icons in Figure 3.1. Two of the three 'normal' cameras were placed at the second level of the workshop space, and the third one was placed on a balcony overseeing the workshop space (Figure 3.2). These normal cameras had a higher and wider view, which ensured capturing the evacuation process of each individual. In order to identify every person clearly, the two 360 cameras were placed at the height of 1.8m above the ground to capture the overall movement of the participants from an aerial view (Figure 3.3). The setup of the field experiment ensured the behaviour of all students could easily be observed throughout the whole evacuation process without the observation being invaded or disturbing their natural behaviour.

All behaviours of the pedestrians (e.g., pre-evacuation behaviour, exit choice) from 5 minutes before until just after the end of the evacuation drill was recorded and afterwards transcribed. No human intervention within the workshop space was required to activate the cameras.



(a) **(b)**

Figure 3. 2: Screenshots of the view of the workshop space by the normal cameras which were located (a) at the corner and (b) the balcony.

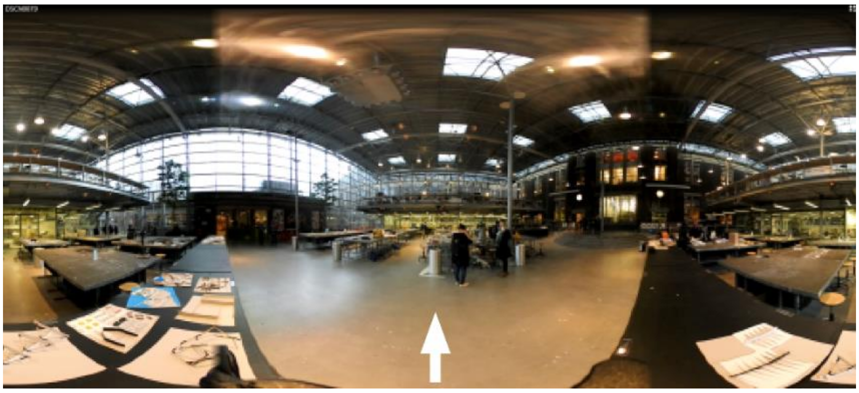


Figure 3. 3: A screenshot of 360° view of the workshop space by the Nikon 360 Camera

3.3.1.3 Experiment procedure of the evacuation drill

The full-scale unannounced evacuation drill of the Architecture Faculty building took place on 23rd November 2017, at 11:13 a.m. In the morning of the evacuation drill, researchers set up the experiment. Questions of students and staff members pertaining to the research installation were answered by stating that we were testing a new video tool.

Before the evacuation drill started, students were performing their assignments at the tables in the workshop space as usual. They were not informed about the pending evacuation drill. At the beginning of the evacuation drill, the evacuation alarm went off, followed by a voice message. In line with the normal operating procedure of during an evacuation training at the Delft University of Technology, voice instructions were broadcasted throughout the entire building repeatedly, asking all people to evacuate the building. The alarm message consisted of a female voice that repeated the following statement: “Attention, please leave the building using the emergency exits as indicated. Do not use the elevators.”. After three minutes, two members of the security staff walked into the workshop area to ensure that students actually left the space.

3.3.2 Evacuation experiment in the virtual environment

The VR experiment was conducted during the International Festival of Technology on 6th, 7th, 8th June 2018 in Delft, the Netherlands. The behavioural data that was collected during these three days was used for the validation study as well as the study into the impact of different types of information. The VR experiment was approved by the HREC of the Delft University of Technology (Reference ID No. 422).

3.3.2.1 Experimental design

A single-factor between-subjects experimental design was used for this study to reduce the learning effects due to repetitive exposure. In order to determine the effect of various types of information on pedestrian exit choice behaviour, four different scenarios were carried out: one scenario to validate the tool and three experimental scenarios (i.e. no additional information, exit sign scenario, direction scenario). Each scenario used the 360-degree video-recording of the abovementioned full-scale unannounced evacuation drill as the benchmark. In essence, participants were immersed in a 360-degree visual environment, which was the video-recording from the Nikon KeyMission 360 Camera. Participants started the experiment at the static vantage point of the video recording (Nikon 360 camera, see Figure 3.1), which is the same location for participants to perceive the virtual environment and locations of eight exits during the experiment. At the start of the experiment, all participants were facing the tables on the right, as indicated by the white arrow in Figure 3.3. The white arrow points to the direction where participants looked at when they were first immersed in the virtual environment. Participants had a 360-degree view of the environment via rotating their head in real life. That is, participants could not move through the virtual environment. Instead, they could only move their field of view by rotating their head. The installation height of the camera (1.80 meters) ensured that participants have a realistic vantage point of the entire workshop area. An alarm sound of the evacuation drill video (Nikon 360 camera) was added to all scenarios in the VR experiment in order to ensure participants received exactly the same information as in the field experiment. As at least two exits are clearly visible from the vantage point of the participants at the start of the VR experiment, we do not expect the notion that there were several exits to induce a bias in the participant's responses.

Besides the four scenarios, a general familiarisation scenario was developed to allow participants to become familiar with the way to observe the virtual environment and the sensation of VR. The familiarisation scenario entailed a 360-degree video of the workshop space, and it excluded any evacuation clues, evacuation alarm, or any pedestrians. In order to help participants to describe their exit choice, “Left” and “Right” signs were added on the ground of all scenarios (Figure 3.4). The participants did not have a visible presence in the virtual environment (i.e., a participant cannot see their own body).

3.3.2.1.1 Validation scenario

In order to test the ecological validity, the Validation scenario presents participants with an identical evacuation scenario as the real-life evacuation drill. Thus, the students present during the evacuation drill were also present in the 360 ° videos, as shown in Figure 3.4.

Figure 3. 4: Screenshots of the Validation scenario.

3.3.2.1.2 Experimental scenario

Next to the Validation scenario, three other scenarios were created to investigate the effect of different types of information on pedestrian exit choice behaviour. The three scenarios featured one without additional information, one with increased visibility of exit signs, and one with additional directional information. The video recording of the validation experiment was used as a benchmark to create these scenarios, which allows us to directly compare the participants' exit choice in three scenarios. All pedestrians appeared in the video recording were removed in the experimental scenarios. For a depiction of the visual changes to the scenario, see Figure 3.5. The changes per scenario are:

- ***No information scenario***: No additional information was added to this scenario (Figure 3.5a).
- ***Exit sign scenario:*** the concept of increasing visibility was incorporated by adding eight emergency exit signs with larger dimensions than the original signs to the environment. The signs were entirely text-based, containing a green background and white text (Figure 3.5b). They were added on top of the original exit signs at the same location.
- ***Direction scenario***: four white arrows were added on the floor in front of the view of participants, which point to four directions directly connected exits (i.e., exit B, C, D, E, F and G) and outside of the building (Figure 3.5c). The arrows were intended to inform the participants about the location of exits which were less easily observed (compare to exit A1 & A2).

(a) No information scenario **(b) Exit sign scenario** **(c) Direction scenario**

Figure 3. 5: Screenshots of three experimental scenarios.

3.3.2.2 Apparatus

This particular VR experiment does not require highly complex and expensive tools because the collected data was focused on pedestrian exit choice behaviour. Thus, a smartphone-based head-mounted display (HMD) device was deemed sufficient to capture the exit choice of participants. The smartphone-powered HMD device comprises an iPhone X and a VR Pro Virtual Reality Glasses. Participants were immersed in the virtual environment via the HMD, which has an approximate 90° horizontal and 110° vertical field of view. Figure 3.6 shows the front view and the top view of the HMD device. The screen was 14 cm length and provided a resolution of 1125 x 2436 pixels for 3D effects. It has a refresh rate of 90 Hz.

(a) **(b)**

Figure 3. 6: The front view (a) and the top view (b) of the head-mounted display was used during the VR experiment.

3.3.2.3 Data collection

The collected data through the VR experiment was mainly two-fold: (1) exit choice behaviour and (2) participants' experience regarding the VR experiment. As the objective of this study was related to exit choice behaviour, the behavioural outcome variables of the VR experiment were the number of exits a participant had identified during the experiment and the actual exit choice of each participant.

In order to obtain participants' exit choice and experiences of participants regarding the VR experiment, participants were asked to complete a questionnaire immediately after the experiment. The questionnaire contained four sections, namely (1) Exit choice behaviour, (2) Simulator Sickness Questionnaire (SSQ), (3) System Usability Scale (SUS), and (4) Presence Questionnaire (PQ).

The first section of the questionnaire recorded participants' exit choice behaviour, in particular, the number of identified exits, final exit choice, and the reason for choosing a certain exit choice. The identified exit is defined as the number of exits participants were able to observe during the experiment. The final exit choice is defined as the final exit participants chose to use at the end of the experiment. The participants were also asked to draw the identified exits immediately after finishing the task on a paper, which is a simplified version of Figure 3.1. In addition, some personal details were collected, such as age, gender, familiarity with the building of the Architecture Faculty and previous experience with VR.

The second section featured the Simulator Sickness Questionnaire (Kennedy et al., 1993), which determined if participants experience sickness, such as nausea, oculomotor discomfort, and disorientation, throughout the experiment. Participants reported on a 4-point Likert scale from 0 (no) to 3 (severe) about how much each symptom affected them.

The third section was the Presence Questionnaire (Witmer & Singer, 1998), which assessed the user’s feeling of presence in the virtual environment. It includes five factors, namely involvement, immersion, visual fidelity, interface quality and sound effect which influence user presence in a virtual environment. The items were rated on a 7-point scale. It contains questions such as, “How involved were you in the virtual environment experience?”, “How completely were all of your senses engaged?”, and “How much did your experiences in the virtual environment seem consistent with your real-world experiences?”.

The fourth section was the System Usability Scale (Brooke, 1996), which assessed the usability of the applied VR system as a pedestrian simulator. The system usability scale consists of 10 items, which were rated on a 5-point Likert scale (i.e., 1=strongly disagree, 5=strongly agree). It includes questions, for instance, “I thought the system was easy to use.”, “I felt very confident using the System.” and “I thought there was too much inconsistency in this system.”.

3.3.2.4 Recruitment of participants

A random sampling approach was applied to recruit participants. Firstly, the festival organiser posted information regarding the experiment on their website. Besides that, a news item featuring the opportunity to try VR was spread via social media: LinkedIn, Facebook and WhatsApp. In addition, the experiment was promoted through the traditional media outlets of the university (i.e., posters and digital news feeds). Finally, participants were also recruited during the festival by the researcher. In total, 94 participants volunteered to take part in the VR experiment.

The information provided at the recruitment stage included a description of the experiment and formal details on the location and the dates of the experiment. Please note, the specific features of the VR experiment were not communicated to the potential participants, e.g., the experiment features an evacuation drill, the experimental building (the Architecture Faculty), or the conditions of the evacuation drill.

3.3.2.5 Experiment procedure

Each participant was randomly assigned to one of four scenarios. The procedure of the VR experiment included four parts, being: (1) introduction, (2) familiarisation, (3) actual evacuation drill, and (4) questionnaire. Underneath the procedure is further detailed.

Introduction: When participants showed interest and indicated that they would like to join the experiment, they were required to read the instructions of the study and were informed of the purpose of the experiment (i.e., to investigate the use of virtual reality for pedestrian behaviour), and their assignment (i.e., to determine which exit to choose). No further information was provided about the scenario that they would experience (i.e., that they would be confronted with an emergency) since this might have led to biases in the participants' response.

VR familiarisation: Accordingly, the participant was instrumented with the head-mounted display. Afterwards, two videos were loaded. Participants firstly explored a familiarisation virtual reality video for 30 seconds. If participants got sick during this period, they were allowed to have a break, and after the break they could decide whether to continue or quit the experiment.

Evacuation: After the first video, the screen faded to black, and after an interval of 7s the trial video started. At the start of the evacuation experiment, participants were asked to choose an exit within 3 minutes. This time limit is based on the time that all pedestrians in field observation required to exit from the building. As such, we do not expect that setting a time limit in the experiment will produce a bias in the choice behaviour due to the time pressure. Participants who got sick during this period were taken out of the experiment because they would already have experienced the evacuation situation. Furthermore, each participant only experienced one scenario, because prior knowledge about the scenario and repeated exposure to the environment is found to influence their exit choice behaviour (Lin et al., 2019; Vilar et al., 2013a).

Questionnaire: After the evacuation experiment was finished, participants were asked to remove the head-mounted display and fill in the questionnaire. After finishing the questionnaire, participants were thanked and some sweets were provided (Figure 3.7).

(a) **(b)**

Figure 3. 7: Participants were (a) experiencing the VR experiment and (b) filling in the questionnaire.

3.4 Results regarding the comparison of exit choice in real life and VR

In this section, the results of the field experiment and the Validation scenario from the VR experiment are detailed. First, the characteristic of the sampling population is presented. Afterwards, the exit choice from both experiments is provided. Next to that, the analysis of ecological validity is presented.

3.4.1 Characteristic of the sampling population

The characteristic of the pedestrians from the field experiment were derived from the video recordings. At the start time of the alarm, 24 individuals were inside of the workshop space performing their assignments, of which 13 were female (54%) and 11 male (46%) students of the Architecture Faculty. All individuals were bachelor or master graduation students, so the age distribution of the participants was between 21–25 years old. Given that the workshop area is a room in which students perform their assignments, the pedestrians involved in the real-life evacuation drill were relatively familiar with the structure of the building.

In the Validation scenario from the VR experiment, 27 individuals participated. One participant did not make the exit choice before the experiment ended, thus the results of the Validation scenario discussed underneath are based on 26 participants including 10 females (48%) and 16 males (52%). The ratio of the distribution of gender of the participants between the field experiment and VR experiment was not significantly different ($p = 0.204$).

Moreover, the distribution of the participants' age in the Validation scenario is slightly different than the field experiment, 16 individuals were in the age range of 18–25 years old and 10 individuals were in the age range of 25-45 years old. Furthermore, of the individuals that participated in the Validation scenario, only 2 participants claimed they are working or studying at the faculty, 12 participants visited there once, and the remaining 12 participants indicated that they had never been in the building before. Results from the Pearson chi-square test demonstrated that there was no significant influence of age ($p = 0.310$), and familiarity ($p = 0.123$) on exit choice in the Validation scenario.

3.4.2 Exit choice behaviour in real-life and VR

Table 3.1 shows the exit choices obtained in the real-life evacuation drill and the VR experiment. During the real-life evacuation drill, most pedestrians either chose exit A1 or C. The other exits were not being chosen. The final exit choice of each individual was visualized in Figure 3.8. It shows that students did not always choose the nearest exit, which implies that distance is not the only factor that influences their exit choice behaviour. To gain insights into the reasons, we analysed the video recordings in detail. In most cases, before starting their decisive evacuation movements to an exit, students decided to undertake a variety of activities, such as packing belongings, searching for others, investigating cues, and seeking confirmation from others. In total, 13 pedestrians showed waiting behaviour and moved to an exit with one or two other pedestrians together. That is, these particular individuals were stalling while waiting, facing and talking to other individuals in the space, before walking out together with the individual they were communicating with. Thus, the students performed so-called herding behaviour relatively frequent (Helbing et al., 2000), where students tend to follow friends or classmates to the exit.

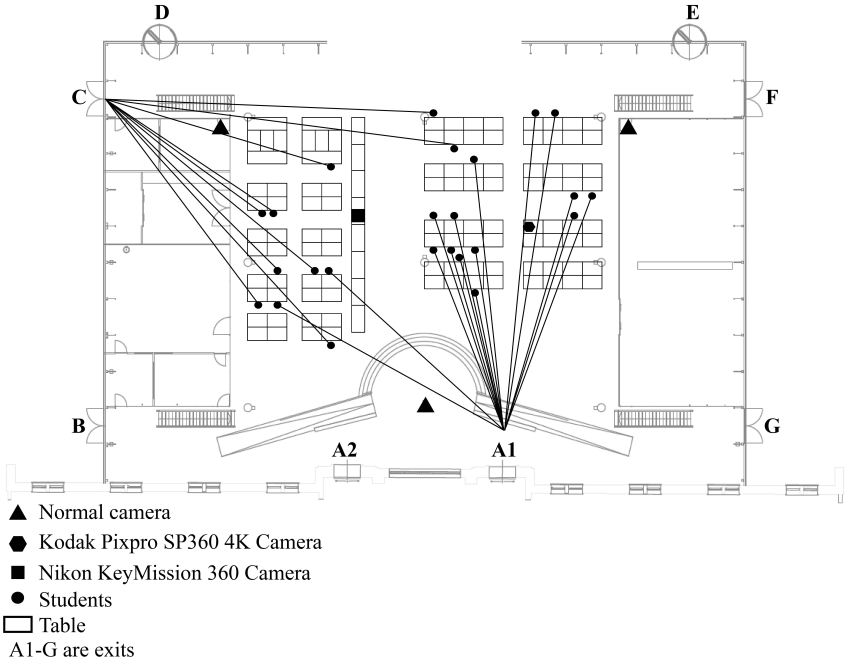


Figure 3. 8: The exit choice of each individual in the field experiment

In the Validation scenario from the VR experiment, similarly, most participants chose exit A1 and C. Some participants also chose exit E. No other exits were chosen. The results of the questionnaire illustrated that herding behaviour was a major source of influence on participants' exit choice behaviour. That is, 7 participants claimed they chose the exit because they saw other people went towards the exit. Besides that, the distance and visibility of the exits were also taken into consideration by the participants. For instance, 8 participants chose the exit according to the nearest distance, and 7 participants chose the exit because of good visibility of the exit and their directness towards outside. Furthermore, the familiarity of the participants was also identified as an influencing factor, 2 participants knew the building so they chose it according to their habit.

Table 3. 1: The exit choice in the field experiment and the Validation scenario.

Exits	**A1**	**C**	**E**	**Total**
Field experiment	15 (62.50%)	9 (37.50%)	0 (0%)	24
Validation scenario	13 (50.00%)	10 (38.46%)	3 (11.54%)	26
Total	28	19	3	50

3.4.3 Ecological validity analysis

To determine whether this VR simulator (i.e., the combination of smartphone-based HMD and 360-degree video) can be used to measure pedestrian behaviour, a justification for ecological validity is needed. In other words, in order to use the VR method for future experiments, it is important to determine whether participants behaved similarly in the virtual environment as they would in the real world (Deb et al., 2017). In this study, because exit choice is a categorical variable, the ecological validity of the results generated from the VR experiment was tested using the Pearson chi-square test. The null hypothesis is formulated as follows: the exit choice behaviour during evacuation does not depend on the experimental method. In order to meet the requirement of the chi-square test for its appropriate use (i.e. no more than 20% of the exits should be chosen less than 5 times), exit A1, B, G are combined into one category. That is because exit A1, B, G were all located at the right side of the workshop area, of which only exit A1 was chosen in both field experiment and Validation scenario. Thus, it results in 2 degrees of freedom for the chi-square distribution.

The Pearson chi-square test with a $\chi 2$ value of 3.12 showed that the probability value is 0.21 at a significance level of 95%, thus we cannot reject the null hypothesis. This indicated that the differences between the two experimental methods did not have a significant influence on the exit choice behaviour of the participants.

Another interesting finding is that in both experiments, the pedestrians’ exit choice was asymmetrical. Although eight exits were available and all the students or participants could see all exits from their position, exit A1 and exit C were used more often than the other six exits. Moreover, the percentage of the participants that chose exit A1 was higher than the percentage that chose exit C in both experiments. Although we do not know the exact reason why pedestrians chose a particular exit in the real-life evacuation drill, the video recording shows that in total 13 pedestrians waited, talked with other students and moved towards exits A1 and C as two-person or three-person groups (Table 3.2). In the Validation scenario, 8 participants indicated that they saw other people move towards exit A1 and C. Thus, it could be argued that pedestrians in both the field experiment and the Validation scenario followed the choice behaviour of other pedestrians, which indicates that the VR method can be used to measure pedestrian exit choice behaviour in a qualitative way.

Table 3. 2: The reasons for choosing a certain exit in the two experiments.

Exits	**Reasons**	**A1**	**C**	**E**	**Total**
Field experiment	Following others	10	3	0	13
	(Unknown)	5	6	0	11
Total		15	9	0	24
Validation scenario	Following others	5	2	1	8
	Distance to exits	3	4	0	7
	Visibility of exits	2	1	0	3
	Familiarity of exits	1	0	1	2
	Path to exits is clear	1	0	0	1
	Direct exits to outside	0	3	1	4
	Others	1	0	0	1
Total		13	10	3	26

Although the quantitative and qualitative results of exit choice are very similar for both experiments, there are some differences in the participants’ exit choice behaviour that cannot be ignored. In the real-life observation, besides exit A1 and exit C, the other exits were not used at all. In comparison, 3 participants in the Validation scenario chose exit E, either because its directness towards outside or because they were very familiar with the environment. Based on the data collected during the two experiments, we cannot determine why the pedestrians in real life did not choose these exits. A possible explanation of the differences is that exits A1 and C were closest to the bicycle parking area, which is the most dominant travel mode of the students. Thus, we still expect familiarity might be an influencing factor, although this was not ratified by the results of this study.

3.5 Results regarding the effect of information on exit choice behaviour

The previous section indicates that the VR experiment generated valid results pertaining to the exit choice in this particular VR setting. This section presents the results of using this VR experiment to investigate the impact of information on exit choice behaviour. First, an analysis of the participants' characteristics is presented in section 3.5.1. Secondly, an analysis of questionnaire data is presented in section 3.5.2. Afterwards, the exit choice behaviour over four scenarios is analysed in section 3.5.3.

3.5.1 Characterisation of participant population

In total, 95 participants took part in the VR experiment, of which only 94 were accounted for the data analysis because one individual failed to make the exit choice before the experiment ended (as mentioned in section 3.3.1). Table 3.3 presents the descriptive statistics of participants and their distribution over four scenarios. No significant differences were found according to the Fisher-Freeman-Halton exact test with regard to the distribution of participants' gender (p = 0.845), age (p = 0.460), familiarity with the building (p = 0.697) or previous VR experience (p = 0.549) over the four different scenarios.

Table 3. 3: Demographic information of participants.

Descriptive information	**Category**	**Scenarios** No information	 Exit sign	 Direction	 Validation
Gender	Male	11	17	13	16
	Female	10	10	7	10
Age	<18	2	0	2	0
	18-25	9	15	10	16
	26-35	8	8	7	7
	36-45	0	2	1	3
	>45	2	2	0	0
Familiarity with the building	Not at all familiar	6	11	11	12
	Slightly familiar	10	11	5	10
	Moderately familiar	4	4	3	2
	Very familiar	1	0	0	0
	Extremely familiar	0	1	1	2
Previous Experience with VR	Never	9	7	5	9
	Occasionally	9	13	13	13
	Frequently	2	7	2	3
	Usually	0	0	0	1
	Always	1	0	0	0

3.5.2 Participant's perception of the virtual environment

Total scores were calculated for each questionnaire of each participant with respect to the Simulator Sickness Questionnaire (SSQ), System Usability Scale (SUS) and Presence Questionnaire (PQ), as shown in Table 3.4. In order to test significant differences of questionnaire results among four scenarios, the non-parametric Kruskal–Wallis was conducted for SSQ, and one-way ANOVA was used to compare the results of the SUS and the PQ between the participant groups. No significant difference was found in the SSQ among four scenarios, $H(3) = 3.044$, $p = 0.385$, as well as in the SUS, $F(3,90) = 2.452$, $p = 0.068$ and in the PQ, $F(3,90) = 1.519$, $p = 0.215$. This finding signals that the differences in perception between the four scenarios are very limited.

Table 3. 4: The mean score and standard deviations of each questionnaire results in four scenarios.

Scenarios		SSQ	PQ	SUS
No information	Mean ± SD	33.84 ± 37.52	72.71 ± 12.76	62.74 ± 8.06
Exit sign	Mean ± SD	25.07 ± 25.72	73.07 ± 12.77	70.00 ± 13.03
Direction	Mean ± SD	23.19 ± 25.81	65.95 ± 14.08	73.75 ± 12.34
Validation	Mean ± SD	20.14 ± 25.17	72.81 ± 12.16	71.06 ± 18.35

Furthermore, the mean scores and standard deviations of each questionnaire results were calculated (Table 3.5). The score of SSQ reflects the symptomatology of participants' experience in the virtual environment. The maximum total score of the SSQ is 236 (Kennedy et al., 2003). In general, the SSQ score of all participants was quite low in the present study. Table 3.6 shows the mean scores and standard deviations of each sub-scale in SSQ. It shows that the subscale of Nausea received the lowest score, increased by Oculomotor and Disorientation. Although the disorientation subscale is related to vestibular disturbances, such as dizziness and vertigo, it may also be an indicator of having experienced higher levels of virtual presence (Barfield & Weghorst, 1993). Meanwhile, none of the participants got sick during the experiment nor showed any symptoms, such as dizziness or nausea.

Table 3. 5: The mean scores and standard deviations of each questionnaire.

	SSQ	PQ	SUS
Mean ± SD	25.26 ± 28.61	71.40 ± 12.99	69.47 ± 14.07

Table 3. 6: The mean and standard deviations of subscales in SSQ.

Subscale	Nausea	Oculomotor	Disorientation
Mean ± SD	19.68 ± 34.25	25.31 ± 30.88	35.91 ± 53.41

Besides that, the score of the Presence Questionnaire was obtained summing the responses of 22 items, scores can range from a minimum of 19 to a maximum of 133. The total scores of PQ with a mean of 71.40 and a standard deviation of 12.99 (Table 3.5) indicated that participants experienced a moderate amount of presence in the VR experiment. The mean scores and standard deviations of the five sub-factors in the PQ questionnaire (Witmer & Singer, 1998) were evaluated in more detail. As shown in Table 3.7, the interface quality receives the highest score, which indicates that the device had little distraction for participants performing their assignments. Meanwhile, the involvement factor also receives a relatively high score, which shows that participants experienced consistent concentration on the assignments they need to perform in the VR experiment. Last of all, the score of the System Usability Scale was calculated via multiplying the sum of the converted responses by 2.5. A SUS score above 68 identifies that the tool's usability is above average (Sauro, 2011). The mean score of SUS in the current experiment is 69.47, which indicates the participants were satisfied with the usability of the VR system.

Table 3. 7: Breakdown of the results of the Presence Questionnaire (range from 1 to 7).

	Involvement	Immersion	Visual fidelity	Interface quality[a]	Sound effect
Mean ± SD	3.24 ± 0.86	3.20 ± 0.72	2.88 ± 0.99	4.61 ± 1.00	2.68 ± 1.41

[a] Reversed items

3.5.3 Exit choice behaviour in four scenarios

The exit choice behaviour of the participants was assessed in three parts, namely the number of exits they identified after the VR experiment (i.e., the choice set), the actual exit that has been chosen by the participants (i.e. the exit choice), and the impact of information on both elements of the exit choice behaviour.

3.5.3.1 The number of identified exits

In the questionnaire, participants filled in the number of identified exits and drew these exits on a sheet of paper. If the location at which a participant drew an exit was reasonably close to the actual location of real-life exits, the exit was counted as one of the correctly identified exits. The results of the number of identified exits per scenario are depicted in Table 3.8, which shows that, on average, participants from the Exit sign scenario identified the most exits (*M* = 5.81, *SD* = 2.11). As expected, the average number of exits identified by participants in the scenario with direction information was higher than the number of exits identified in the No information scenario. At the same time, in the No information scenario, participants identified the least exits (*M* = 2.62, *SD* = 1.12).

Table 3. 8: The number of identified exits.

Scenarios	Mean ± SD	Maximum	Minimum
No information	2.62 ± 1.12	5	1
Exit sign	5.81 ± 2.11	8	1
Direction	3.20 ± 1.47	8	2
Validation	2.88 ± 1.24	6	1

The Kolmogorov–Smirnov test revealed that the number of identified exits in the Exit sign scenario and the Direction scenario did not significantly deviate from a normal distribution, but in the No information scenario and the Validation scenario was non-normally distributed. Thus the impact of information on the number of recognised exits for each scenario was analysed using the non-parametric Kruskal–Wallis test and in combination with Dunn post hoc test.

Results from Kruskal–Wallis test demonstrated that there was a significant difference of the mean number of identified exits among four scenarios ($H (3) = 22.895$, $p < 0.001$), which provided strong evidence of a difference between the mean number of identified exits at least one pair of scenarios. Afterwards, Dunn's post hoc test was conducted to test pairwise comparisons, namely the between scenario differences for the number of identified exits. The results showed that there are significant differences of the number of identified exits between the Exit sign scenario and the Validation scenario ($p < 0.001$), the Exit sign scenario and the Direction scenario ($p = 0.001$), and the Exit sign scenario and the No information scenario ($p < 0.001$). Meanwhile, there was no evidence of a significant difference between other pair scenarios. This finding identifies that participants tend to recognise and identify more exits when additional information about exit sign was provided than if there was no information, directional information or the presence of other pedestrians. This finding confirms that increasing the visibility of exits has a significant influence on pedestrian identifying the exits during evacuations.

3.5.3.2 Final exit choice

On the same paper where the participants drew the location of exits, they also indicated which exit was their final exit choice, which is presented in Table 3.9. Even though eight exits were available, the exit choices were mainly distributed over exits A1, A2, C and D, which are the nearest exits compared to exit E, F and G. Besides that, the results show that participants had a variety of final exit choices amongst the four scenarios. As one can see, in these experimental scenarios (i.e., No information, Exit sign, Direction) a wider variation of final exit choices was considered than in the Validation scenario (i.e., exits A1 and C were most chosen). At the same time, when there was no additional information provided (i.e., the No information scenario) exits A1 and D were most often chosen. In the Direction scenario, the majority of participants chose exits C and D. Yet, in the increased visibility of exits in the Exit sign scenario, there is a fairly even division in terms of exit choices. Compared to the other three scenarios, the distribution of the participant's final exit choice in the Exit sign scenario was more symmetrical.

Table 3. 9: The participants' final exit choices for all four scenarios.

Exits	A1	A2	B	C	D	E	F	G	Total
No information	6 (28.57 %)	4 (19.05 %)	0 (0%)	1 (4.76 %)	8 (38.10 %)	0 (0%)	2 (9.52 %)	0 (0%)	21
Exit sign	5 (18.52 %)	5 (18.52 %)	0 (0%)	5 (18.52 %)	5 (18.52 %)	5 (18.52 %)	1 (3.70 %)	1 (3.70 %)	27
Direction	3 (15.00 %)	0 (0%)	0 (0%)	5 (25.00 %)	9 (45.00 %)	3 (15.00 %)	0 (0%)	0 (0%)	20
Validation	13 (50.00 %)	0 (0%)	0 (0%)	10 (38.46 %)	0 (0%)	3 (11.54 %)	0 (0%)	0 (0%)	26

In order to test whether different types of information significantly influence participants' exit choice, the Fisher-Freeman-Halton exact test was conducted. The results revealed that participants' final exit choice in the Validation scenario is significantly different to the No information scenario ($p < 0.001$), the Exit sign scenario ($p = 0.002$), and the Direction scenario ($p = 0.001$). These results suggested that among the four scenarios, the presence and choices of other pedestrians in the Validation scenario had a significant impact on participants' final exit choice. Meanwhile, there was a significant difference between the No information scenario and the Direction scenario ($p = 0.013$). However, there were no significant differences either between No information scenario and Exit sign scenario ($p = 0.137$), or Exit sign scenario and Direction scenarios ($p = 0.266$). This indicates that compared to the scenario without any additional information, directional information and other pedestrians both had significant influences on the participant's exit choice. At the same time, increased visibility of exits did not have a significant influence on final exit choice.

3.6 Discussions

3.6.1 Discussion pertaining to the validation results

The results and findings of the exit choice behaviour from the field experiment and the VR experiment were presented in section 3.4. These findings illustrate that the methodological differences between the two experiments do not result in significant differences regarding the pedestrians' exit choice behaviour.

Up to this point, only a few studies validated pedestrian evacuation behaviour collected by means of VR experiments, most of which used a projection VR (Kobes et al., 2010a) or an HMD with a simulated virtual environment (Kinateder & Warren, 2016). The current validation study is complementary to studies showing that results regarding pedestrian exit choice behaviour are valid through different types of VR equipment. By comparing exit choice of participants in a real-life evacuation drill and an identical virtual environment, preliminary steps are taken to validate this particular VR simulator (smartphone-based HMD and 360-degree video) to study pedestrian exit choice behaviour during evacuations. Please note, that this chapter only provides the first step towards comprehensively establishing the validity of this VR simulator, namely ecological validity. More research is required to also establish the content, construct and criterion validity of this particular VR simulator. The current VR experiment still includes several confounding factors (e.g. level of familiarity and age distributions) and only includes one repetition of one particular scenario. It is important to, in follow-up research, attempt to eliminate these issues via a quasi-controlled research setup.

Moreover, the findings highlight the influence of herding behaviour on pedestrian exit choice, where pedestrians choose to follow others during evacuations. In agreement with previous work (Helbing et al., 2000; Lovreglio et al., 2016; Moussaïd et al., 2016), herding behaviour was found in both the field experiment and VR experiment. While we found other factors influenced pedestrian exit choice (e.g., distance to exits, visibility of exits), herding behaviour was a main influential factor consistent across in both experiments, in spite of the fact that the individuals from the field experiment were very familiar with the environment, while the participants in the VR experiment had a relatively low familiarity with the building.

3.6.2 Discussion pertaining to the effect of information

Section 3.5 presented the findings regarding the effect of different types of information on pedestrian exit choice behaviour amongst four different scenarios in the VR experiment, as well as the results regarding participants perception of the virtual environment. Now we turn to the implications of these findings for deepening our understanding of pedestrian exit choice behaviour during evacuations and application of VR experiments for pedestrian safety research.

First, this study shows that pedestrians were more likely to recognise exits during evacuations when additional information was provided in the environment. Especially increasing the visibility of the exit sign allows pedestrians to, on average, recognise more exits. These results are consistent with studies demonstrating the effect of the visibility of exit signs on pedestrian’s recognition of exits during evacuations (Kobes et al., 2010a; Tang et al., 2009; Wong & Lo, 2007).

Second, the results suggest that the exits are not evenly used. This result is in line with other studies that look at the influence of spatial distribution of exits on pedestrian exit choice (Haghani & Sarvi, 2016a; Liao et al., 2014). Similarly, when other people are present, the usage of the exits is also asymmetrical. Moreover, increased visibility of the exits is also found to ensure a more symmetrical usage of the exits. Besides that, as suggested in the literature, this study finds that pedestrians were overall more likely to choose the nearest exits (Feng et al., 2020a; Guo et al., 2012; Haghani & Sarvi, 2016a; Kobes et al., 2010a; Li et al., 2019; Liao et al., 2017).

Third, this study shows that although good visibility of exit sign helps participants identify exits in the environment, it does not have a significant influence on their final exit choice. Instead, other pedestrians and directional information have significant influences on the participant's final exit choice. That is, participants were more likely to choose the exit which other pedestrians had already chosen. They perceived other individuals as potential sources of information. These findings are in line with the results of studies that researched the impact of other pedestrians on pedestrians' exit choice (Kinateder et al., 2018a; Kinateder & Warren, 2016). Moreover, this study also finds that pedestrians prefer to choose the exit where the directional signs point to. These findings are complementary to studies that only investigated one type of information strategy on pedestrian exit choice behaviour during evacuations (e.g., Wong & Lo, 2007).

Finally, the results demonstrate that the current VR experiment was applicable to study pedestrian exit choice behaviours during evacuations. Primarily, the ecological validity is established via comparing pedestrian exit choice in real-life evacuation drill and VR experiment. Moreover, the questionnaire results illustrated that the virtual environment was relatively immersive and the equipment's usability was sufficient for the purpose of this experiment. It also reports low simulator sickness. These results show that this experimental setup can be used as a research tool to study exit behaviour during evacuations. Yet, different from more expensive or complex VR systems, our VR experiment used a combination of HMD device and a 360-degree video-recording of the real-life evacuation drills. The fact that this rather 'simple' experimental setup provides valid results suggests that the choice of suitable VR devices may depend more on the behavioural data researchers want to collect than the sophistication of the VR equipment.

3.7 Conclusion and future work

This paper investigates pedestrian exit choice behaviour during evacuations using both VR experiments and field experiment. In particular, four different information strategies were realised in the VR experiment and the effects of these strategies on pedestrian exit choice behaviour were examined. This included three types of information, namely increased visibility of exit signs, directional signs to outside, and information provided by other pedestrians.

Firstly, this study provides preliminary proof of the ecological validity of the VR simulator using the results from a field experiment and a similar VR scenario. The results demonstrated that the combination of smartphone-based HMD and 360-degree video can be used to conduct evacuation experiments under controlled experimental conditions, which allows researchers to control specific variables of interest systematically and to test pedestrian exit choice behaviour in well-specified scenarios (Kinateder et al., 2018a). Secondly, the impact of different types of information strategies was investigated using the validated VR experiment method. It was found that the presence of other people and information pertaining to the direction of the exits has a significant influence on pedestrian exit choice. Moreover, pedestrians' exit choice was found to be asymmetrical, especially in the scenario involving other pedestrians. Furthermore, the behavioural findings of this research and questionnaire data pertaining to the usability of this particular VR system add new much-needed insights to the discussion around the validation and usage of VR for pedestrian behaviour research.

These results provide useful information to evacuation management officials to develop (better) strategies to facilitate efficient evacuation (e.g., how to use exits evenly to avoid crowd in front of exits) in an environment with an open field and multiple exits. Moreover, this study provides a new VR tool that can be used to test new information strategies before they are implemented in the field in order to determine their effectiveness and/or train evacuation management personnel.

There are several limitations in this study. Firstly, even though we have attempted to recreate the scenario as close as possible, differences exist between the real-life evacuation drill and the validation scenarios in the VR experiments. That is, in real life, pedestrians were able to navigate freely and interact with other people, while the participants in the VR experiment only have visual rotation within the captured 360-degree field of view. Besides that, the distance between the exits and pedestrians is different in real life (i.e., next to the tables) than in the virtual environment (i.e., the middle of the room). Moreover, although limited influences of the environmental factors were expected, they could also not be completely excluded in the festival setting. In future studies, it is better to choose a more isolated environment to separate participants from the real-life environment, such as noise, lighting, sound. Secondly, although the used mobile-based HMD device was easier to operate and quicker to set up than more elaborate VR devices, some features, such as eye-tracking and free movements, are not available in this ‘simple’ VR device. This means that some aspects of pedestrian evacuation behaviour could not be recorded nor analysed in this study (e.g., pre-evacuation behaviour, gazing behaviour). Thirdly, the questionnaire data revealed that participants experienced a relatively lower feeling of presence compared to more advanced VR devices (e.g., Deb et al., 2017). More research (e.g., experiments with similar scenario settings) is required to establish whether the static vantage point and the limited set of features of this VR simulator do not hamper other types of validity (e.g. construct, discriminant and internal validity).

Yet, even when accounting for these limitations, there is benefit in using a low-cost HMD device, VR environment setup and relatively comparable conditions for pedestrian safety research. Especially, when unclarity exists regarding which independent variables should be included in the comprehensive pedestrian behaviour study, a preliminary pilot study featuring the combination of 360-degree video and smartphone-based HMD can allow researchers to get more grip on the actual set of influential factors. However, the last limitation of this VR experiment setup (i.e., lower level of presence) is difficult to solve using the current device. Thus, the next steps in this research featuring exit choice behaviour will be to enhance participants’ feeling of presence in the virtual environment by using a more sophisticated smartphone-based VR device and involving interactions with the virtual environment.

Chapter 4

Development and evaluation of a VR research tool to study wayfinding behaviour in a multi-story building

Results in Chapter 3 showed that the use of Mobile VR could be considered as a research tool to study pedestrian exit choice behaviour during evacuations. Yet, although the used Mobile VR device was easier to operate and quicker to set up than more elaborate VR devices, some aspects of pedestrian evacuation behaviour could not be recorded or analysed. Thus, a more sophisticated VR device and more complex scenarios are needed to develop to analyse pedestrian wayfinding behaviour in depth.

This chapter presents a new VR research tool, called WayR, to systemically study pedestrian wayfinding behaviour in a complex building. WayR supports free navigation and collects pedestrian walking trajectories, head movements and gaze points automatically. Section 4.2 summarises studies that applied VR methods to study pedestrian wayfinding behaviour. Section 4.3 presents the developing process of the VR research tool. Accordingly, section 4.4 details the experiment method applying WayR. The results of this experiment and WayR's validity and usability are discussed in section 4.5. This chapter ends with conclusions and recommendations for future avenues of research.

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4.1 Introduction

While walking in a building, pedestrians constantly make choices to find their way to reach their destination. This process of pedestrian wayfinding can be easy if the layout of the building is relatively simple. Yet, often building layouts are not simple and most people face wayfinding in complex multi-story buildings on a daily basis. Previous studies have shown that finding one's way in multi-story buildings is inherently difficult (Hölscher et al., 2013). In particular, in case of emergencies, pedestrian wayfinding behaviour is of vital importance to their survival (Arthur & Passini, 1992). Consequently, to ensure pedestrian safety and design comfortable buildings, many disciplines (i.e., architecture, fire safety engineering, and civil engineering) require investigation of pedestrian wayfinding behaviour in complex multi-story buildings (Feng et al., 2021a).

Traditionally, in order to investigate pedestrian wayfinding behaviour, field experiments have been widely applied in both normal and emergency conditions. The major advantage of field experiments is that pedestrians walk in a real-life environment and are most likely to behave naturally. During field experiments, pedestrian movement data is collected in real-life conditions under uncontrolled (e.g., Galea et al., 2017; Heliövaara et al., 2012; Kobes et al., 2010b; Nilsson & Johansson, 2009) or controlled conditions (e.g., Fang et al., 2010; Hölscher et al., 2005; Jeon et al., 2011; Zhu & Shi, 2016). In order to record pedestrian movement behaviour in specific situations or particular locations, digital equipment (e.g., cameras) is usually used. Pedestrian wayfinding behaviour has been investigated by means of field experiments in different contexts, such as schools, universities, theatres, hospitals, tunnels, and offices (Fang et al., 2010; Fridolf et al., 2013; Heliövaara et al., 2012; Imanishi & Sano, 2019; Kobes et al., 2010b; Nilsson & Johansson, 2009; Peacock et al., 2012; Rahouti et al., 2020; Zhu & Shi, 2016). These studies have illustrated that field experiment is a valuable method to study pedestrian wayfinding behaviour.

Despite the proven value of field experiments, there are also limitations in field experiments. Due to the complexity of most pedestrian infrastructures and natural variation of human behaviour in such environments, the experimental scenarios and external factors are generally difficult to control (Feng et al., 2021a; Haghani, 2020b). Besides that, using controlled field experiments to study pedestrian behaviour in risky situations is often restricted by ethical considerations featuring the mental and physical health of participants (Haghani & Sarvi, 2018). Meanwhile, studies into pedestrian wayfinding behaviour have limited themselves to investigate pedestrian movement on the horizontal levels (Hölscher et al., 2005), most likely to curb the complexity of the experimental setup. Performing field experiments generally require large labour and monetary investments. Moreover, the raw data captured during a field experiment cannot be analysed directly as the data still need to be extracted from a video recording afterwards, or the data is often not accurate and reliable enough to perform intricate data analysis. Therefore, field experiments have limitations to isolate the effect of external variables on pedestrian behaviour within a complex context, capture detailed data to characterise pedestrian behaviour (Almeida et al., 2017), perform experiments and extract accurate information cost-efficiently. Consequently, literature applying field experiments has limitations when capturing pedestrian wayfinding behaviour in complex buildings.

In order to overcome these limitations, researchers have attempted to use Virtual Reality (VR) technologies to study pedestrian wayfinding behaviour, especially during evacuations (e.g., Cao et al., 2019; Feng et al., 2019, 2020b; Fu et al., 2021a; Kinateder et al., 2018; Kobes et al., 2010a; Lovreglio et al., 2018; Ronchi et al., 2016; Vilar et al., 2014a; Zhang et al., 2021). Compared to field experiments, VR provides possibilities to obtain complete experimental control and collect accurate behavioural data related to pedestrian movement and choice behaviour (e.g., route choice and exit choice) automatically (Feng et al., 2021a). With VR, it is also possible to collect advanced behavioural data, such as gaze points and head rotations, which are difficult to extract when using more traditional methods. Moreover, VR allows participants to be virtually immersed in dangerous environments without the risk of facing actual physical dangers. Consequently, VR technologies can offer benefits to researchers who want to capture detailed behavioural data (i.e., personal characteristics, psychological data, and movement data) simultaneously under controlled conditions in a complex scenario (Feng et al., 2021a).

Despite these benefits, there are three major research gaps in the usage of VR for studying pedestrian wayfinding behaviour. Firstly, few studies have investigated pedestrian wayfinding behaviour in multi-story buildings. Existing VR studies have predominantly investigated pedestrian wayfinding behaviour in simplified virtual scenarios, mostly pedestrian movements on one horizontal level have been studied (e.g., Cao et al., 2019; Feng et al., 2020b; Fu et al., 2021a; Hsieh et al., 2018; Kinateder et al., 2018a; Ruddle et al., 1999; Vilar et al., 2014a; Zhang et al., 2021). Moreover, several VR studies recorded issues of the unrealistic representation of the real world, such as lack of natural movements, missing details of real-life situations, simulation sickness, which might lead to the unrealistic perception of the virtual environment (Meng & Zhang, 2014; Orellana & Al Sayed, 2013). Secondly, although some VR technologies support collecting comprehensive behavioural data, most of the analysis focused on traditional behavioural variables, such as route choice, exit choice, travel speed, travel time (Feng et al., 2021b; Fu et al., 2021a; Kinateder, Müller, et al., 2014; Kinateder & Warren, 2016; Kobes et al., 2010a; Ronchi et al., 2014; Vilar et al., 2014a; Vilar et al., 2013). Only a few studies attempted to capture and analyse more advanced behavioural data, such as gaze point and head rotation (e.g., Meng & Zhang, 2014; Schrom-Feiertag et al., 2017; Zhang et al., 2021). Thirdly, amongst the studies that applied VR to study pedestrian wayfinding behaviour, only a few studies attempted to verify the validity of the results (e.g., Feng et al., 2019; Kinateder & Warren, 2016; Kobes et al., 2010a; Li et al., 2019). Successful usage of VR for the experiment does not guarantee the validity of the results (Schneider & Bengler, 2020). Critical is to measure whether participants behaved in the virtual environment as they would in real world to establish the validity of VR. Several aspects of validity are relevant here, namely construct validity, content validity, face validity and ecological validity (Deb et al., 2017). To summarize, there are research gaps in using and validating VR for collecting comprehensive pedestrian wayfinding behaviour in realistic and multi-story buildings (for an exception, see Dong et al., 2021).

The objective of this study is to address these research gaps and unlock the potential of VR technologies for the study of pedestrian wayfinding behaviour in immersive, realistic and complex multi-story buildings. This study aims to develop a VR research tool, called WayR, and apply it to study pedestrian wayfinding behaviour in a multi-story building under both normal and emergency situations. WayR represents a multi-story building and features multiple emergency exits. It supports natural navigation through the entire building and collects pedestrian walking trajectories, head movements and gaze points automatically. This paper focuses on the development process of WayR and provides a preliminary evaluation of WayR's validity (i.e., face validity, content validity, construct validity, and ecological validity) for pedestrian wayfinding behaviour study. Please note, the comparison between behavioural results generated by means of VR technologies and in the real-life environment is not included in the current paper. Wayfinding experiments with 36 participants were conducted to evaluate WayR using objective measures (i.e., route choice, evacuation exit choice, wayfinding performance, and observation behaviour) and subjective measures (i.e., realism, feeling of presence, system usability, and simulation sickness).

This study contributes to the literature in three ways. Firstly, the study develops and describes the detailed development process of the VR research tool: WayR. Secondly, the study contributes WayR itself, a VR research tool that is capable of capturing detailed behavioural data and investigating pedestrian wayfinding behaviour in a multi-story building. Thirdly, through using WayR this study establishes the validity and usability of using VR to investigate pedestrian wayfinding behaviour in a complex multi-story building,

The rest of the chapter is organised as follows. Section 4.2 summarises studies that applied VR methods to study pedestrian wayfinding behaviour. Based on the insights of the previous VR study, section 4.3 identifies the functional requirements of WayR and details the developing process of WayR. Section 4.4 details the experiment method applying WayR. The results of this experiment and WayR's validity and usability are discussed in section 4.5. The paper ends with preliminary conclusions pertaining to WayR's validity and usability to study pedestrian behaviour and provides directions for future research.

4.2 Background: VR experiments to study pedestrian wayfinding behaviour

People need to find their way through buildings while moving from one location to another. This behavioural process may be as easy as moving from one room to another or as difficult as trying to escape a building that is under emergency (Dogu & Erkip, 2000). Due to the above-mentioned limitations of field experiments, researchers have explored VR as an innovative experimental approach to study pedestrian wayfinding behaviour. This section provides an overview of VR wayfinding studies and the gained insights for developing a VR research tool for pedestrian wayfinding study.

With VR technologies, it is possible to automatically collect detailed behavioural data in various virtual contexts. Existing research has applied VR to investigate pedestrian wayfinding behaviour in normal conditions or evacuations. For instance, Ruddle et al. (1999) and Hsieh et al. (2018) investigated pedestrian wayfinding performance in virtual mazes. Li & Giudice (2013) studied pedestrian wayfinding performance in two-story virtual buildings. Meng & Zhang (2014) investigated pedestrian wayfinding performance during a fire emergency in a virtual hotel. Kinateder et al. (2014a) and Ronchi et al. (2014) analysed pedestrian wayfinding behaviour and evacuation paths in tunnel evacuations. Andree et al. (2015) studied pedestrian exit choice behaviour in a high-rise building evacuation. More recently, Cao et al. (2019) specifically looked at pedestrian travel distance and travel time during an evacuation in a virtual museum. Fang et al. (2020) used a desktop VR to investigate pedestrian evacuation paths, directions, and times in fire scenarios. Shi et al. (2021) studied firefighter's wayfinding performance with emergency scenarios in an office maze.

Another benefit of VR is that external factors that potentially influence pedestrian behaviour in the virtual environment can be easily manipulated and controlled (Feng et al., 2021a). It can be used to analyse precisely how specific controlled factors influence pedestrian behaviour in environments that are not likely to encounter in real-life or scenarios that are too dangerous to expose a participant due to the health risks. A large number of studies have investigated the impact of external factors on pedestrian wayfinding behaviour under emergencies, which including crowdedness (Li et al., 2019; Lin et al., 2020a; Zhao et al., 2020), signage (Duarte et al., 2014; Feng et al., 2021b; Kinateder et al., 2019; Tang et al., 2009; Vilar et al., 2014a, 2014b), building configuration (Ronchi et al., 2016; Suzer et al., 2018; Vilar et al., 2013b), visual cues (Cao et al., 2019; Zhu et al., 2020a), social influence (Fu et al., 2021a; Kinateder et al., 2014a; Kinateder & Warren, 2016), smoke (Fu et al., 2021b; Kobes et al., 2010a), and personal characteristics (Kinateder et al., 2018a; Lin et al., 2019; Lin et al., 2020).

With the rapid development of immersive VR technologies, such as head-mounted displays (HMD) and cave automatic virtual environment experiments (CAVE), more comprehensive data (e.g., head movements, eye movements) describing pedestrian wayfinding behaviour can be collected. Conroy (2001) focused on pedestrian pause behaviour during wayfinding in different types of immersive virtual environments under normal situations, while Duarte et al. (2014) and Zhang et al. (2021) focused on participants' pause behaviour during evacuations. Regarding head and eye movements, Meng & Zhang (2014) recorded participants' eye movements with an eye tracker during an evacuation and compared eye fixation during wayfinding under normal and emergency conditions. Schrom-Feiertag et al. (2017) used a CAVE in combination with a mobile eye-tracking system to examine participants' gaze behaviour during wayfinding in public transport infrastructure. Suma et al. (2010) and Zhang et al. (2021) used HMD to investigate pedestrian head rotations during wayfinding in a 3D maze and a building evacuation, respectively,.

A critical issue of using VR to study pedestrian wayfinding behaviour is to establish its validity (Kinateder & Warren, 2016), namely whether participants behaved in virtual experiments align with pedestrian wayfinding behaviour in real life. Few studies have established the validity of using VR to study pedestrian wayfinding behaviour. Kobes et al. (2010a) conducted the first validation study to compare pedestrian wayfinding and evacuation behaviour in a real and virtual hotel. Kinateder & Warren (2016) compared pedestrian evacuation behaviour (e.g., walking speed, distance, and time) in the matched physical and virtual room (14 m x 16 m), which demonstrated the ecological validity of immersive VR for studying evacuation behaviour in emergency situations. More recently, Li et al. (2019) verified the validity of using VR to investigate route choice in simple space (14.4 m x 3.3m) via comparing pedestrian route choice in field observation and a similar virtual scenario. In their

VR experiment, participants only had top-down perspectives using desktops and controlled their movement by clicking the mouse. Feng et al. (2021b) contrasted pedestrian exit choice behaviour in a real-life evacuation drill and an identical virtual environment. They validated that the combination of smartphone-based HMD and 360° video can be used to measure pedestrian exit choice behaviour during evacuations. Ewart & Johnson (2021) found that participants' route choices during wayfinding were similar between a real-life building and an identical virtual building. Although the above studies demonstrated the validity of using VR to study pedestrian behaviour, some conflicting findings were also found. For instance, Suma et al. (2010) found significant differences in travel distance and head rotation between a real-world multilevel maze and an identical virtual environment. Most recently, Dong et al. (2021) compared pedestrian wayfinding behaviour in a real-life two-story building and a virtual building. They found that participant's wayfinding performance was overall similar between the two environments but their visual behaviour (i.e., visual information processing and virtual information searching) exhibited significant differences.

These studies illustrated VR is a safe, engaging and appealing approach to study pedestrian wayfinding behaviour. Moreover, these studies also provided some valuable insights regarding the optimal development and usage of VR technologies for pedestrian wayfinding research. Firstly, the realism level of the virtual environment can affect the accuracy of the behavioural data (Stanney et al., 1998). Existing studies have predominantly investigated simplified environments, such as a single room or a single floor (e.g., Cao et al., 2019; Duarte et al., 2014; Hsieh et al., 2018; Kinateder et al., 2019; Shi et al., 2021; Tang et al., 2009; Vilar et al., 2014a, 2014b), studies featuring pedestrian wayfinding behaviour in complex multi-story buildings are still rare (e.g., Andree et al., 2015; Li et al., 2019). Pedestrian wayfinding behaviour is affected by the layout of the architectural setting and the quality of the environmental information (Dogu & Erkip, 2000). Since the complexity and difficulty of pedestrian movements in complex environments are very different (Jeffery et al., 2013), findings pertaining to simplified environments cannot be directly generalised to complex buildings. In order to collect more accurate and comprehensive pedestrian wayfinding behavioural data, the developed virtual environments should represent realistic and complex real-life scenarios. Moreover, it is important to design realistic soundscapes to envelop the user in the ongoing situation, especially during emergencies (Li et al., 2017; Meng & Zhang, 2014). Secondly, only a few studies have attempted to validate results pertaining to pedestrian wayfinding behaviour generated from VR, but conflicting results existed. Most of the validation studies feature simplified environments and few perspectives of pedestrian wayfinding behaviour were compared (e.g., exit choice and route choice). Thus, it is important for future studies to establish the validity of the VR system, namely to test whether the results generated from VR experiments align with the actual behaviours of pedestrian in the real world. Thirdly, the literature suggests that more immersive virtual environments help participants behave closely to their behaviour in reality and consequently promise improved validity (Feng et al., 2018; Kinateder et al., 2014c). Moreover, compare to desktop VR, highly immersive VR systems, such as HMD and CAVE systems can provide more or full immersion for participants with more realistic feelings and collect new types of behavioural data (e.g., Bauer et al., 2018; Kinateder et al., 2014a, 2019; Li et al., 2019; Lovreglio et al., 2018; Schrom-Feiertag et al., 2017; Vilar et al., 2014a; Zhu et al., 2020a). Furthermore, VR systems equipped with motion tracking devices (e.g., head tracking devices) can more precisely measure visual attention and help researchers to gain a deeper understanding of how pedestrian interact with the environment (e.g., Meng & Zhang, 2014; Schrom-Feiertag et al., 2017; Zhang et al., 2021). Lastly, the VR system should be easy to understand, use and interact with so that it reduces the possibilities for participants experiencing simulation sickness (Cavallo et al., 2016; Simpson et al., 2003)

To summarise, although pedestrian wayfinding behaviour has been increasingly studied using VR experiments, there is a strong need for VR research tools to collect comprehensive pedestrian wayfinding behavioural data in realistic and complex multi-story environments. Moreover, it is important to validate the behavioural results generated by VR and ensure the VR research tool is easy to use.

4.3 Development of the VR research tool - WayR

To provide a new opportunity to study pedestrian wayfinding behaviour in multi-story buildings, a new VR research tool (WayR) has been developed. The development process of this VR research tool considers four steps, namely (1) to define the functional requirements of the VR research tool, (2) to choose the virtual environment, (3) to construct the virtual environment, and (4) to implement the interactive elements in the virtual environment. This section details the steps one by one.

4.3.1 Functional requirements of the VR research tool

The aim of the study is to develop and evaluate a VR research tool to study pedestrian wayfinding behaviour in a multi-story building. Based on the aim of the study and review of previous studies pertaining to experimental designs to study pedestrian wayfinding behaviour, we have identified five key functional requirements for the development of the new VR research tool.

Firstly, in order to study pedestrian wayfinding behaviour across horizontal and vertical levels, the VR research tool needs to allow users to perform wayfinding in multi-story buildings. Thus, the virtual environment is required to represent a building including multiple floors that are connected by means of staircases. Meanwhile, a minimum of two sets of route choices on both horizontal and vertical levels is required.

Secondly, in order to allow for the validation of the VR research tool, the virtual environment should feature scenarios that can be reproduced in reality, including all its intricacies. That is, the visualisation of the geometry, colour and texture in the virtual environment should be realistic to represent the real-world experience. Moreover, the visual and auditory perceptions of the environment should be similar as well. Thus, the details of the environment (e.g., signage and soundscapes) should be similar to a real-world experience.

Thirdly, in order to ensure the validity of the VR research tool, the interaction between users and the virtual environment should be natural so that the participant can behave and react to events (e.g., evacuation) similarly to their real-life behaviour. To achieve the most natural response possible, the virtual environment needs to be immersive and interactive. To achieve full immersion, the VR research tool should integrate natural navigation, namely participants should be able to freely navigate in the virtual building and have similar movement speed as in real life without experiencing motion sickness.

Fourthly, the VR research tool is particularly designed to perform experiments. Thus, a major requirement of the VR research tool is its ability to collect pedestrian behaviour data. In particular, the VR research tool should be able to track participant's movements, choices and observation behaviour (e.g., walking trajectory, timestamp, head rotation, and gaze point). Moreover, the VR research tool should be able to repeatedly perform (almost) identical experiments with varying participants. Therefore, it should support slightly alter of the experimental setup per participant, while ensuring an as similar as possible experience. For instance, the viewpoint of participants should be able to be adjusted according to their height.

Lastly, the VR research tool should be easy and comfortable to use for the participants and the researcher. This requirement relates not only to the participants' ability to quickly learn how to use and interact with the VR research tool but also the participants' mental and physical load of using the VR research tool should not cause simulation sickness. Moreover, the interface between the researcher and the VR environment should be relatively well-balanced in order to ease the operation of VR experiments. It ensures that when using the VR research tool, researchers can repeat the experimental procedure in the same order and timing, in order to provide a precise replication of the experimental settings for all participants.

The following sections address how we achieve the above-mentioned requirements and develop the VR research tool.

4.3.2 Virtual environment layout

WayR aims to be able to study pedestrian wayfinding behaviour in multi-story buildings, which better reflect the actual situations people experience. Thus, the experimental environment should ideally be a building with multiple floors that enable pedestrians to choose between multiple routes and exit choices. Moreover, in the later stage of this research project, the authors aim to compare the results generated by WayR with a variety of field experiments. Thus it should be possible to recreate the VR scenario in a real-life setting. Consequently, the choice has been made to recreate an existing real-life multi-story building in VR at a high level of detail.

In this case, the building of the Civil Engineering and Geoscience Faculty of the Delft University of Technology has been chosen as the real-world benchmark of the virtual environment. This faculty building consists of seven floors; most of which feature two parallel running hallways, elevators and staircases that run through all levels of the building. Students mainly occupy the lower two floors and the top floor of the faculty building, while the faculty staff have their offices on the second to fifth floors.

To limit the difficulty of assignment performance and reduce the chance of experiencing simulation sickness in the virtual environment, the three intermediate floors of the building (the second, third and fourth floor) and one exit floor were chosen as the experimental area (see

Figure 4.1). This is the smallest number of floors required to test pedestrian wayfinding behaviour featuring both horizontal and vertical levels. The layout of the three intermediate floors is in a way similar but the interior is quite different. Each floor has certain small corridors connecting the two main corridors. Besides that, each floor has five staircases and five elevators. On the exit floor, there are eight exits and all of them are emergency exits.

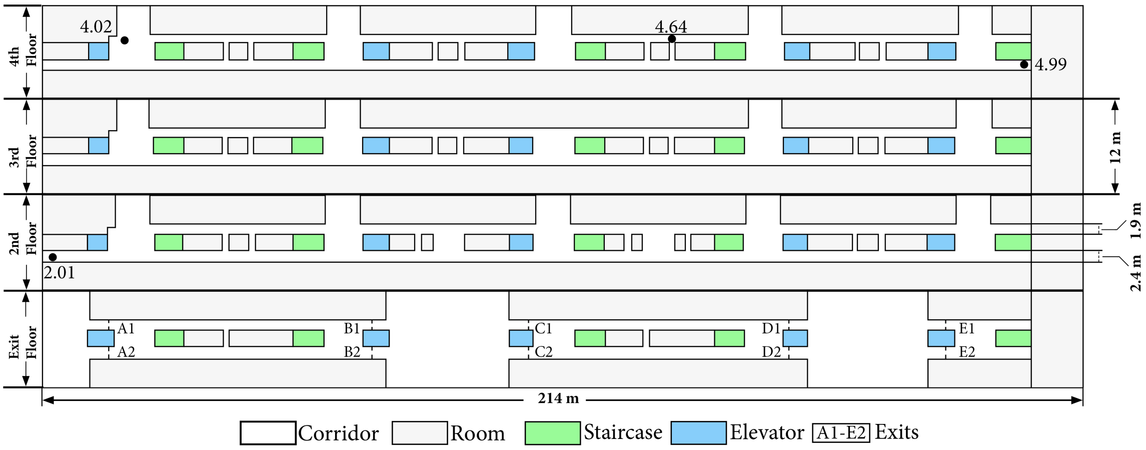


Figure 4. 1: Floorplan of the virtual building.

4.3.3 Construction of the virtual environment

The construction of the virtual environment featured two steps, namely the development of a 3D model of the building and the creation of the virtual environment. Firstly, the 3D model of the building was developed. Secondly, the virtual environment was developed based on the 3D model.

The first step was logging the details of the existing building by means of a pre-existing outdated 3D model of the building, site visits and photographs were taken at the building by the researchers. Afterwards, the building was modelled in 3D using the combined information from different sources featuring the major characteristics of the building. The overall geometry for the 3D model was created using Autodesk Maya. Here, three floors were created separately. The fourth floor was first built, and the second and third floors were built using the fourth floor as a base model because the main geometry of each floor is quite similar. Lastly, an exit floor was developed which connects to the second floor of the building. There were ten exits located on the exit floor. The main entrance of the building is Exit C1 and C2. Figure 4.2 shows an overview of the comprehensive virtual building.

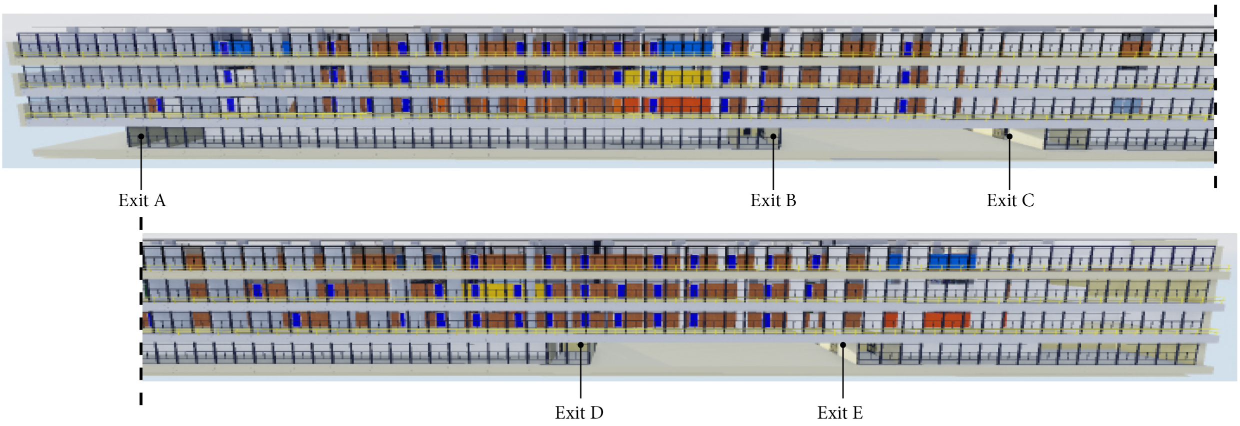
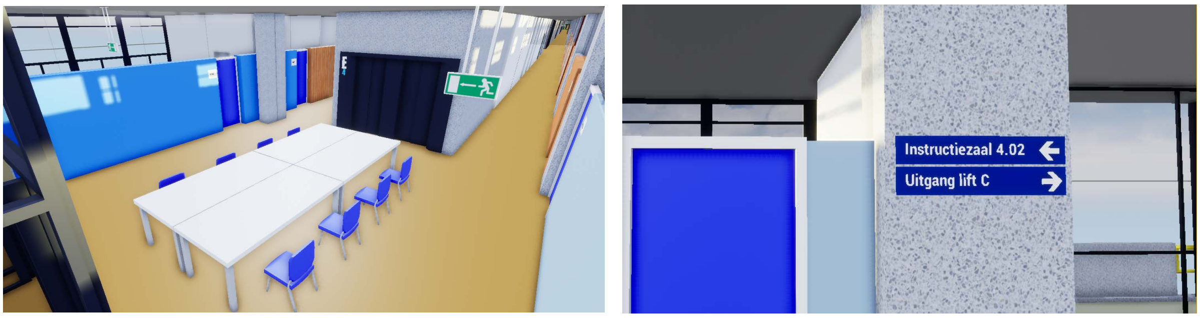


Figure 4. 2: The overview of the virtual building.

Once the overarching geometry (i.e., the internal layout of the building, walls, and staircases) was finished, additional environmental elements were added to the 3D model to improve the accuracy of the building's representation and increase its realism. Four types of features were identified by Weisman (1981) as four classes of environmental variables that influence pedestrian wayfinding behaviour within built environments, namely (a) visual access which provides views that one can see other parts of the building from a given location (e.g., glass windows), (b) architectural differentiation, which is the difference of objects in the building regarding size, colour, location, etc. (e.g., chairs, cabinets, and tables), (c) signs to provide identification or directional information (e.g., evacuation signs, exit signs, and room numbers), and (d) plan configuration of the building (e.g., floor plan) (Hölscher et al., 2005; Raubal & Worboys, 1999). These types of features were modelled in the virtual building in a way that they, as much as possible, resembled the current details in the building and were placed in their original position. Figure 4.3 shows four examples of the above-mentioned features that were added to the virtual environment.

The second step was creating the virtual environment. Using the 3D model of the building, the virtual environment was created in a game development engine, being Unreal Engine 4 (UE4). UE4 is an open and widely used game engine developed by Epic Games (Epic Games, 2019). The UE4 was chosen for developing the complex virtual environment because it provides all the tools required to produce a high-quality virtual environment and its built-in support for VR development makes it easy to work with VR hardware (e.g., HTC Vive and Oculus Rift). Furthermore, UE4 builds game levels that are texture-baked, compiled binaries that the game engine can adequately operate when running the application (Arendash, 2004).

a. glass window b. different chairs and tables



c. evacuation sign d. floor plan

Figure 4. 3: Samples of four types of features added to the virtual environment.

The 3D model was imported from Autodesk Maya to UE4 using the FBX file format, which is directly readable by UE4. This static model in UE4 was accordingly used to render the virtual environment. For the lighting, Sky Light and Directional Lights were added in the virtual environment. Regarding the shading of the objects in the virtual environment, Default Lit, which is the default shading model in UN4, was applied. Figure 4.3 and 4.4 show the visual effect of objects in the virtual building. Rendering effects include, for instance, textures, shadow, lighting, reflection, transparency. Deferred Renderer was selected as the rendering solution for the virtual environment, which is the default setting of UE4. Compared to forward rendering that lighting has to be calculated for each vertex or pixel, deferred renderer is able to only run a single fragment shader for each render target, which optimises complex scenes with a number of lights.

The colours and textures of objects in the virtual environment resemble those of objects in the current faculty building as much as possible. In the virtual building, the corridors featured a mixture of yellow linoleum, coloured plaster walls (e.g., yellow, blue, and orange), wooden panelling, rough concrete pillars and walls, and glass walls (Figure 4.4). Special attention was paid to ensure the correct representation of these four materials, given that they severely influence pedestrian’s experience in the corridors and visibility of the stairs. Figure 4.5 shows one example of the final rendering of the virtual environment and the real-world view.

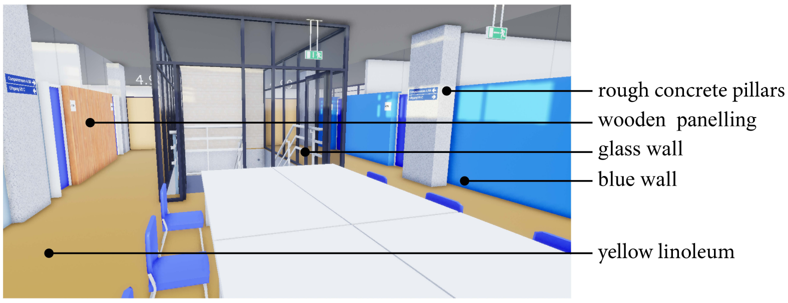


Figure 4. 4: Illustration of one corridor in the virtual building.

a. virtual building view

b. real world view

Figure 4. 5: Pictures of (a) the virtual building and (b) the real world view.

4.3.4 Implementation of interaction elements

In addition to constructing a realistic virtual environment, WayR should support user interaction and provide an immersive environment to perform experiments. Thus, it is necessary to integrate navigation, viewpoint, trigger, soundscape, and data recording. This section details the integration of these elements to the VR research tool using UE4.

1. Navigation and locomotion

In order to enable free navigation in the virtual building, similar to how pedestrians move freely in a real-life building, a combination of the open-world navigation solution and steering locomotion was implemented. This combination of both solutions reduces the chance that users would experience motion sickness.

The open-world solution (Lovreglio et al., 2018) was achieved via implementing Navigation Mesh (NavMesh) in UE4, which defines the area users are able to walk in the building in order to explore the virtual environment (Figure 4.6). The NavMesh was only built within the walkable space in corridors, while the spaces of offices, elevators, or obstacles (e.g., walls, furniture, and objects) were not included. This NavMesh was adopted because of two reasons. Firstly, it protects users from running into walls or other obstacles in the virtual building to initiate unrealistic experiences. Secondly, it is on the authors' assumption that when people are required to evacuate from the building, office's doors and elevators would be inaccessible and unreachable. Thirdly, for the preliminary experiment, participants were not required to enter any of the rooms. Please note, in the current development of WayR, only collision avoidance with objects in the environments was taken into account when designing the physical interaction between users and objects.

Figure 4. 6: One example of implemented Navigation Mesh, indicated by green colour.

In order to be able to move and navigate in the virtual building, the steering locomotion method was adopted (Li et al., 2021; Santos et al., 2009). Steering locomotion provides continuous movement flow in virtual space using a hand controller. This particular locomotion method allows for effective exploration and interaction with the virtual environment. In the prototype tests, we also found the implemented technique of steering locomotion generates less motion sickness compared to the teleportation method. Besides that, the lack of continuous motion during teleportation might weaken presence and alert users that they are in a virtual environment (Boletsis & Cedergren, 2019). The direction of participant's movement in the virtual environment was controlled by their head rotations towards the direction they want to walk. This solution reduces the sickness as the rotations in the virtual and physical environments are the same.

Through the prototype tests, the maximum movement speed in the virtual environment was limited to 140 cm/s to ensure that participants in the virtual building have, as much as possible, the same walking pace as pedestrians have in real life (e.g., Fitzpatrick et al., 2006; Li et al., 2021). Moreover, our pilot tests showed that the speed limit also minimises the motion sickness of participants while moving in the virtual environment.

2. Viewpoint and avatar

In UE4, participants' viewpoints are represented by a camera. Participants viewed the environment from the first-person perspective. Upon starting the simulation, the camera was located at a pre-defined start point. Once tracking is established and the user locates the starting position, the viewpoint is automatically calibrated to the actual height of the participant. As such, the user's vantage point in the virtual environment matches their actual eye height in real life.

Literature has found that pedestrian wayfinding behaviour is affected by two major physical factors: the layout of the setting and the quality of the environmental information (Hölscher et al., 2005). Moreover, studies have shown that decision-making in the virtual environment is more affected by the environment than by social factors (Kinateder & Warren, 2016). Thus, in the current state of development and evaluation of WayR, we were primarily interested in how pedestrians interact with the environment and no other avatars were added to the environment at this stage. It means in the current study, the social interaction between pedestrians was not investigated.

3. Trigger

The virtual environment was designed in a way that participants can perform wayfinding assignments through the building. Thus, at various specific locations in the building, triggers were placed in order to present information messages to participants. When participants enter these specific locations in the building, information messages would be triggered. These messages appear on the VR glasses screen and present a new (wayfinding) assignment to the participant. The virtual environment contained a sequence of different triggers. In case if participants enter one of the triggers' location without finishing the last assignment, the next trigger would not be activated.

4. Soundscape

In order to investigate pedestrian wayfinding behaviour during an evacuation, a scenario of evacuation drill was also stimulated. Thus, a 3D soundscape with realistic alarm sounds was incorporated that is also used during official evacuations at the faculty building of Civil Engineering and Geosciences. The alarm sound contains a female voice that repeates the following statement: “Attention, please leave the building using the emergency exits as indicated. Do not use the elevators.”. Other sounds (e.g., talking sound and environmental noise) were not presented in this study as participants were alone in the environment.

5. Data recording

In order to function as a research tool, WayR needs to be able to record specific data points for later analysis. The position of the participant inside the virtual environment is obtained via the tracking system. All the parameters related to viewpoint's locations, such as positional data (x, y, z), head rotations (yaw, roll, pitch), gaze points, and timestamps are recorded in milliseconds. All information is saved in separate CSV files per participant, which can be easily interpreted using data analytic toolboxes such as Python, R and Matlab. It can also be visualised in the virtual building using the built-in playback system to review what happened at a specific location or timestamp. For instance, Figure 4.7 shows the distribution of one user’s walking trajectories (lines) and gaze points (dots) in the virtual building.

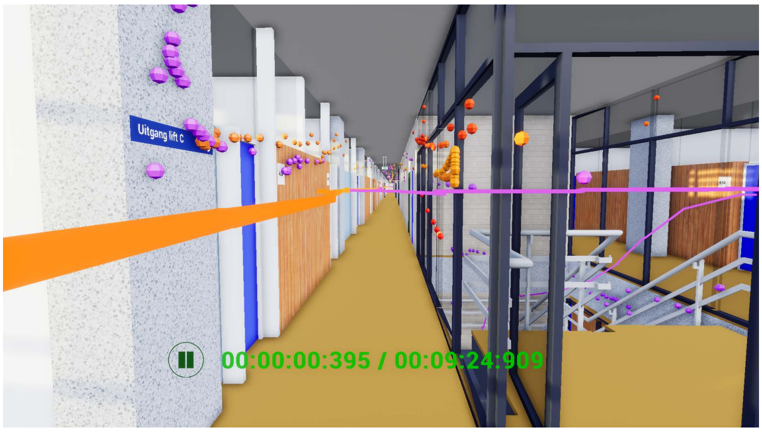


Figure 4. 7: One example of the distribution of walking trajectories and gaze points in the virtual building.

4.4 Evaluation VR experiment

In order to evaluate WayR, a VR experiment was designed and conducted. Section 4.4.1 first details the experimental design. Next, the adopted apparatus for this study is introduced in section 4.4.2. Section 4.4.3 describes the experimental procedure. Accordingly, section 4.4.4 and section 4.4.5 details the data collection by the VR experiment and participant's characteristics.

4.4.1 Experimental design

The experiment aims to evaluate WayR by investigating pedestrian wayfinding behaviour in the virtual building. Four different wayfinding assignments with increasing complexity were deliberately designed, namely (1) a within-floor wayfinding assignment, (2) a between-floor wayfinding assignment (i.e., across the horizontal and vertical level), (3) a more complex between-floor wayfinding assignment, and (4) an evacuation assignment. The first three assignments featured wayfinding assignments under normal conditions and the last assignment was under emergency. The details of the four assignments are as follows. In assignment 1, pedestrian wayfinding behaviour at the horizontal level was investigated. Participants were asked to find their way from room 4.02 to room 4.99 (see Figure 4.1), which ensures they need to cross from one main corridor to the other and walk the length of the building. In assignment 2, pedestrian wayfinding behaviour across horizontal and vertical levels was investigated. Participants were asked to find their way from room 4.99 to room 2.01. This assignment required participants to move between floors and walk the length of the building. In assignment 3, pedestrian wayfinding behaviour on both horizontal and vertical levels was again investigated. Participants were asked to find their way from room 2.01 to room 4.64. The major difference between assignment 2 and 3 is that assignment 2 has a clearer destination to locate than assignment 3. In assignment 4, pedestrian wayfinding behaviour and their exit choice during an evacuation were investigated. Participants were asked to evacuate from 4.64 and find an exit on the first floor (the exit floor underneath the second floor). When participants arrived at an exit on the first floor, the experiment ended.

All assignments have no formal time limit. These assignments are designed in a way that the complexity deliberately increases when the variation of the assignments changes. In accordance with the experiment description, participants consider all the information provided to them in the virtual environment and walk through the building.

4.4.2 Experiment apparatus

Especially in a complex or large-scale virtual environment, immersion is one of the major key factors for being able to intuitively perceive all aspects of the scene (Hilfert & König, 2016). In this experiment, participants were immersed in the virtual environment via a pair of earphones and the HTC Vive system, which consisted of a head-mounted display, one controller and two laser-based base stations. The UE4 and the SteamVR were used to run the virtual environment. All experiments were taken in a 3.4m x 2.5m room with a 2.5m high ceiling, lighted by fluorescent lighting, with no reflective surfaces and no exposure to natural lighting (Figure 4.8).

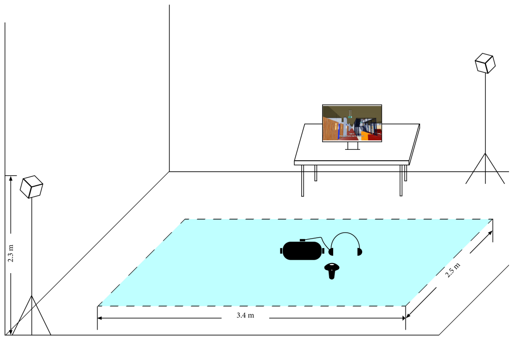


Figure 4. 8: A simple illustration of the room setup.

An HTC Vive head-mounted display (HMD) VR system was used in this study. The HMD display has 360-degree head tracking with a 110-degree field of view. It has two 3.4-inch RGB LCD screens, and each provides a resolution of 1080 x 1200 pixels (2160×1200 combined resolution) for 3D effects. It has a refresh rate of 90 Hz. Head tracking mechanisms translate movements of the participant’s head into virtual camera movements (Hilfert & König, 2016). Participants used one hand controller to move in the environment. Figure 4.9 shows one participant using the HMD display and one controller during the experiment. By simply holding the home pad of the controller, participants can move forward; by releasing the home pad, participants can stop moving. The direction of the movement was controlled by the orientation of the participant’s head.

Figure 4. 9: One participant using the HMD display and hand controller during the VR experiment.

HTC Vive provides a room-scale technology that allows the user to freely walk in real-life space and reflects their movement in the virtual environment. It is achieved by using tracking equipment, namely the base station (also called lighthouse). The base stations track the position and orientation of the headset and the controller and translate this into the virtual environment in real-time. The base stations were replaced opposed to each other in the room with a 3.4m x 2.5m tracking area, which enables participants to move anywhere and re-orient themselves in any position within the range of the base stations. They were mounted on stable tripods at the height of 2.3m from the ground and were connected to each other via the sync cable. Once participants can move freely in the pre-defined area, it is necessary to protect them from running into the walls in the room. The measure here is showing participants the edge of the area when participants attempt to go beyond the tracking region.

In addition to the HTC Vive system, a pair of headphones was used by the participants. The headphone provided audio information to the participants and isolated them from the real-life environmental noise.

4.4.3 Experiment procedure

The procedure of the VR experiment included the following parts, participants: 1) were introduced about the usage of the HMD and procedure of the experiment; 2) were familiarised with the test virtual environment and the HMD device in a simple training scenario; 3) took part in the official experiment; 4) filled in the questionnaire. Underneath, the four parts of the procedure are further explained. The VR experiment was approved by the Human Research Ethics Committee of the Delft University of Technology (Reference ID 944). All participants volunteered to join the experiment and took part in the experiment one by one.

1. Introduction. Before the experiment, we made sure participants have normal sight or use corrective lenses. Once the participant arrived at the experiment room, the procedure of the experiment was introduced to the participant via a written instruction manual in order to ensure all participants had exactly the same information when entering the virtual environment.

2. Familiarisation. Participants were invited to wear the headset and headphone to walk through a test environment, which features a square area with obstacles randomly located in the area. Signs with letters were added on the wall in the test environment. Participants were instructed to walk from A to B to C (Figure 4.10). This training assignment was used to familiarise the participants with the control of the device and discover any tendency of motion sickness in participants. During the assignment, participants needed to perform basic movement operations in the test VR environment and get acquainted with the system's mode of operation. The familiarisation phase lasted approximately 3 minutes. Participants who felt sick during this period were allowed to have a break, and after the break, they could decide whether to quit or continue the VR experiment.

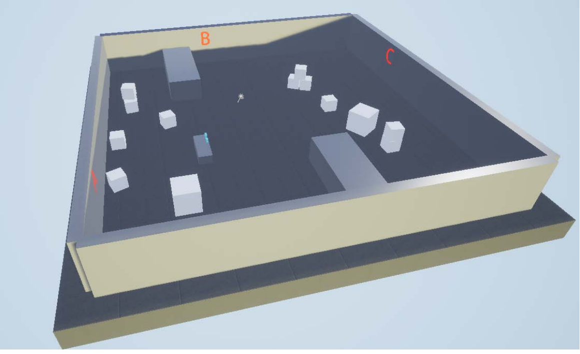


Figure 4. 10: A screenshot of the test environment.

3. Performing the assignments. After the familiarisation phase, participants were teleported to the actual virtual building. As stated in section 4.4.1, the start position is room 4.02 (see Figure 4.1), where participants were instructed to begin the first assignment. When participants reached the destination of an assignment, an informational text appeared which instruct participants to begin the next assignment (see Figure 4.11). At the beginning of the fourth assignment, the evacuation alarm sound was automatically triggered, followed by a voice message instructing all people to evacuate from the building.

Task 2:
Please find your way to room 2.01

Figure 4. 11: A screenshot of participant's view during the experiment, showing the current assignment.

4. Answering the questionnaire. A questionnaire was provided to the participants directly after participants finished their assignments, which they answered digitally using a desktop computer located in the experiment room. Before participants were allowed to leave the experimental room, the researcher ensured that participants felt all right.

4.4.4 Data collection

The experiment collected two types of data, namely behavioural data and questionnaire data. Firstly, participant’s behaviour in the virtual environment was recorded. In particular, participant's positions, head rotations, gaze points, and timestamp were recorded at a frequency of 10 Hz within the UE4. Here, a gaze point is defined as the location where the gaze direction of the head hits the nearest object (geometry) in the virtual environment. Jointly, these data capture a rich set of information related to pedestrian wayfinding behaviour, which can be translated into three types of behavioural information, namely (1) route and exit choices, (2) wayfinding performance (i.e., time, speed, and distance), and (3) observation behaviour (i.e., head rotations, gaze points, and hesitations).

Secondly, a questionnaire was designed to obtain the personal features and experiences of each participant regarding the virtual experiment. The questionnaire contained five sections: (1) participant's information, which included their socio-demographic information and their experience with VR and computer gaming, (2) the face validity questionnaire, which assessed the realism of the virtual environment, (3) the Simulator Sickness Questionnaire (Kennedy et al., 1993), which determined if participant's experience sickness throughout the experiment, (4) the System Usability Scale (Brooke, 1996), which assessed the usability of the applied VR system as a pedestrian simulator, (5) the Presence Questionnaire (Witmer et al., 2005), which measured participant's experience of presence in the virtual environment. Here, the authors have explicitly chosen to use a very comprehensive questionnaire to ensure that the authors are able to study the face validity of the virtual environment and participant’s VR experience in great detail.

4.4.5 Participant’s characteristics

In total, 38 participants took part in the VR experiment. Of those, two participants asked to take a break during the third assignment and did not finish the whole experiment. Thus, the results discussed underneath are based on 36 participants, which included nineteen females and seventeen males. The age of these participants ranged from 17 to 41 years (*M* = 28.66, *SD* = 6.00). Table 4.1 presents the descriptive statistics of the participants, which shows that the participants were generally familiar with computer gaming and not very familiar with VR. Moreover, most of the participants had a relatively high education level.

Table 4. 1: Demographic information of participants.

Descriptive information	Category	Number (percentage)
Gender	Male	17 (47.22%)
	Female	19 (52.78%)
Highest education level	High school or equivalent	5 (13.88%)
	Bachelor’s degree or equivalent	6 (16.67%)
	Master’s degree or equivalent	19 (52.78%)
	Doctoral degree or equivalent	6 (16.67%)
Previous experience with VR	Never	11 (30.55%)
	Seldom	18 (50.00%)
	Sometimes	6 (16.67%)
	Often	1 (2.78%)
	Very often	0 (0.00%)
Familiarity with any computer gaming	Not at all familiar	6 (16.67%)
	A-little familiar	6 (16.67%)
	Moderately familiar	8 (22.22%)
	Quite-a-bit familiar	7 (19.44%)
	Very familiar	9 (25.00%)

4.5 Results and discussion

Using WayR, we conducted a series of wayfinding experiments, including normal and evacuation conditions. The main objective of the wayfinding experiment is to evaluate the validity and usability of WayR from objective measures and subjective measures. Section 4.5.1 first evaluates the ability of WayR to collect pedestrian wayfinding behavioural data, namely pedestrian route choice behaviour, exit choice behaviour, wayfinding performance, and observation behaviour. Based on the behavioural results and their comparison with the literature, the content validity and construct validity are assessed. Next, section 4.5.2 examines the realism and usability of WayR based on the results of the questionnaire and discusses the face validity and ecological validity of WayR.

4.5.1 Objective measures

Literature has identified three levels of metrics to evaluate pedestrian wayfinding behaviour in buildings, which includes decision making (e.g., route and exit choice), wayfinding task performance (e.g., time, speed, and distance), and observation behaviour (e.g., head rotation, gaze point, and hesitation) (Ruddle & Lessels, 2006). To evaluate the difference in the above-mentioned metrics and their respective differences among the four assignments, different analyses were performed. For numerical variable data, the Shapiro–Wilk test was first conducted to examine whether the data is normally distributed. If the normality requirements were not satisfied for parametric test, the Friedman test and post hoc Wilcoxon signed-rank tests were conducted for each metric. For categorical variable data, the Fisher-exact test was conducted. For pair comparisons, a Bonferroni correction was applied, which resulted in a significance level at $p = 0.0083$. This section presents an analysis of objective behavioural data collected during the VR experiment using the abovementioned metrics. First, section 4.5.1.1 details the results pertaining to route and exit choice behaviour. Afterwards, section 4.5.1.2 presents the wayfinding task performance results, and section 4.5.1.3 details the result of observation behaviour. Subsequently, the content validity and construct validity of WayR are discussed in section 4.5.1.4.

4.5.1.1 Route and evacuation exit choice behaviour

To analyse participants' route and evacuation exit choice behaviour, the complete set of walking trajectories was split into four separate sequences featuring each assignment. Figures 4.12-4.15 show the walking trajectories of all participants during four assignments. Pedestrian route choice can be seen as a series of decisions (Hoogendoorn & Bovy, 2004). The walking trajectories enabled an analysis of participants' route and exit choice behaviour in detail, including wayfinding strategy, decision point, path, and evacuation exit choice. Interestingly, both along the horizontal level as well as the vertical levels, high degrees of route variability are encountered. The following section first analyses the overall wayfinding strategy during four assignments. Accordingly, decision points, path and the evacuation exit choice behaviour is analysed more in-depth.

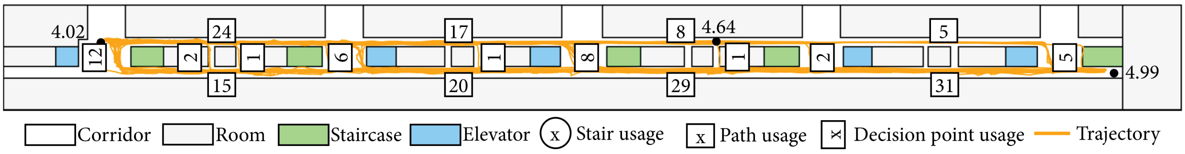


Figure 4. 12: Participants' trajectories during assignment 1: room 4.02 → room 4.09.

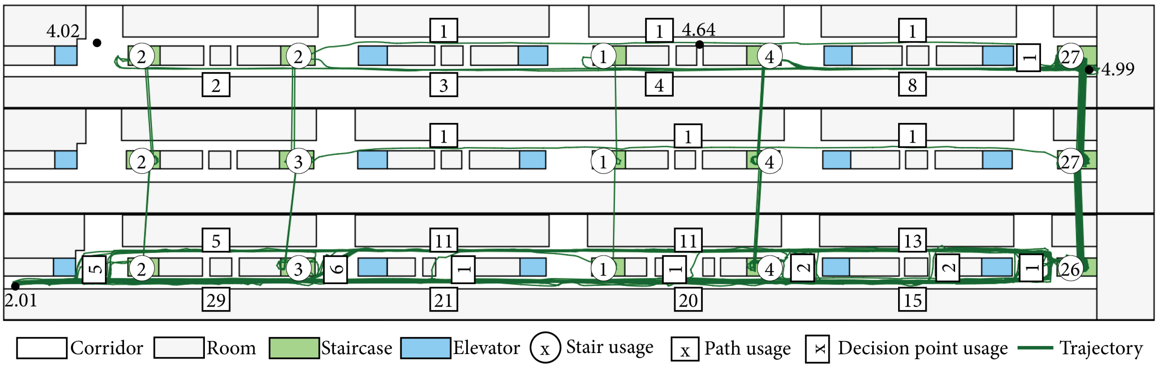


Figure 4. 13: Participants' trajectories during assignment 2: room 4.99 → room2.01.

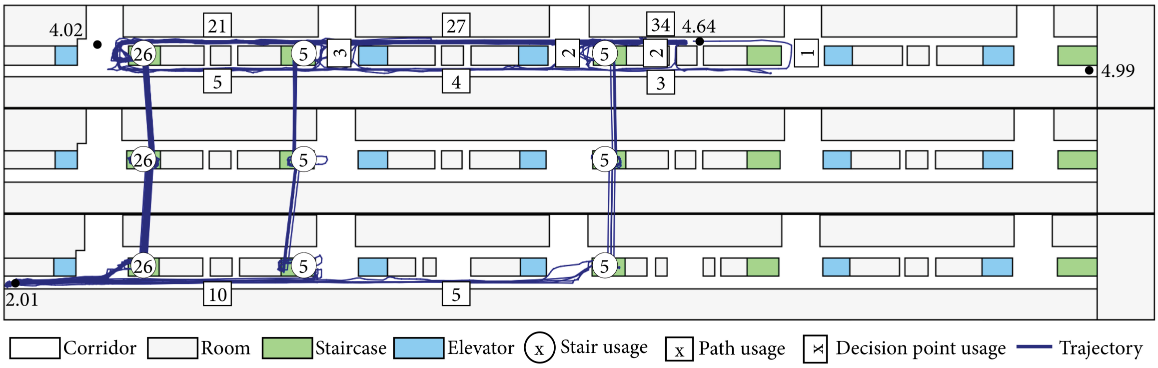


Figure 4. 14: Participants' trajectories during assignment 3: room 2.01 → room 4.64.

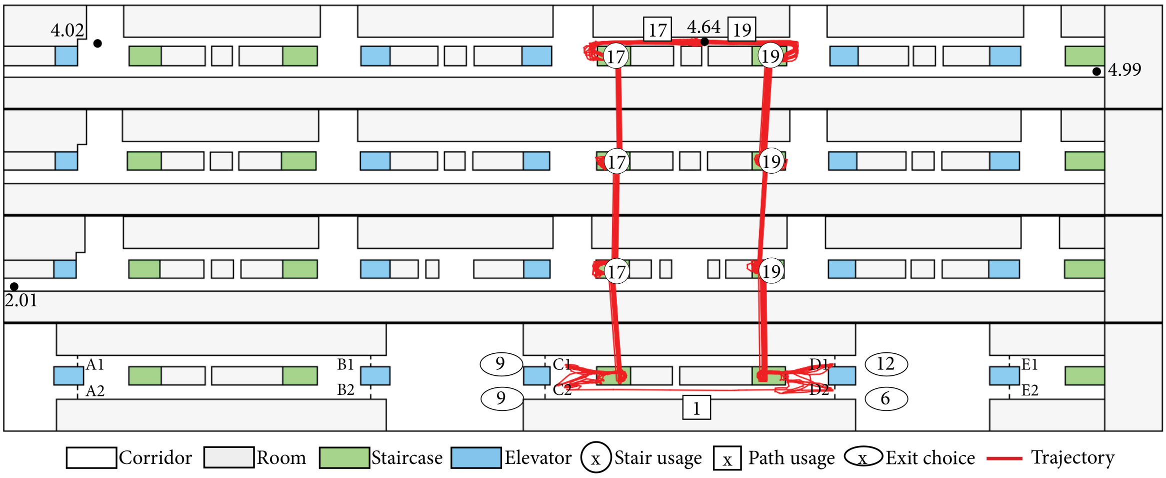


Figure 4. 15: Participants' trajectories during assignment 4: room 4.64 → an exit.

1. Wayfinding strategy

Literature identifies three distinct wayfinding strategies for pedestrians to find their way in multi-story buildings, namely the floor strategy (i.e., first find one' way to the floor of the target room), the direction strategy (first move to the horizontal position of the target room) and the central point strategy (find the way by using the well-known parts of the building) (Hölscher et al., 2007). Figure 4.16 shows the movement trajectory of one participant during all assignments. When applying the classification of wayfinding strategies identified in Hölscher et al. (2007), this participant employed the direction strategy during assignment 1 (orange trajectory), the floor strategy during assignment 2 (green trajectory), the direction strategy during assignment 3 (blue trajectory), and the floor strategy during assignment 4 (red trajectory).

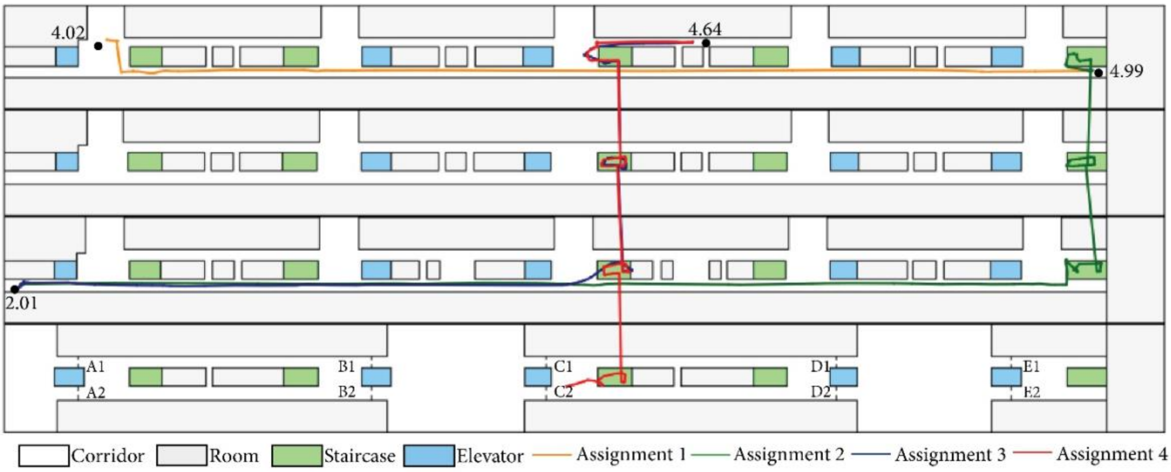


Figure 4. 16: Trajectories of one participant during all four assignments.

Table 4.2 shows the number of employed wayfinding strategies per assignment of all assignments. The results show that the dominant wayfinding strategy during assignment 1 was the central point strategy. That is, when assignment 1 started near room 4.02, participants chose to first move straight to the first interaction into the even-numbered corridor, then used the wider intersections to cross towards the other corridor, on which side the uneven-numbered room 4.99 resides, and then continued walking towards the destination. During assignments 2 and 3, participants predominantly applied the floor strategy. That is, participants first went down or up to the floor using the first staircase they encountered and subsequently searched for the target room on the floor. During the last assignment, all participants employed the floor strategy (i.e., they first chose to go to the exit floor, then find one exit).

Table 4. 2: Employed wayfinding strategy of participants.

Assignment	The floor strategy	The direction strategy	The central point strategy
Assignment 1	0	12	24
Assignment 2	27	9	0
Assignment 3	26	10	0
Assignment 4	36	0	0

In order to determine whether the identified difference in the employed wayfinding strategies is significant among the four assignments, Fisher-exact tests were conducted. The results of pairwise comparisons showed significant differences exist between assignment 1 and 2 ($p < 0.001$), 1 and 3 ($p < 0.001$), 1 and 4 ($p < 0.001$), 2 and 4 ($p = 0.002$), 3 and 4 ($p = 0.002$).

In particular, compared to the within-floor assignment (assignment 1), participants employed significantly different wayfinding strategies for the between-floor assignments (assignment 2, 3, 4). In a multi-story building with between-floor assignments, the floor strategy was predominantly employed. In the current setting, providing participants with the destinations' information as room numbers contain floor number might have provoked them predominately choose the floor strategy. The findings indicate that the wayfinding strategy is strongly influenced by instruction provided with the wayfinding assignment, as suggested in the literature (Hölscher et al., 2006). The results also indicate when evacuation happens, the combination of situation awareness and destination instruction can affect the wayfinding strategy, namely all participants adopted the floor strategy when evacuating in a multi-story building.

2. Decision point and path

Literature shows that the arrangement of decision points and their linking paths contribute prominently to the complexity of buildings regarding wayfinding (Hölscher et al., 2005). Here, decision points are defined as locations where pedestrians have over one choice of direction to continue the route (Raubal & Egenhofer, 1998) and a path is defined as the section connecting two decision points.

First, the number of used decision points was analysed. Here, a 'used' decision point is a decision point where a participant turns from one side to another side of the building. In order to evaluate the difference in the number of used decision points among the four assignments, we subtracted the number of minimum required direction changes along the shortest route for that assignment from the number of used decision points. Shapiro–Wilk tests showed the number of decision points during each assignment is not normally distributed (all $p < 0.001$). The Friedman test, moreover, showed statistically significant differences in decision point ratio among four wayfinding assignments: $X^2(3) = 38.17$, $p < 0.001$. Wilcoxon signed-rank tests found significant differences in decision points between assignment 1 and 2 ($Z = 0.00$, $p < 0.001$), 2 and 3($Z = 6.00$, $p = 0.005$), 2 and 4 ($Z = 0.00$, $p < 0.001$), 3 and 4 ($Z = 0.00$, $p = 0.008$). These results indicate that the number of used decision points is highest during assignment 2 ($M_2 = 0.53$) and significantly lower during assignment 3 ($M_3 = 0.22$), assignment 1 ($M_1 = 0.06$) and assignment 4 ($M_4 = 0$). Meanwhile, the number of decision points during assignment 3 ($M_3 = 0.22$) is significantly higher than assignment 4.

Second, participant's preference for wide and narrow path during each wayfinding assignment is studied. The wide path is defined as any path along the two main corridors; the narrow path is the path vertical to the main corridor. Shapiro–Wilk tests showed the number of the used path during each assignment is not normally distributed (all $p < 0.001$). Wilcoxon signed-rank test showed there were significant differences in wide and narrow path usage during all assignments (all $p < 0.001$). The results indicate that participants always preferred to use the wide path over the narrow path.

Knowing which directions to turn to at decision points is critical for successful wayfinding (Richter et al., 2008). Our findings indicate that participants indeed tried to reduce the number of turns to change the direction of walking while finding their way. The number of decision points was highest during assignment 2 ($M_2 = 0.53$) indicate that after the first time of level change, participants were disoriented and not entirely sure about which direction to go. The results also indicate after assignment 2, even when the assignment and complexity of the environment increased, participants were less likely to use decision points to change the direction of walking ($M_3 = 0.22$, $M_4 = 0$). From this finding, learning effects can be observed as participants learned the general structure of the building (i.e., corridors are parallel to each other and rooms are located on even/uneven sides) and they were more aware of the location of the destinations. Therefore, participants stayed more at the side of the corridor where the destinations were located, which required less change of sides and less usage of decision points. Regarding the usage of the wide and narrow path, our findings are consistent with literature suggests that people prefer to use wider paths than narrow paths and paths with longer lines of sight in buildings when several alternatives were available (Frankenstein et al., 2012; Vilar et al., 2013b, 2014b; Wiener et al., 2012). This finding also indicates that participants can realistically perceive the difference in environmental features in the virtual building.

3. Exit choice

As Figure 4.15 shows, during the evacuation assignment, participants chose to go down using the first staircase they met when going right or left in front of room 4.64. Even though 10 evacuation exits were available, only the exits C1, C2, D1, D2 were chosen, which shows the usage of the building's exits is asymmetrical. Interestingly, this behaviour is in line with other studies that look at exit usage (Duives & Mahmassani, 2012; Feng et al., 2021b; Liao, Zheng, et al., 2014; Zhu & Shi, 2016), although the layout of their experimental space was relatively simple. Amongst the four chosen exits, 9 participants chose C1, 9 participants chose C2, 12 participants chose D1, and 6 participants chose D2. These exits are the relatively closest four exits for all participants. This result is consistent with the studies which found that pedestrians were overall more likely to choose the nearest exits and shortest routes (Fang et al., 2020, 2010; Feng et al., 2021b; Guo et al., 2012; Kobes et al., 2010b; Li et al., 2019; Liao et al., 2017).

4.5.1.2 Wayfinding performance

After considering route and exit choice behaviour, we investigate pedestrian wayfinding performance. Pedestrian wayfinding performance explains how well participants navigate through the building (Kuliga et al., 2019). Wayfinding performance can be accessed by three metrics, namely travel time, travel distance and travel speed.

The wayfinding travel time is defined as the time period between the moment in time that a participant starts an assignment and the moment in time the participant arrives at the destination of the assignment. It is one of the most important factors that measure wayfinding performance (Suzer et al., 2018). On average, participants spent 568.90 seconds (SD = 62.16 s) to finish all four wayfinding assignments. Figure 4.17 shows the distribution of the travel time of participants during each assignment. On average, participants spent the most time during assignment two (M_2 = 201.30 s, SD_2 = 18.30 s), followed by assignment one (M_1 = 160.79 s, SD_1 = 20.19 s) and assignment three (M_3 = 140.14 s, SD_3 = 24.02 s). The least time was spent during assignment four (M_4 = 66.67 s, SD_4 = 11.37 s). This is in line with our expectations, as the minimum distance required to travel for each assignment also decreases in the same order. Besides that, we see that travel time is clustered around the mean with a light tail. These two findings suggest that the variation in the travel time was limited.

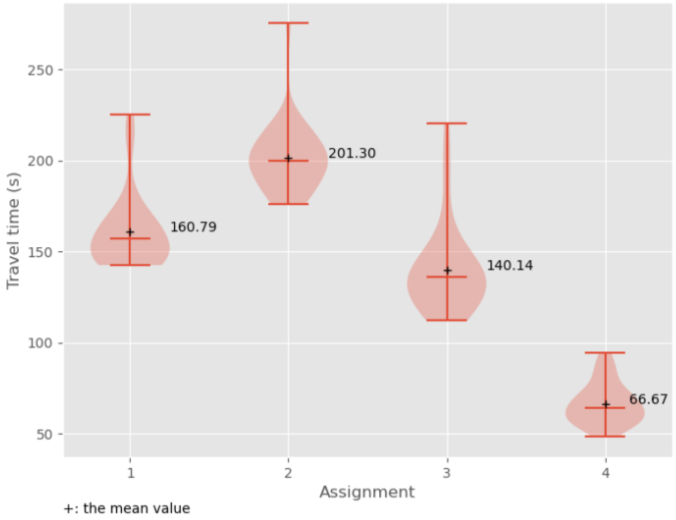


Figure 4. 17: Violin plot of the time spent by the participants during four assignments.

Travel distance is defined as the actual distance participants walked from the start location of the assignment to the end location, which includes the distance travelled in the corridors and on the staircases. In order to compare travel distance among four assignments, superfluous travel distance was calculated by dividing the actual travel distance by the shortest travel distance of the optimal path (Hölscher et al., 2007). It indicates the relative amount of superfluous distance participants travelled per assignment (Hölscher et al., 2005, 2007; Kuliga et al., 2019). The distribution of superfluous travel distance during each assignment is presented in Figure 4.18. Shapiro–Wilk tests showed the superfluous travel distance during each assignment is not normally distributed (all $p < 0.001$). The Friedman test showed statistically significant differences in superfluous travel distance among four assignments: $X^2(3) = 90.53$, $p < 0.001$. Wilcoxon signed-rank tests found significant differences in superfluous travel distance among all pair-comparison (all $p < 0.001$), except for assignment 2 and 3 ($Z = 303.00$, $p = 0.637$). The results indicate that the superfluous travel distance during assignment 4 is highest ($M_4 = 1.60$, $SD_4 = 0.19$) and significantly exceeded assignment 3 ($M_3 = 1.07$, $SD_3 = 0.06$), assignment 2 ($M_2 = 1.06$, $SD_2 = 0.02$), and assignment 1 ($M_1 = 1.01$, $SD_1 = 0.03$).

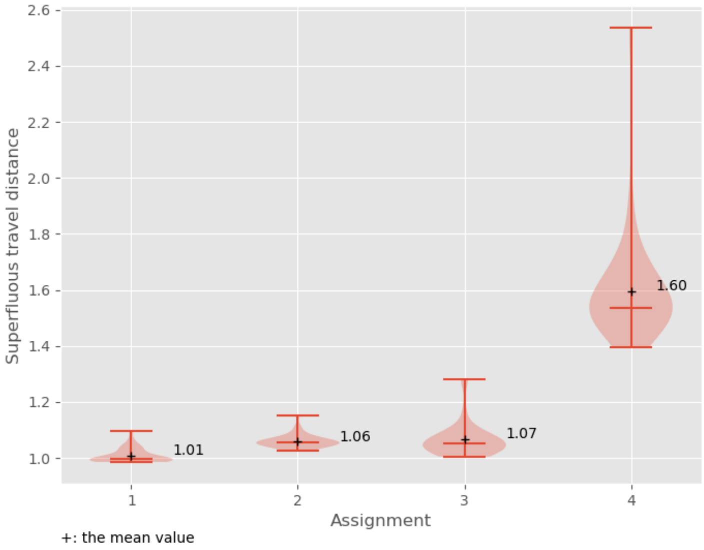


Figure 4. 18: Violin plot of the superfluous travel distance of all participants during four assignments.

The average travel speed per participant was calculated by dividing the total travel distance by the total travel time. The distributions and mean values of average travel speed during each assignment are displayed in Figure 4.19. Results of Shapiro–Wilk test rejected the hypothesis that the average travel speed is normally distributed during assignments 1 and 3 ($p < 0.05$). The Friedman test indicated statistically significant differences in the average travel speed among four assignments: $X^2(3) = 18.43$, $p < 0.001$. Wilcoxon signed-rank tests only found significant differences between assignment 2 and 3 ($Z = 131.00$, $p = 0.002$), and assignment 3 and 4 ($Z = 119.00$, $p = 0.001$). Although the mean value of travel speed is similar during assignment 2 ($M_2 = 1.19$ m/s, $SD_2 = 0.09$) and assignment 3 ($M_3 = 1.18$ m/s, $SD_3 = 0.13$), we expect the difference of standard deviation cause the significant difference in travel speed between two assignments. Participants had significantly the lowest average travel speed during assignment 4 ($M_4 = 1.12$ m/s, $SD_4 = 0.15$). Moreover, the lower tail of the average travel speed becomes heavier and heavier in each subsequent assignment, while the upper tail increases only slightly. This suggests that more and more participants adopt a lower average travel speed and the variation in travel speeds increases.

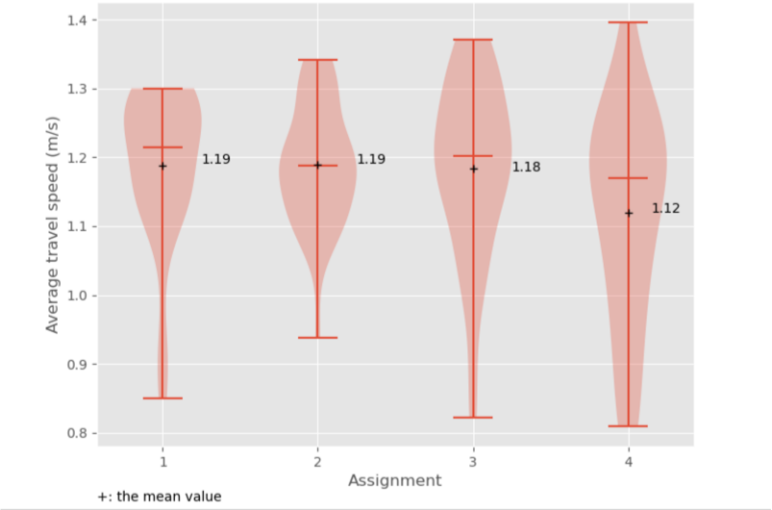


Figure 4. 19: Violin plot of the average travel speed of all participants during four assignments.

We would expect that the more difficult a wayfinding assignment is, the higher the superfluous travel distance and the lower the average travel speed. The results pertaining to the travel time, the travel distance and the travel speed indicate a clear variation in assignment difficulty, as intended by the experimental design. As expected, the results suggest that assignment 1 was the easiest assignment and the evacuation assignment (assignment 4) was the most difficult. That is, during the evacuation assignment, participants significantly travelled the slowest and had the longest superfluous distance than other assignments. Assignment 4 was the most difficult assignment because the destination was unclear, participants needed to perform wayfinding during an evacuation and navigate longer on the staircases. This finding is also aligned with previous studies that suggest pedestrians have poorer way-finding performance during emergencies than normal conditions (Cao et al., 2019; Lin et al., 2019; Meng & Zhang, 2014) and level change is a key source of disorientation in a building, especially when many turns are required during navigation (Hölscher et al., 2006; Kuliga et al., 2019). Moreover, the medium complexity of assignments 2 and 3 was confirmed by the fact that they scored between assignments 1 and 4 regarding the travel distance and the travel speed. This finding confirms that the difficulty of find one's way increased when participants needed to across floors and the assignment became more complex.

4.5.1.3 Observation behaviour

While performing the assignment, participants were required to keep searching for information along the route to find the destination. In order to better understand participant's observation behaviour during the wayfinding assignments, participants' hesitation, head rotation and gaze point are analysed per assignment.

1. Head rotation change

For the head rotation analysis, we only focus on head rotation along the Yaw axis (i.e., rotate the head left/right) to limit noise caused by participants who shake their heads while walking

(Zhang et al., 2021). Participants' average head rotation change along Yaw axis $\bar{Y}$ during each assignment is calculated by Formula 4.1 and 4.2:

$$Y(t) = \min(360 - |Y_{t+dt} - Y_t|, |Y_{t+dt} - Y_t|) \tag{4.1}$$

$$\bar{Y} = \frac{\sum_1^T Y}{T} \tag{4.2}$$

where $Y(t)$ is the instantaneous rotation change, Y_t is the current Yaw coordinate of the participant at t timestep and dt is the timestep interval (0.1s), T is the travel time of the assignment. Figure 4.20 shows the distribution of the average head rotation change of participants. The Friedman test showed statistically significant differences in head rotation change among four assignments: $X^2(3) = 97.73$, $p < 0.001$. Wilcoxon signed-rank tests found significant differences in head rotation change among all pair-comparison (all $p < 0.001$). The results show that participants had significantly highest average head rotation changes during assignment 4 ($M_4 = 27.47$ °/s, $SD_4 = 7.06$°/s) and significantly lower during assignment 3 ($M_3 = 13.61$ °/s, $SD_3 = 3.41$°/s), assignment 2 ($M_2 = 10.7$ °/s, $SD_2 = 2.52$°/s) and assignment 1 ($M_1 = 7.38$ °/s, $SD_1 = 4.00$°/s).

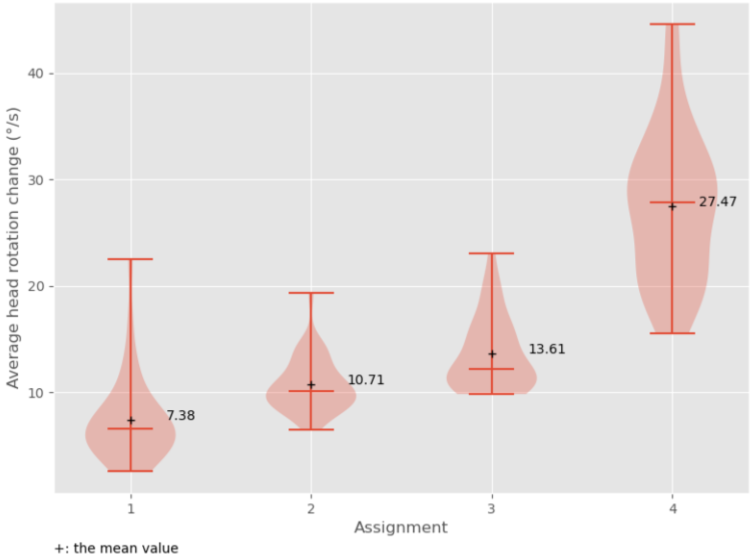


Figure 4. 20: Violin plot of average head rotation change (Yaw) of all participants during four assignments.

In order to better understand if the difference in head rotation change was caused by searching behaviour in the environment or the head-turning movements on the staircases, only the average head rotation change along the corridors, the first staircase landing and the last staircase landing was analysed. Figure 4.21 shows the distribution of the average head rotation change (except staircases part) of participants. The Friedman test showed significant differences in average head rotation change among four assignments: $X^2(3) = 77.03$, $p < 0.001$. Wilcoxon signed-rank tests revealed significant differences among all pair-comparison (all $p < 0.001$), except for assignment 1 and 2 ($Z = 207.00$, $p = 0.048$). Combine with previous results, this result further indicates that the significant difference in head rotation change between assignments 1 and 2 is caused by movements along the staircases, while the differences in head rotation change among other pair-comparison were caused by observing behaviour. Similar to previous results, participants still had significantly highest average head rotation changes during assignment 4 (M_4 = 20.71 °/s, SD_4 = 7.23°/s) than assignment 3 (M_3 = 9.82 °/s, SD_3 = 2.97°/s), assignment 2 (M_2 = 8.51 °/s, SD_2 = 3.44°/s) and assignment 1 (M_1 = 7.38 °/s, SD_1 = 4.00°/s).

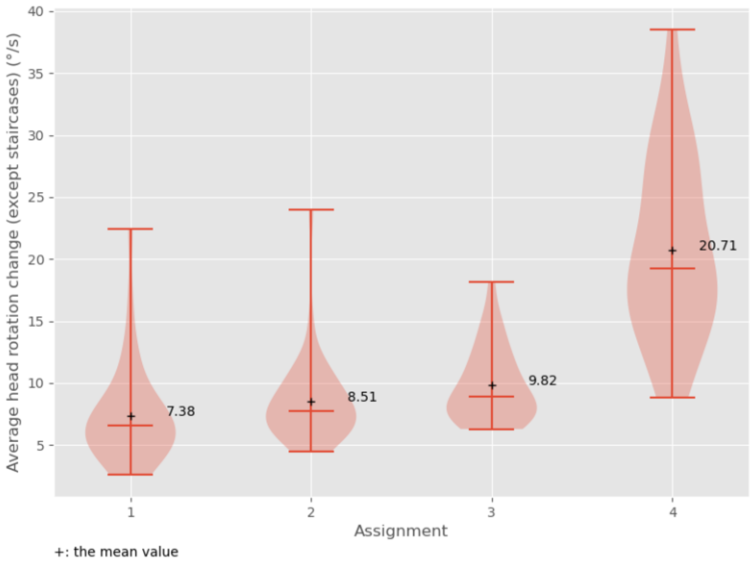


Figure 4. 21: Violin plot of average head rotation change (except staircases) of all participants during four assignments.

The amount of average head rotation change in the current study is similar to Suma et al. (2010) that investigated pedestrian head rotation in a real-world maze but slightly higher than Suma et al. (2010) and Zhang et al. (2021) that studied pedestrian head rotation in a virtual maze and a virtual shopping mall. Meanwhile, the study of Suma et al. (2010) also showed that participants in the real-world maze turned their heads significantly more to observe. This result shows that participants in the current experiment experienced a more realistic and immersive environment, which make it more natural and intuitive to look around.

The results suggest that participants had the highest head rotation change during the evacuation assignment to react and find an exit, similar findings were also observed in (Zhang et al., 2021). Overall, participants had significantly higher rotation in between-floor assignments (2 - 4) than within-floor assignment (1). However, no significant difference in head rotation change was found between assignment 1 and 2 when participants' head rotation on staircases was excluded. The results indicate that the significant difference in head rotation change between assignment 1 and 2 is caused by movements along the staircases. Besides that, we also found participants had significantly higher head rotation change in the more complex between-floor assignment (i.e., assignment 3) than the simple between-floor assignment (i.e., assignment 2). The increase in the average head rotation change can be explained in two ways. Firstly, assignment 2 requires participants to use staircases for the first time, participants needed to adjust their direction of walking in the virtual building by physical body rotation in the real world. In order to turn along the staircases, participants need to simultaneously turn in the real world, which increases the chance of disorientation (Hölscher et al., 2007) and the average head rotation between assignment 1 and 2. Second, when the complexity of the assignment increases, participants need to search for more information to find the destination. While the first reason is the cause of the difference in head rotation change between assignment 1 and 2, the second reason explains the difference in head rotation change amongst other assignments.

2. Hesitation and gaze point

In order to better understand where people search for information and what objects in the building catch their attention, participant's hesitation and gaze point during wayfinding are analysed.

A hesitation point is a location where people stop or pause for a significant amount of time (Conroy, 2001; Ewart & Johnson, 2021). Based on the study of (Suzer et al., 2018), in this study, a hesitation is defined as a location where participants stopped for at least three seconds[1], which indicates where participants paused during wayfinding. To avoid the noise caused by participants' head movement on the staircases, only the hesitation on the horizontal plane was analysed. Figure 22 shows the spatial distribution of hesitation points in the virtual building during all four assignments, which illustrates the hesitation points were mainly distributed near starting position, destinations, decision points and staircase landings.

In order to compare the hesitation behaviour amongst four assignments, hesitation frequency is calculated and compared. Literature suggests that hesitations are made at locations that offer high levels of information (Conroy, 2001; Orellana & Al Sayed, 2013), thus the virtual building was divided into multiple segments. One segment is defined as a rectangle area connected by every four decision points near the floor plan (see Figure 4.22). The hesitation frequency per assignment is calculated by dividing the total number of hesitation points by the total number of segments along the shortest route for that assignment. The Friedman test showed significant differences in hesitation frequency among four wayfinding assignments: $X^2(3) = 18.16$, $p < 0.001$. Wilcoxon signed-rank tests found significant differences between assignment 1 and 2 ($Z = 134.50$, $p < 0.001$), assignment 2 and 4 ($Z = 62.00$, $p < 0.001$), assignment 3 and 4 ($Z = 109.00$, $p < 0.001$). The results show that participants had the highest hesitation frequency during assignment 4 ($M_4 = 27.47$, $SD_4 = 24.12$) than assignment 3 ($M_3 = 14.09$, $SD_3 = 76.45$) and assignment 2 ($M_2 = 9.60$, $SD_2 = 42.94$). Moreover, participants had significantly higher hesitation frequency during assignment 1 ($M_1 = 17.71$, $SD_1 = 63.48$) than assignment 2.

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[1] Because participants might slightly rotate their body when they stop moving, for the sake of calculation, we calculate a hesitation point as the location where participants moved less than 30cm within 3s.

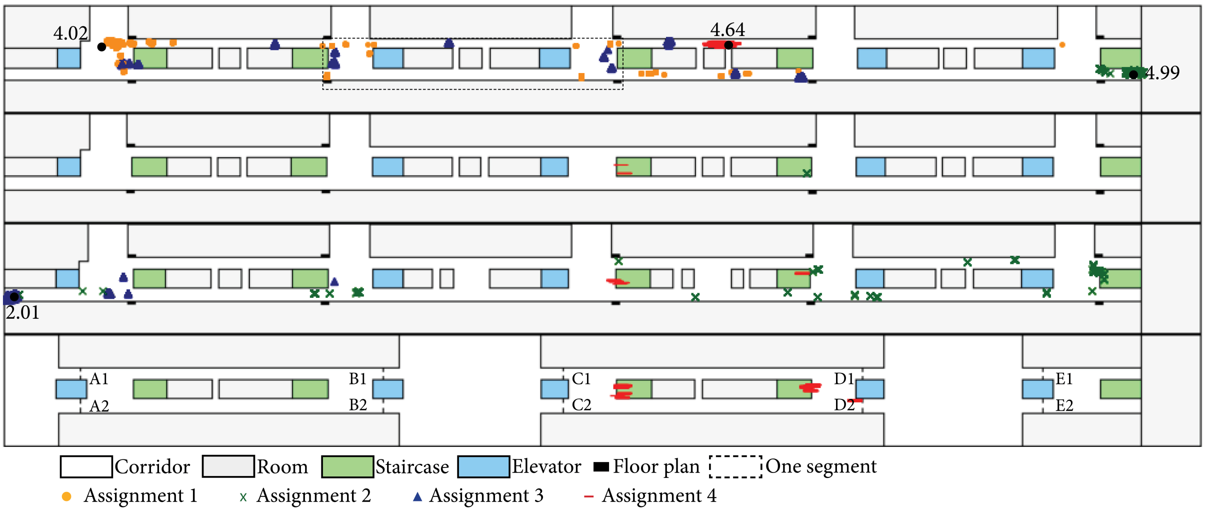


Figure 4. 22: Spatial distribution of participant's hesitation points in the virtual building during all four assignments.

In our study, the hesitation points were mainly located near starting position, destinations, decision points and staircase landings in the building. These locations are areas with extra information provided that could assist in wayfinding (e.g., decision points with floor plan provided) and areas provided the widest view (i.e., near staircases). Moreover, participants made hesitations at the staircase landings where they sought information for the next move. These findings are consistent with previous studies that have shown that hesitations are made at locations that offer high levels of information, afford long lines of sight and large isovist areas (Conroy, 2001; Ewart & Johnson, 2021; Orellana & Al Sayed, 2013). Moreover, hesitations can happen when uncertainty and confusion appear. In our study, participants paused at areas where they needed to make decisions of which direction to move but no clear information is provided (i.e., decision points without floor plan provided). Interestingly, it is noted that participants had the highest hesitation frequency during the final evacuation assignment, which shows that participants had more uncertainty about the situation and the need for more information. This finding confirms the results of recent studies that found hesitation points were located around areas of confusion (Ewart & Johnson, 2021; Zhang et al., 2021). Additionally, participants paused near the assignment's destinations to ensure if they have arrived at the right locations (e.g., room 4.99 and room 2.01). Furthermore, the significant decrease of hesitation frequency between assignment 1 and 2 and the significant increase of hesitation frequency between assignment 2, 3 and 4 shows that when participants are more familiar with the environment, the need of pausing declines; but emergencies can trigger more pause and searching behaviours of participants.

The point of interest in the virtual environment is determined using a gaze point analysis. Here, the density of the dots indicates the number of times the gaze direction collided with an object at this location and, as such, the time duration of one's gaze on a specific AOI (area of interest). The higher the gaze point density is, the longer participants looked towards that area. More sparse distribution of the dots indicates that fewer gaze points were created, which means that participants paid less attention to that area. Figure 4.23 and 4.24 show the scatter of participants' gaze points during assignment 2 and evacuation assignment. Figure B.1 and B.2 in Appendix B show the spatial distribution of participants' gaze points during 1 and 3. The gaze point analysis shows that during the first three assignments, the main visual attractions in the building are room numbers, floor plans, fire doors, starting position and destinations, which are indicated by the dots along with the room, dots near the floor plans, vertical lines across the main corridors, and dots near the starting position and destinations. Literature suggests that environmental elements that provide as sources of information, such as signs, route instructions, maps, architectural features most frequently attract people's attention and contribute to wayfinding (Büchner et al., 2007; Dogu & Erkip, 2000; Hessam & Debajyoti, 2018; Hölscher et al., 2013; Montello & Sas, 2006; Pati et al., 2015; Schrom-Feiertag et al., 2017). Our findings are in line with these results. Besides that, we found participants paid more attention to the exit signs during the last evacuation assignment, which is indicated by the red dots near the staircases. This finding is in agreement with previous studies that show exit sign is the most important information indicator during wayfinding in case of evacuations (Bode et al., 2014; Duarte et al., 2014; Kobes et al., 2010b; Olander et al., 2017; Tang et al., 2009). Moreover, the spatial distribution of gaze points also reflects in the hesitation pattern of participants. As both the gaze points and hesitation points were mainly distributed near starting position, destinations and floor plans. The behaviour of observing room numbers in hesitation analysis was not as obvious as in gaze point analysis is because participants can pay attention to room numbers without necessarily stopping moving.

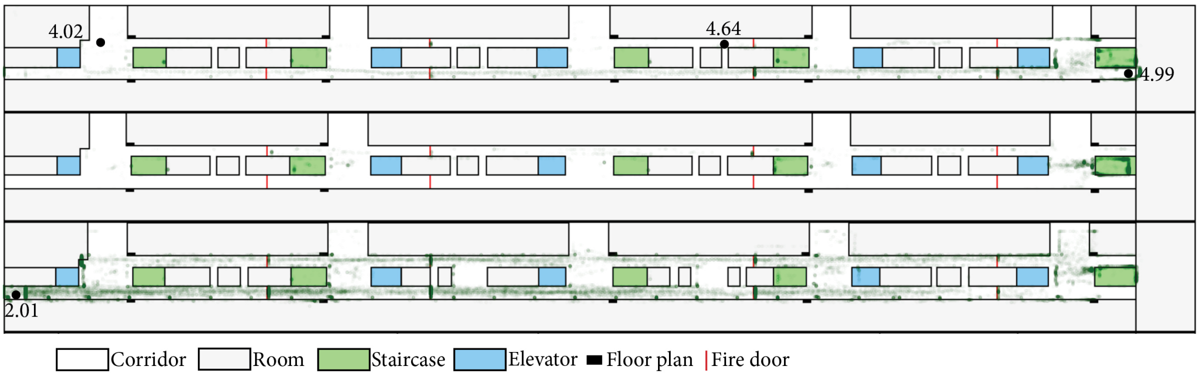


Figure 4. 23: Spatial distribution of participants' gaze points during assignment 2.

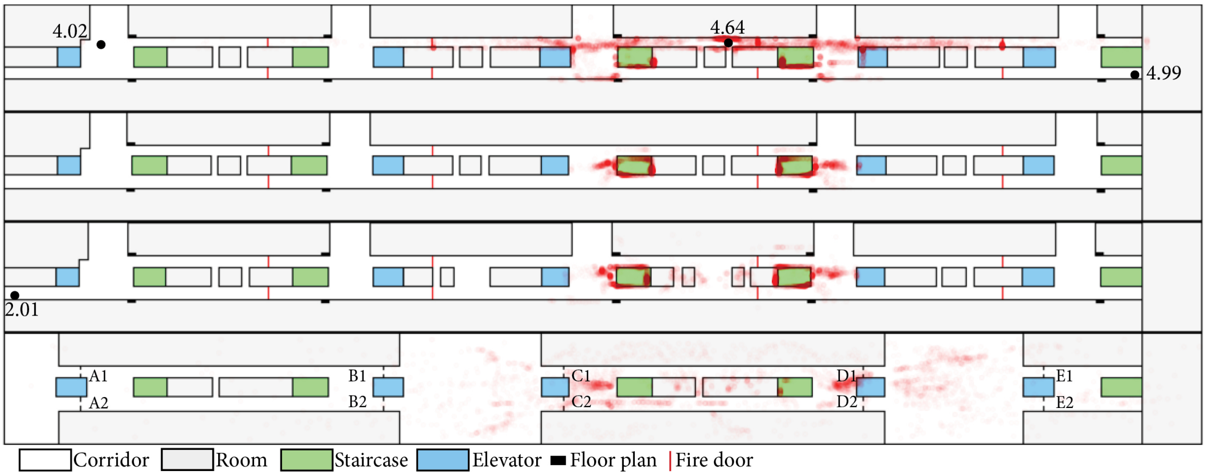


Figure 4. 24: Spatial distribution of participants' gaze points during assignment 4.

4.5.1.4 Content and construct validity of WayR based on the objective measures

The aim of the wayfinding experiments was to evaluate the capabilities and validity of WayR to study pedestrian wayfinding behaviour in a multi-story building. The results featuring the objective measures can be used to assess the content validity and construct validity of WayR as a research tool to study pedestrian wayfinding behaviour.

1. Content validity of WayR

Content validity refers to the extent to which a tool/method adequately includes the items that are essential to measure what it means to measure (Westen & Rosenthal, 2003). In our case, content validity refers to the extent WayR includes all the items that are essential to measure pedestrian wayfinding behaviour. In order to determine whether the content validity is achieved, we compare the types of behavioural data collected by WayR with commonly used metrics to measure pedestrian wayfinding behaviour in literature. The most commonly used metrics to study pedestrian wayfinding behaviour are metrics to quantify decision making (e.g., route choice and exit choice) (Andree et al., 2015; Duives & Mahmassani, 2012; Frankenstein et al., 2012; Liao et al., 2014; Vilar et al., 2014b; Wiener et al., 2012; Zhu & Shi, 2016), wayfinding task performance (e.g., time, distance, speed) (Cao et al., 2019; Fang et al., 2020; Li & Giudice, 2013; Meng & Zhang, 2014; Schrom-Feiertag et al., 2017; Shi et al., 2021; Suzer et al., 2018), and physical behaviour (e.g., locomotion and observation behaviour) (Conroy, 2001; Duarte et al., 2014; Feng et al., 2021b; Kobes et al., 2010b; Meng & Zhang, 2014; Ruddle & Lessels, 2006; Schrom-Feiertag et al., 2017; Zhang et al., 2021). However, due to the constraints of traditional data collection methods, it is almost impossible to simultaneously collect all the above-mentioned data types in one traditional experiment. In the current study, participant's positions, head rotations, gaze points, and timestamp were recorded in milliseconds by WayR. These data can be translated into three types of behavioural information, namely (1) route and exit choices (i.e., wayfinding strategy, path, and decision point), (2) wayfinding performance (i.e., travel time, travel speed, and travel distance), and (3) observation behaviour (i.e., head rotation, gaze point, and hesitation). Our analysis of these behavioural data shows that the collected data can reflect pedestrian wayfinding behaviour from different perspectives and allows the meaning of the data to be readily comprehended. Thus, the content validity of WayR as a tool to study pedestrian wayfinding behaviour is established.

2. Construct validity of WayR

Construct validity refers to the extent to which the tool, in this case, WayR, adequately assesses what it claims to measure (Deb et al., 2017). To determine how well WayR captures pedestrian wayfinding behaviour in a multi-story building, the construct validity of VR is evaluated pertaining to pedestrian wayfinding behaviour itself and the difference of wayfinding behaviour in relation to assignment complexity.

Three aspects of pedestrian wayfinding behaviour are compared with previous studies in the literature to ensure the construct validity of WayR. Firstly, from the decision-making perspective of pedestrian wayfinding behaviour, our findings show that the floor strategy was predominantly adopted in a multi-story building and the wayfinding assignment instruction strongly affect pedestrian's wayfinding strategy, as suggested by Hölscher et al. (2006). Moreover, we found that participants prefer to use paths that are wide and with longer lines of sight, which was also indicated by other studies (Frankenstein et al., 2012; Vilar et al., 2013b, 2014b; Wiener et al., 2012). Besides that, our finding shows that participants were more likely to choose the nearest exits and shortest routes during evacuations, as also indicated in the literature (Guo et al., 2012; Kobes et al., 2010a; Li et al., 2019; Liao et al., 2017). Secondly, regarding pedestrian wayfinding performance, our findings suggest that level changes make navigation more difficult, which is in line previous work (Hölscher et al., 2006; Kuliga et al., 2019) that found level change is a key source of disorientation in a multi-story building. Moreover, in agreement with (Cao et al., 2019; Lin et al., 2019; Meng & Zhang, 2014), we found participants had worse way-finding performance during emergencies compare to normal conditions. Thirdly, with respect to the results of observation behaviour, the current study shows that participants had the most head rotation changes during evacuations (Zhang et al., 2021). Moreover, we found that hesitations were more often made at locations with high levels of information provided or confusion aroused, which is in line with the findings of other studies (Conroy, 2001; Ewart & Johnson, 2021; Orellana & Al Sayed, 2013; Zhang et al., 2021). Additionally, we also found that room numbers, floor plans, fire doors and exit signs were the major attractors during wayfinding. This finding is consistent with previous literature in pedestrian wayfinding behaviour in buildings (Bode et al., 2014; Büchner et al., 2007; Dogu & Erkip, 2000; Duarte et al., 2014; Hessam & Debajyoti, 2018; Hölscher et al., 2013; Kobes et al., 2010b; Montello & Sas, 2006; Pati et al., 2015; Schrom-Feiertag et al., 2017).

Next, we compared the above-mentioned measurements with each other during the four assignments with different complexity. The results show that, in general, participants behaved significantly different across four assignments, which aligns with what we would expect based on our experimental design and what would be expected in the real world. Our findings show that with the increased complexity of the four assignments (i.e., from within-floor assignment to between-floor assignments, and from normal wayfinding assignments to evacuation assignment), overall, participants travelled longer distances, travelled at a slower speed, hesitated more often and had more head rotation changes. Moreover, the learning effect is also observed as participants made fewer turns and adopted a more effective wayfinding strategy.

Similar results pertaining to wayfinding behaviour in relation to assignment complexity have been described in the studies of (Cao et al., 2019; Lin et al., 2019; Meng & Zhang, 2014).

The findings pertaining to the general wayfinding behaviour of the participants in WayR and the differences in their behaviour among different assignments are in line with literature. Together, it provides evidence that participants in the current study behaved realistically in the virtual building. Thus, we conclude that WayR is able to measure what it is designed to measure. Therefore, we establish the construct validity of WayR for studying wayfinding behaviour.

4.5.2 Subjective measures

Besides understanding whether WayR allows researchers to collect adequate data and measure what it is supposed to measure, it is also essential to establish whether participants experience WayR realistically and WayR is easily usable. We have undertaken various questionnaires to establish the realism and usability of WayR. This sub-section describes the results of subjective data derived by means of the questionnaires, namely the face validity questionnaire, the Simulation Sickness questionnaire, the Presence questionnaire and the System Usability Scale questionnaire.

4.5.2.1 Realism

A face validity questionnaire was used to evaluate the realism of the virtual environment. This questionnaire evaluated the realism of four elements, namely the virtual building, the furniture, the movement ability and the evacuation alarm. The questionnaire used a five-point Likert scale ranging from 1 (not at all realistic) to 5 (completely realistic). The results of the face validity are provided in Table 4.3. Amongst four elements, the realism of the evacuation alarm sound received the highest score (*M* = 4.75), which shows participants were highly engaged in the assignment and felt threaten during the emergency. Participants assigned the lowest score to the realism of the movement ability (*M* = 3.17). As participants needed to hold the controller's button while walking in the virtual environment, this result is in line with our expectations. Overall, the average score of the face validity questionnaire was 4.04 (*SD* = 0.36) and three scores (out of four) were above 4, which indicate that WayR has a relatively high degree of realism. This score is similar to previous studies that applied VR to study pedestrian behaviour (Bourhim & Cherkaoui, 2020; Bourhim & Cherkaoui, 2018; Schwebel et al., 2008)

Table 4. 3: Rating of WayR's realism (range from 1 to 5).

The realism of the WayR	Mean	SD
The realism of the virtual building	4.08	0.63
The realism of the virtual furniture (chairs, doors, etc.)	4.17	0.55
The realism of the movement ability	3.17	0.79
The realism of the evacuation alarm sound	4.75	0.66

4.5.2.2 Simulation sickness

Simulation sickness is generally defined as the discomfort that arises from using simulated environments (Deb et al., 2017). When designing a VR research tool, it is essential to evaluate whether the tool potentially causes simulation sickness. The Simulator Sickness Questionnaire (Kennedy et al., 1993) is a well-established questionnaire that determines participant's experience pertaining to a set of symptoms (e.g., fatigue and headache) related to simulation sickness in a 4-point Likert scale, from 0 (none) to 3 (severe). Based on the results, a total symptom score can be derived, as well as scores of three subscales, namely Nausea, Oculomotor disturbance, and Disorientation. The total score is calculated by summing the reported values in each subscale and accordingly multiplying the result by 3.74 (Kennedy et al., 1992). The total score of SSQ can range from 0 to 236. For each subscale, the scores are based on the reported scores for each symptom and then multiplied by the weight for that particular subscale.

In our study, the average total score of the Simulation Sickness Questionnaire was 15.06 (*SD* = 15.19) with up to thirteen minutes of exposure to the virtual environment. The total score is similar to (Kinateder et al., 2014a; Oberdörfer et al., 2019; Suma et al., 2010) and relatively lower compared to the study of (Dominic & Robb, 2020; Feng et al., 2021b). According to the categorisation of symptoms (Kennedy et al., 2003), only negligible symptoms or minimal symptoms were found amongst all participants in the current experiment. Table 4.4 presents the results of each subscale of SSQ, which shows that the subscale of Disorientation received the highest score, followed by Oculomotor and Nausea. The relatively high Disorientation score might be the result of rotation-induced effects. That is, while participants walking through the virtual environment, they can rotate their head side to side, which might cause a response lag. Besides that, the current experiment assignments involved changing floors and some turning movements on the staircases in the virtual building, which are key sources of disorientation about one’s heading and position in a building. The relation between disorientation and floor changes was also found in (Hölscher et al., 2006). Moreover, although the Disorientation subscale is related to vestibular disturbances such as dizziness and vertigo, high disorientation may be an indicator of having experienced higher levels of virtual presence (Barfield & Weghorst, 1993).

Table 4. 4: Subscales of SSQ: Means and standard deviations.

Subscale	Mean	SD
Nausea	9.80	14.69
Oculomotor	13.69	12.13
Disorientation	16.63	20.73

4.5.2.3 Feeling of presence

The sense of presence reported by participants is a key factor to evaluate the effectiveness of virtual environments (Witmer et al., 2005). This study evaluates the sense of presence by means of the Presence Questionnaire (PQ), which is a wildly applied questionnaire to measure the degree of participant's feeling of presence in a virtual environment. It consists of four subscales, namely Sensory fidelity, Immersion, Involvement and Interface quality (Witmer et al., 2005). Participants used a 7-point scale to rate 29 questions.

The total PQ score per participant was counted by summing the reported scores of the 29 items. The average total PQ score was 146.00 (*SD* = 13.63) in this study, which indicates that the participants had a strong sense of presence. The PQ score is slightly higher than the studies that also used VR to study pedestrian behaviour (Deb et al., 2017; Lin, Cao, et al., 2020; Zhu et al., 2020). In addition, the four subscales in the PQ questionnaire are analysed (see Table 4.5). The Immersion subscale received the highest score, which confirms that the participants felt a high level of immersion in the designed virtual environment. Meanwhile, the relatively high score for Sensory fidelity (4.91/7) established the accuracy of the sensory stimulation. The Involvement score indicates that participants were able to focus their attention and energy in the virtual environment. The Interface quality score shows that the VR control devices induced little distraction for the participants and the participants were able to concentrate on the assignments. Furthermore, participants' response to Question 8, (i.e., “How much did your experience in the virtual environment seem consistent with your real-world experience?”, *M* = 5.13, *SD* = 0.96) indicates that the participants’ experiences in the virtual building were consistent with their real-world experiences walking through buildings.

Table 4. 5: Subscales of PQ: Means and standard deviations (range from 1 to 7).

	Involvement	**Sensory fidelity**	**Immersion**	**Interface quality [a]**
Mean	4.81	4.91	5.78	4.17
SD	0.62	0.87	0.50	0.97

[a] Reversed items

4.5.2.4 Usability

To evaluate the usability, the System Usability Scale (SUS) questionnaire was adopted, which represents a composite measure of the overall usability of the simulator system (Brooke, 1996). The SUS questionnaire contains questions such as, "I thought the system was easy to use" and "I found the various functions in this system were well integrated". Participants rated the ten items of this questionnaire on a 5-point Likert scale (i.e., 1 = strongly disagree, 5 = strongly agree). The total score of SUS is calculated by summing the converted responses on ten items and accordingly multiplying the result by 2.5. The total score of SUS ranges from 0 to 100.

The total score of the SUS questionnaire can be translated into ratings for interpreting the results, such as 'worst imaginable', 'poor', 'OK', 'good', 'excellent', 'best imaginable' (Bangor et al., 2009). In the present study, the average score of WayR was 83.75 (SD = 11.92), which suggests the 'excellent' usability of WaR. The score of the current study is slightly higher than several other studies (Boletsis & Cedergren, 2019; Deb et al., 2017; Feng et al., 2021b; Stigall & Sharma, 2019) that also measured SUS concerning the usage of VR technologies for studying pedestrian behaviour.

4.5.2.5 Face validity and usability of WayR based on the subjective measures

As mentioned before, WayR should not only be able to collect valid behavioural data, but also provide participants realistic experiences. Moreover, it should be easy and comfortable to use for participants and researchers alike. Based on the results of four subjective measures, this section discusses the face validity and usability of WayR.

Face validity refers to the degree to which a simulator's realism compares to the real situation (Deb et al., 2017). The result of the face validity questionnaire shows that the average score was 4.04 (out of 5), indicating that WayR has a relatively high degree of realism and, as such, can resemble the experience in the actual building well. This was also confirmed by comments from participants, for instance, ‘I feel like I am walking in the faculty’, and ‘I feel the urge to get out of this building’, ‘I want to be out of this building as quick as possible’ for the evacuation assignment. Moreover, participants' score (5.13 out of 7) to one particular question in the Presence Questionnaire related to realism (i.e., “How much did your experience in the virtual environment seem consistent with your real-world experience?”) indicates that participants’ experiences in the virtual building are consistent with the real-world experience. To conclude, the results indicate that the virtual environment was realistic and the assignments were engaging. Thus, this study establishes the face validity of WayR.

The overall usability of WayR is evaluated based on the results of the Simulator Sickness Questionnaire (SSQ), the Presence Questionnaire (PQ) and the System Usability Scale questionnaire (SUS). Firstly, the total score of SSQ reflects the severity of the symptomatology of participants using WayR and indexes the troublesomeness of a simulator (Kennedy et al., 2003). In the present study, the average total SSQ score is relatively low and only negligible symptoms or minimal symptoms were found among all participants according to the categorisation of symptoms (Kennedy et al., 2003). Secondly, the PQ results revealed that participants experienced a high level of presence. Moreover, participants felt a high level of immersion and were able to focus their attention in the virtual building. Thirdly, based on the ratings for interpreting the SUS results (Bangor et al., 2009), the SUS score of the current study suggested 'excellent' system usability of WayR. Overall, the usability of WayR is established by low simulator sickness incidence as well as high level of presence, immersion and system usability.

4.5.2.6 Ecological validity

Ecological validity refers to whether participants’ perceptions and responses in the virtual environment can be generalized to real-life situations (Brewer, 2000). In the current study, the ecological validity can be assessed via comparing findings with studies in the literature and the results of face validity and the presence questionnaire.

Firstly, although this study did not directly compare pedestrian wayfinding behaviour in the real-life building and the virtual building, the findings of the current study are in line with previous studies that investigate pedestrian wayfinding behaviour in real-life buildings. Similarities can be found pertaining to the adoption of wayfinding strategies in multi-level buildings (Hölscher et al., 2006), the difficulty of level changes in multi-level buildings

(Hölscher et al., 2006; Kuliga et al., 2019), locations where hesitations are made (Orellana & Al Sayed, 2013), and locations of major attractors during wayfinding (Büchner et al., 2007; Dogu & Erkip, 2000; Hessam & Debajyoti, 2018; Hölscher et al., 2013; Kobes et al., 2010a; Montello & Sas, 2006; Pati et al., 2015). Secondly, the results of face validity (M = 4.04, SD = 0.36) and the presence questionnaire (M = 146.00, SD = 13.63) show that participants experience a high level of realism and presence in the virtual building. Particularly, regarding question 8 in the presence questionnaire (i.e., "How much did your experience in the virtual environment seem consistent with your real-world experience?"), participants' score was 5.13 on average, which indicates that participants had similar experiencing walking in the virtual building as they would do in the real-life building. While the ecological validity of WayR needs further assessment, these preliminary results show that similar behavioural and experiential responses can be observed in this study as in real-life buildings.

4.6 Conclusions and future research

This study aims to develop a VR research tool (i.e., WayR) and evaluate its validity and usability for studying pedestrian wayfinding behaviour in a multi-story building. WayR supports free movements in all directions and automatically records walking trajectories, head movements and gaze points of participants. A VR experiment was conducted featuring four wayfinding assignments with varying complexity, which includes within-floor wayfinding assignment, between-floor assignments, and an evacuation assignment.

Based on the results from objective and subject measures, the validity (i.e., content validity, face validity, construct validity, and ecological validity) and overall usability of WayR are evaluated. We demonstrate the content validity by showing the behavioural data collected by VR can reflect pedestrian wayfinding behaviour from the metrics identified by literature (i.e., decision making, wayfinding performance, and observation behaviour) and allows the meaning of the data to be readily comprehended. The face validity is established based on participants' high score of the realism of the virtual environment and the consistency of their experience in the virtual building and real world. The construct validity is determined by showing participants' wayfinding behaviour is consistent with pedestrian wayfinding behaviour studies in the literature. Moreover, as expected, participants behaved overall differently amongst wayfinding assignments with various complexity. The ecological validity is assessed by comparing current findings with previous work in the literature and the results of questionnaire related to realism. The usability of WayR is established by showing it offers a highly immersive feeling, high usability, and low simulation sickness incidence. Together, our findings confirm that WayR is capable of collecting valid pedestrian wayfinding behavioural data in a complex multi-story building.

WayR addresses several limitations with respect to using VR for wayfinding behaviour research, such as free movement across the horizontal and vertical level in a complex environment, the accurate collection of comprehensive data related to pedestrian behaviour, the initial validation of using VR to study pedestrian behaviour in complex buildings. This creates the possibility to share an innovative data collection tool with the pedestrian community that can cover the gap of studying pedestrian wayfinding behaviour in complex buildings in order to ensure pedestrian safety.

Several limitations exist in the current study and need to be addressed in future work. First, although significant differences in pedestrian wayfinding behaviour among different wayfinding assignments are found according to statistical tests, the relatively small sample size of this study should not be neglected. Future work should investigate pedestrian wayfinding behaviour using WayR with larger sample sizes. Second, pedestrian wayfinding behaviour in buildings is also influenced by other factors, amongst others, other pedestrians. Currently, no other agents or other socially relevant variables were added because the goal of the current study is to provide the initial evaluation of WayR. For more complex interaction scenarios in buildings, it is essential to add other users to the environment and investigate the impact of the interaction with other virtual pedestrians (and their behaviour) on pedestrian wayfinding behaviour. Third, future studies should continue working on improving the realism of users' experience in VR. One of the advantages of VR is the ability to rapidly change the scenario and add other elements to the virtual environment. To increase the realism of experience in VR, realistic characteristics can be added to the virtual environment and various interaction functions can be developed, such as environmental noise in normal conditions, smoke and fire during evacuations, and the ability to manipulate objects in the virtual environment. Moreover, future development of WayR should integrate a more sophisticated speed control interface or mechanism to allow participants to adjust their walking speed in the virtual building in order to provide more realistic movements. The researchers of this study are continuing to explore the use of WayR in other perspectives of pedestrian wayfinding behaviour, for example, add multiple users, obstacles, dynamics signage in the environment simultaneously and investigate their influence on pedestrian behaviour. Fourth, although face validity, content validity and construct validity of WayR are established and the ecological validity is initially assessed, they serve as a foundation for further validation. In the future study, we will conduct pedestrian wayfinding experiments in the actual building and directly compare pedestrian behaviour in VR and the real world. Due to COVID-19, it has until now been impossible to conduct the experiment in the faculty building. Lastly, the current applied HMD device only uses head tracking to present participants' movement in the environment. In future research, applying other sensors, such as eye-tracking and body-tracking, would allow researchers to track pedestrian gaze points and movements more precisely.

Chapter 5

Wayfinding behaviour in a multi-level building: A comparative study of HMD VR and Desktop VR

Another consideration of using VR to study pedestrian behaviour is which VR equipment to use. Chapter 4 demonstrated the validity and usability of WayR as a research tool to study wayfinding behaviour in a complex multi-story building. So far, the knowledge regarding the effectiveness of the Head-Mounted-Display (HMD) VR and the traditional Desktop VR is still limited.

Applying WayR, this chapter compares pedestrian wayfinding behaviour in a multi-level building and user experience using different VR technologies. Section 5.2 provides a review of the studies using VR to study pedestrian wayfinding behaviour. Section 5.3 presents the research methodology for the VR experiment. Section 5.4 presents the results obtained from the HMD VR and the Desktop VR. Based on the results, section 5.5 discusses the findings regarding differences in pedestrian wayfinding behaviour and user experience between the usage of HMD and Desktop VR. This chapter ends with conclusions and suggestions for future research.

This chapter is based on the journal publication: **Feng, Y.**, Duives, D. C., & Hoogendoorn, S. P. (2022). Wayfinding behaviour in a multi-level building: A comparative study of HMD VR and Desktop VR. *Advanced Engineering Informatics*, *51*, 101475.

5.1 Introduction

Pedestrians perform wayfinding activities in buildings on a daily basis. Wayfinding here is defined as a decision-making process in which pedestrians determine the route to a destination and finding an exit to leave the building (Shields & Boyce, 2000). Performing wayfinding in large-scale and multi-level buildings, such as train stations, hospitals, and shopping malls, can be difficult because of the complexity of the three-dimensional environment (Jeffery et al., 2013). That is, the complexity of finding one's route and exit in multi-level buildings increases by the multiple floor layouts, complex spatial structures, many indoor objects, and moving along vertical distances (Andree et al., 2015; Kruminaite & Zlatanova, 2014; Kuliga et al., 2019). In case of an emergency, pedestrian route and exit choice are of vital importance to their survival.

Traditionally, field experiments and surveys have been widely used to investigate pedestrian wayfinding behaviour under both normal and emergency situations (e.g., Galea et al., 2017; Heliövaara et al., 2012; Imanishi and Sano, 2019; Kobes et al., 2010b; Nilsson & Johansson, 2009; Rahouti et al., 2020). However, these methods have constraints in terms of experimental control, cost, and data accuracy for studying pedestrian wayfinding behaviour (Feng et al., 2021a). Most experimental studies focused on a single-level or simplified environment with an experimental area of limited size (e.g., Heliövaara et al., 2012; Hsieh et al., 2018; Lin et al., 2019; Santos et al., 2009; Tang et al., 2009; Vilar et al., 2014a). Consequently, most experimental conditions featured in traditional pedestrian wayfinding studies differ greatly from actual reality where pedestrians are faced with more complex situations. Moreover, the accuracy of behavioural data is highly influenced by the sensor setup and techniques, and it often requires a large investment in labour to extract the collected data (Feng et al., 2021a). Additionally, it is time-consuming and challenging to obtain approval to perform a field observation or create an artificial experiment environment. Furthermore, there are ethical and financial constraints to create real and stressful situations to provide participants with a strong sense of presence to make them fully participate and keep focused on the task (Feng et al., 2021b). We suspect that the existing constraints of the traditional data collection methods (partially) induce a lack of studies featuring pedestrian wayfinding behaviour in large-scale and multi-level buildings (Feng et al., 2021a).

To overcome the existing constraints of traditional data collection methods, the usage of Virtual Reality (VR) to investigate pedestrian wayfinding behaviour has become increasingly popular. With VR, it is possible to place participants in complex or hazardous situations that are costly, stressful or even impossible to simulate in the real world (e.g., Cosma et al., 2016; Lin et al., 2020b, 2019; Zhang et al., 2021). VR allows researchers to perform controlled experiments that have high internal validity due to their experimental design and provide enhanced ecological validity due to the high-fidelity virtual environment (Birenboim et al., 2021). Additionally, it provides the possibility of accurate tracking and recording a large variety of data pertaining to pedestrian's movement and choice behaviour in complex environments, such as timestamp, pedestrian movement trajectory, head rotation, and eye movement.

Different VR technologies have been used to study pedestrian wayfinding behaviour, such as head-mounted-display (HMD) (e.g., Cao et al., 2019; Cosma et al., 2016; Duarte et al., 2014; Feng et al., 2021b; Kinateder et al., 2019; Suzer et al., 2018; Tucker et al., 2018; Vilar et al., 2014a; Zhu et al., 2020a), Desktop VR (e.g., Bode et al., 2014, 2015; Moussaïd et al., 2016a; Silva et al., 2013; Tang et al., 2009) and cave automatic virtual environment (CAVE) (e.g., Bauer et al., 2018; Kinateder et al., 2014b; Ronchi et al., 2019). Although studies have demonstrated the effectiveness of VR to study pedestrian behaviour in a variety of cases, one unresolved issue is that the suitability of different VR technologies for pedestrian wayfinding behaviour study is still open to debate. Different VR technologies have different characteristics, it may cause people to perceive the virtual environment differently and behave in the virtual environment differently (Santos et al., 2009).

While VR technologies are more and more readily available to study wayfinding behaviour, researchers have limited insights into the impact of the adopted VR technologies on their research findings. To date, only a few studies have compared pedestrian wayfinding behaviour or evacuation behaviour using different VR technologies. For example, Santos et al. (2009) found better performance with Desktop VR compare to HMD VR, Ruddle & Péruch (2004) found no difference in wayfinding performance between HMD VR and Desktop VR, Ronchi et al. (2019) showed consistent results of evacuation behaviour between a mobile-HMD and CAVE system in a tunnel emergency scenario. However, the above-mentioned studies did not directly compare the presentation of the same virtual environment using different VR technologies on pedestrian wayfinding behaviour across a variety of wayfinding tasks, and their experimental environments were relatively simple (i.e., single-level, limited size, and maze layout). In order to identify the influence of VR technology on pedestrian wayfinding behaviour in large-scale and multi-level environments, it is essential to directly compare VR technologies regarding their impact on pedestrian wayfinding behaviour and user experience in one environment.

The objective of this chapter is to compare the adoption of different VR technologies (i.e., HMD VR and Desktop VR) for pedestrian wayfinding studies, via investigating the difference in pedestrian wayfinding behaviour and user experience. HMD VR and Desktop VR are two VR technologies that have been increasingly applied to study pedestrian behaviour. Compared to CAVE, which is very costly and requires a large space for the screen monitors or multiple television projection systems (Mujber et al., 2004), HMD VR and Desktop VR provides cost-effective solutions. Moreover, the access to CAVE system is generally restricted to few institution laboratories, while HMD VR and Desktop VR are more accessible and affordable to a wider range of researchers who are interested in using VR. Meanwhile, compare with HMD VR, Desktop VR decreases technical complexity to implement and even provides lower-cost and off-the-shelf alternatives.

In the current study, we conduct VR experiments in which participants use either HMD VR or Desktop VR to perform a set of wayfinding tasks. In particular pedestrian behaviour data (i.e., three-dimensional movement trajectories, head rotations, and gaze points) and participant's experience using VR (i.e., perceived realism, usability, feeling of presence, and simulation sickness) are collected synthetically. Previous studies from literature argue that the different features of HMD VR and Desktop VR may cause users to perceive the virtual environment differently and behave differently in the virtual environment (e.g., Lee et al., 2010;

Li & Giudice, 2013; Seibert & Shafer, 2018; Soler-Domínguez et al., 2020). Thus, the collected data were analysed quantitatively to examine whether pedestrian wayfinding behaviour, such as route and exit choice, observation behaviour, and wayfinding task performance as well as user experience are different between HMD VR and Desktop VR. Accordingly, four hypotheses related to pedestrian wayfinding behaviour and user experience are formulated, namely:

H 1. There is a significant difference in route and exit choice behaviour (i.e., wayfinding strategy, paths, decision points, staircases, and evacuation exit choice) between the participants that adopted Desktop VR and HMD VR.

H 2. There is a significant difference in observation behaviour (i.e., head rotation and gaze point) between the participants that adopted Desktop VR and HMD VR.

H 3. There is a significant difference in wayfinding task performance (i.e., time, speed, and distance) between the participants that adopted Desktop VR and HMD VR.

H 4. There is a significant difference in user experience (i.e., realism, presence, simulation sickness, and usability) between the participants that adopted Desktop VR and HMD VR.

There are three major contributions of this study, namely we (1) investigate pedestrian wayfinding and evacuation behaviour in a complex and multi-level building using VR, (2) provide a direct comparison of pedestrian wayfinding behaviour and user experience between two different VR technologies, and (3) recommend which VR technology to use to perform pedestrian wayfinding behaviour studies.

The paper is organised as follows. Section 5.2 provides an overview of used metrics to measure wayfinding behaviour and a review of VR - wayfinding studies. Section 5.3 describes the experimental method. Accordingly, section 5.4 reports the results pertaining to pedestrian wayfinding behaviour in the virtual environment and user experience. Based on the results, section 5.5 discusses the findings regarding differences in pedestrian wayfinding behaviour and user experience between the usage of HMD and Desktop VR. Finally, section 5.6 presents the conclusions and future work of this study.

5.2 Related work

The current study focuses on comparing pedestrian wayfinding behaviour in a multi-level building and user experience of the VR technology between the adoption of HMD VR and Desktop VR. Therefore, this section first provides an overview of commonly used metrics to measure pedestrian wayfinding behaviour in previous studies. Second, this section gives a summary of wayfinding studies that employed different VR technologies.

5.2.1 Wayfinding behaviour in multi-level buildings

Pedestrian wayfinding studies investigate how people orient themselves and navigate from an origin to a destination (Raubal & Egenhofer, 1998). The term “wayfinding” was originally introduced by Lynch (1960) where he defined human wayfinding as “a consistent use and organization of definite sensory cues from the external environment”. Afterwards, multiple disciplines, such as engineering, psychology, and architecture have developed a wide variety of theories to understand this behavioural process. Jamshidi & Pati (2020) classifies wayfinding theories into four categories, namely theories of (1) perception, (2) spatial knowledge development, (3) mental representation of spatial knowledge, and (4) spatial cognition. In general, the act of wayfinding can be viewed as a continuous problem-solving process requiring information about the environment (Arthur & Passini, 1992; Passini, 1984a, 1984b; Shields & Boyce, 2000), which contains the process of perception, cognition and decision making (Arthur & Passini, 1992; Jamshidi & Pati, 2020). To be more specific, wayfinding refers to the process that people acquire information regarding their environment through their senses, understand and manipulate this information, establish a plan, transfer this plan into behavioural activities, and execute these activities in the environment (Arthur & Passini, 1992; Passini, 1984a; Suzer et al., 2018).

Wayfinding behaviour has been widely explored in various spatial settings, including urban spaces (e.g., Kiefer et al., 2014; Natapov & Fisher-Gewirtzman, 2016; Raubal & Winter, 2002; Zomer et al., 2019) and buildings (e.g., Kuliga et al., 2019; Li et al., 2019; Lin et al., 2019; Raubal & Egenhofer, 1998; Raubal & Worboys, 1999; Suzer et al., 2018; Vilar et al., 2014a). Everyday people need to find their way in complex and multi-level buildings, such as offices, university buildings, train stations, hospitals and shopping malls. Previous studies have observed the difficulty (e.g., disorientation, frustration, and stress) of people finding their way in complex and multi-level buildings (Carlson et al., 2010; Hölscher et al., 2005; Soeda et al., 1997). Wayfinding in multi-level buildings has been considered complex due to the navigation of multiple floor layouts, (turning) staircases, differences in visual accessibility, and architectural differentiation. In general, literature identifies three levels of metrics to evaluate pedestrian wayfinding behaviour, namely decision making (e.g., wayfinding strategy, route choice, and exit choice), observation behaviour (e.g., head rotation and gaze point), and wayfinding task performance (e.g., time, speed, and distance) (Hölscher et al., 2005; Li et al., 2019; Ruddle & Lessels, 2006; Vilar et al., 2014a). The explanations of these metrics and wayfinding studies in which these metrics are measured are given below.

Regarding the *decision-making level*, the usage of decision points and paths are found to be closely related to route choice and exit choice (Suzer et al., 2018). That is, if a person chooses a long route between an origin and a destination (exit), the number of decision points and length of path increase (Suzer et al., 2018). Literature shows that the arrangement of decision points, their linking paths and the position of staircases contribute prominently to the experienced complexity of buildings (Hölscher et al., 2005). Moreover, Hölscher et al. (2007) illustrated that the adopted wayfinding strategy can also influence the efficiency of pedestrian wayfinding in multi-level buildings. Here, each element included at the decision-making level can be operationalized as follows:

1. *Decision points* - locations where pedestrians have more than one choice of direction to continue the way (Raubal & Egenhofer, 1998). Studies showed that the number of decision points is positively related to the difficulty of wayfinding tasks (Arthur & Passini, 1992; Best, 1970; Suzer et al., 2018).

2. *Staircases* - important vertical interconnections between different floors in a mulita-level building. Staircases could be seen as decision points on the vertical level. Literature found that floor changes that involve vertical movement on staircases can cause disorientation and hinder wayfinding performance (Hölscher et al., 2005; Passini, 1984a; Soeda et al., 1997)

3. *Paths* - the smallest segment connecting two decision points that people can move along (Jamshidi et al., 2020; Lynch, 1960). When choosing between available paths, studies found that people prefer paths with longer lines of sight and are wider (Frankenstein et al., 2012; Vilar et al., 2013b, 2014b; Wiener et al., 2012).

4. *Wayfinding strategy* - the strategy that people adopt to identify their optimal path. According to literature, wayfinding strategy can be categorised into three classifications, namely (1) the floor strategy: the individual first moves to the floor of the destination, (2) the direction strategy: the individual first moves to the horizontal position of the destination as directly as possible (irrespective of level-changes), and (3) the central point strategy: the individual finds the way by visiting the well-known parts of the building (Hölscher et al., 2007).

Wayfinding performance measures how well participants perform wayfinding tasks (Kuliga et al., 2019). Often, wayfinding performance is measured using either travel time, travel distance, and/or travel speed. Weisman (1981) provided four types of environmental elements that influence pedestrian wayfinding performance in buildings, which were investigated by many studies including (1) visual access to see other parts of the building from a given location (e.g., Guo et al., 2012; Omer & Goldblatt, 2007; Zhu et al., 2020a), (2) the degree of architectural differentiation, which is the difference between objects in the building (e.g., Suzer et al., 2018; Vilar et al., 2013b; Zhang et al., 2021), (3) signs and room numbers to provide identification or directional information (e.g., Conroy, 2001; Feng et al., 2020b; Tang et al., 2009; Vilar et al., 2014a, 2014b), and (4) plan configuration of the building (e.g., Hölscher et al., 2006, 2005; Raubal & Worboys, 1999). Therefore, these environmental factors should be taken into account while developing the virtual building for VR studies. Besides the environmental factors, literature has shown that personal factors, such as gender (e.g., Suzer et al., 2018; Vila et al., 2003; Vilar et al., 2014a), age (e.g., Head & Isom, 2010; Lee, 2010), and familiarity with the environment (e.g., Kinateder et al., 2018a; Lin et al., 2020a) can affect wayfinding performance. Moreover, the influence of interaction with other people on wayfinding performance has also been studied by (Fu et al., 2021b; Kinateder et al., 2014a; Li et al., 2019; Lin et al., 2020b).

Regarding the *observation behaviour*, pedestrians aid their navigation by looking around in the environment during wayfinding (Ruddle et al., 1999), and their gaze behaviour can reveal insights into the information acquisition process that supports the wayfinding tasks (Wiener et al., 2012). With the development of tracking technologies, such as eye-tracking, motion-tracking, it is possible to detect and collect people's head movements and eye movements during their navigation. Collected data can be used to measure how space is perceived and how specific elements attract individual's attention during wayfinding (Kiefer et al., 2017; Tang, 2020). The usage of eye-tracking and head-tracking in wayfinding studies has been studied in real-life scenarios and virtual environments, such as buildings and urban spaces (e.g., Bae et al., 2020; Kiefer et al., 2014; Lander et al., 2017; Ohm et al., 2017; Schrom-Feiertag et al., 2017; Schuchard et al., 2005; Viaene et al., 2016; Wiener et al., 2012).

5.2.2 Wayfinding studies in VR

Virtual reality (VR) is defined as a system composed of interactive computer simulations that senses participant's position and responds to their movement, thereby giving participants the feeling of being immersed in a virtual environment (Reid, 2003). Due to the rapid advancements of high-quality simulations and computer processing power, in combination with the reduction of computer power costs, VR has been applied increasingly to study pedestrian wayfinding behaviour (e.g., Feng et al., 2021b; Kinateder et al., 2014b; Lin et al., 2020b). By using VR, researchers can create environments that are suitable for their research objectives with high experimental control, and let participants experience the virtual world through a continuous stream of high-realistic images and sound landscapes. Human performance in the virtual environment is generally influenced by the individual's level of experienced immersion in the virtual environment (Stanney et al., 1998; Witmer & Singer, 1998). Regarding the level of immersion, VR studies can be generally categorised into two groups, namely non-immersive VR and immersive VR.

Non-immersive VR utilises common PC monitors or projections to allow participants to view the virtual environment. Participants typically use abstract interfaces (e.g., joystick, mouse, and keyboard) to control their movements. Several studies applied non-immersive VR to study pedestrian wayfinding and evacuation behaviour. For instance, Desktop VR has been used to study pedestrian wayfinding behaviour during evacuations (e.g., Bode et al., 2015, 2014; Silva et al., 2013; Tang et al., 2009). Projection-based VR has been applied to investigate pedestrian route selection during evacuations (e.g., Kobes et al., 2010a; Vilar et al., 2013b). Generally, using non-immersive VR, participants can still view the real world, which might limit their sense of immersion (Costello & Patrick, 1997).

Immersive VR usually requires participants to wear a headset that blocks participants from their real-life environment. Participants interact with the virtual environment through specialist simulator control devices (e.g., controller and gloves) and motion tracking hardware (e.g., eye, head and motion tracking devices). One type of immersive VR is the Cave Automatic Virtual Environment (CAVE), which displays the virtual environment on huge screen monitors or multiple television projection systems simultaneously (Mujber et al., 2004). The CAVE has, for instance, been applied to investigate pedestrian wayfinding in high-rise buildings (Andree et al., 2015), tunnels (Fridolf et al., 2013; Kinateder et al., 2014b, 2014a; Ronchi et al., 2019), and train stations (Bauer et al., 2018). However, the installation of CAVE systems requires large spaces and the cost is relatively high. Therefore, studies using CAVE were conducted by few research groups with the resources for a CAVE (Schneider & Bengler, 2020).

Another type of frequently used immersive simulator is the head-mounted display (HMD), which typically features high-resolution displays. A large body of studies used HMD to investigate pedestrian wayfinding behaviour. One major research theme using HMDs focused on the influence of environmental characteristics on pedestrian wayfinding behaviour, amongst other things, the influence of signage (Duarte et al., 2014; Feng et al., 2021b; Kinateder et al., 2019; Vilar et al., 2014a), lighting conditions (Cosma et al., 2016; Suzer et al., 2018) and visual cues (Cao et al., 2019; Tucker et al., 2018; Zhang et al., 2021; Zhu et al., 2020b). Another theme of studies focused on the impact of social influence on pedestrian wayfinding behaviour (e.g., Kinateder et al., 2018a; Li et al., 2019; Lin et al., 2020b; Zhu et al., 2020a). Compared to CAVE, HMD VR can be built with high flexibility and low cost.

As mentioned in section 5.2.1, spatial perception and cognition are important elements during wayfinding in real-life environments, which is the process of obtaining information through individual's senses (Suzer et al., 2018). The same applies to navigation in a virtual environment, where people need to perceive and obtain knowledge from the virtual environment. Various VR technologies are available in today's market. These VR technologies have different characteristics, such as levels of immersion, interaction ability, and in particular, the costs associated with their installation and use for research purposes vary greatly (Ronchi et al., 2019). A number of studies showed that the usage of different VR technologies can have a varying impact on the user, particularly related to their sense of immersion and presence (Lee et al., 2010; Seibert & Shafer, 2018; Soler-Domínguez et al., 2020), usability (Boletsis & Cedergren, 2019), and motion sickness (Rand et al., 2005; Sharples et al., 2008). The differences in experiencing and perceiving the environments may cause people to behave differently during wayfinding and affect their wayfinding performance (e.g., Lee et al., 2010; Li & Giudice, 2013; Seibert & Shafer, 2018; Soler-Domínguez et al., 2020). Therefore, it has become important for researchers who are considering the usage of VR for wayfinding study to understand the assets and limitations of each VR technology.

Although studies have illustrated the effectiveness of VR to study pedestrian wayfinding behaviour, very few studies investigated the impact of different VR technologies on the actual pedestrian behaviour of participant's and their user experience. Several studies compared participant's performance of navigation tasks between Desktop VR and HMD VR (Hsieh et al., 2018; Ruddle et al., 1999; Ruddle & Péruch, 2004; Santos et al., 2009). Ruddle & Péruch (2004) found that there was no difference in wayfinding performance and route knowledge between Desktop VR and HMD VR. At the same time, Ruddle et al. (1999) found that people who used HMD VR travel quicker than people who used Desktop VR, while Hsieh et al. (2018) found that people find destinations quicker using Desktop VR than HMD VR and Santos et al. (2009) found better performance with Desktop VR compare to HMD VR. In these studies, the experimental environments were abstract mazes, and the tasks were relatively simple (Dogu & Erkip, 2000). More recently, one study used a HMD and a PC screen to compare task performance in a multi-level indoor environment, which showed that the performance of navigation tasks was better in the Desktop VR than in the HMD VR (Li & Giudice, 2013). However, another study compared pedestrian evacuation behaviour using smartphone-based HMD and CAVE and showed the consistency of pedestrian behaviour between the two VR systems (Ronchi et al., 2019).

In reality, pedestrians need to find their way in multi-level buildings and their wayfinding behaviour is affected by the layout of the architectural setting and the quality of the environmental information (Dogu & Erkip, 2000). Simple and abstract environments have a significant lack of detailed environmental elements that aid pedestrian wayfinding, such as architectural differentiation, distinguishable decorations, visual accessibility, and information signage, which are of great importance for people perceiving the environment (Weisman, 1981). Moreover, the multiple floor layouts in multi-level buildings require movements on a vertical space, which further increases the complexity of wayfinding. Since the complexity and difficulty of wayfinding in multi-level buildings increase (Passini, 1984a), findings featured in simplified environments cannot be directly generalised to multi-level buildings, which highlight the importance of investigating the differences in pedestrian behavioural outcomes in multi-level buildings and user experience between the adoption of different VR technologies.

In conclusion, VR technologies, especially HMD VR and Desktop VR, have been adopted increasingly to study pedestrian wayfinding behaviour. These VR technologies have very different characteristics regarding their usability and levels of immersion, presence, simulation sickness, which may cause people to perceive the virtual environment differently and behave differently in the virtual environment (Lee et al., 2010; Li & Giudice, 2013; Seibert & Shafer, 2018; Soler-Domínguez et al., 2020). Currently, the impact of different VR technologies on the behavioural outcomes of the experimental studies, especially pedestrian wayfinding behaviour studies, is undetermined. Moreover, the few studies that compared the behavioural outcomes of different VR technologies featured relatively simple experimental setups. Consequently, the findings of these VR studies cannot be generalised to complex buildings. Thus, up to the moment, no studies directly compared pedestrian wayfinding behaviour in complex multi-level buildings as well as user experience between the adoption of different VR technologies. In our study, we fill this gap by conducting four wayfinding experiments in a multi-level building using both HMD VR and Desktop VR, and comparing the resulting wayfinding behaviour and user experience of participants.

5.3 Materials and method

In the current study, we designed and conducted VR experiments with HMD VR and Desktop VR. The VR experiment was approved by the Human Research Ethics Committee of the Delft University of Technology (Reference ID 944). This section presents a detailed description of the experimental method.

5.3.1 The virtual environment

The virtual environment featured a virtual building that comprises four floors. Figure1 shows the front view of the virtual building. Each floor features two parallel hallways, multiple intersections, four staircases and four elevators. There are five major exits on the ground floor (see Figure 5.1). This virtual environment was originally developed as a VR research tool to study pedestrian wayfinding behaviour in a multi-level building (see Feng et al., 2022). The VR tool was developed using Maya and Unreal Engine 4 (UE4), which supports free navigation and collects pedestrian walking trajectories, head rotations and gaze points automatically.

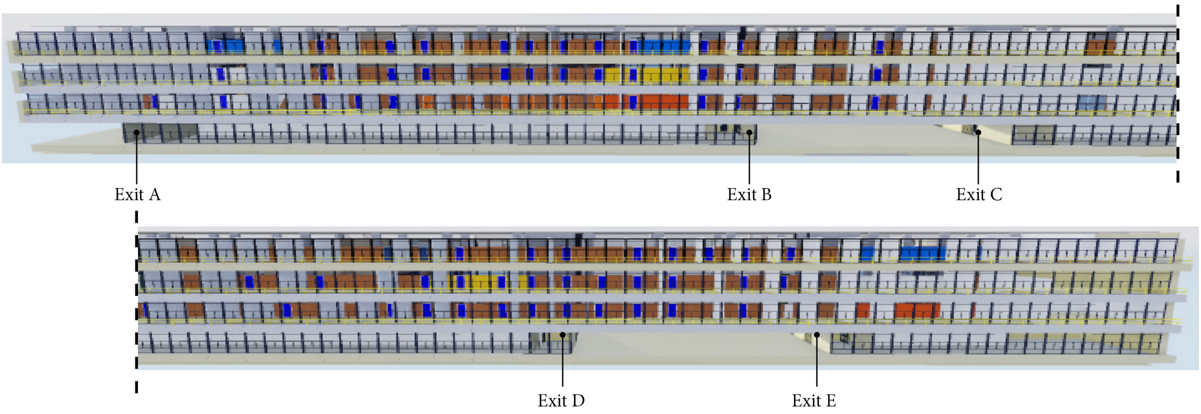


Figure 5. 1: The front view of the virtual building.

The virtual building is based on the building of the Faculty of Civil Engineering and Geoscience of the Delft University of Technology. In addition to the overarching geometry (i.e., the internal layout of the building, walls, escalators, and staircases), detailed environmental elements were also included in the virtual environment in order to improve the accuracy of the building's representation and increase its realism. Weisman (1981) identified four classes of environmental elements that influence pedestrian wayfinding in buildings, including (1) visual access which provides views that one can see other parts of the building from a given location, (2) architectural differentiation, which is the difference of objects in the building regarding size, colour, location, etc., (3) signs to provide identification or directional information, and (4) plan configuration of the building (Hölscher et al., 2005; Raubal & Worboys, 1999). To implement these elements, detailed environmental objects were added in the virtual building accordingly, namely (1) glass windows to represent visual access, (2) various furniture such as chairs, cabinets, and tables that represent architectural differentiation, (3) evacuation signs, exit signs, and room numbers represent signs, and (4) floor plan represent plan configuration (see Figure 5.2). The colour and texture of these environmental objects in the virtual environment were modelled as close as possible to realistically represent the real-world experience.

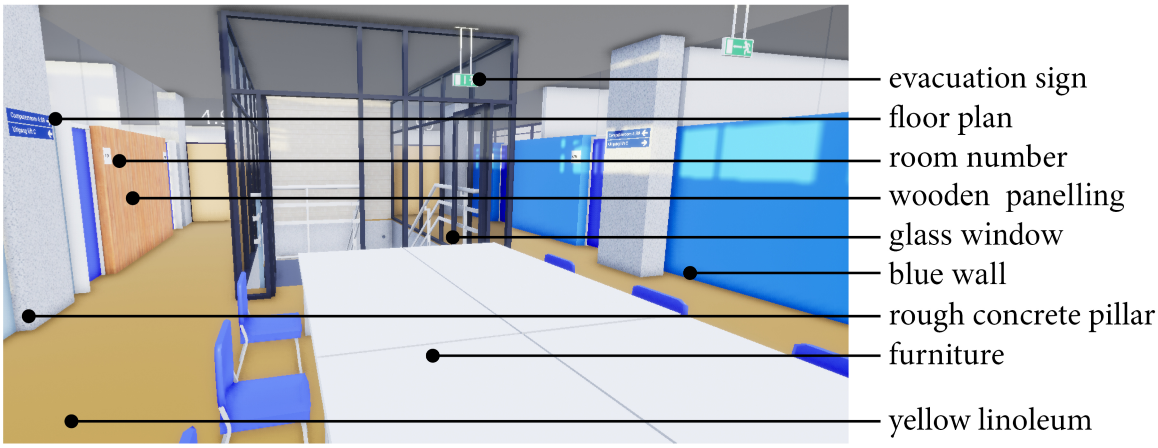


Figure 5. 2: Screenshots of the details in the virtual building.

In the virtual environment, the participants have a first-person perspective. The participant's viewpoint is represented by a virtual camera. Participants could move in the virtual environment at a maximum constant speed of 140 cm/s. This speed limit was determined based on pilot tests, which to ensure that participants could have a similar walking pace as in real-life environments without causing simulation sickness (e.g., Choi et al., 2014; Fitzpatrick et al., 2006).

5.3.2 Experimental setup

The versions of HMD VR and Desktop VR of the VR research tool were developed for this study. This sub-section introduces the general setup of the experiment and the setup of HMD VR and Desktop VR.

5.3.2.1 General technique setup

The VR experiment with the HMD group and the Desktop group were both conducted in the same room (4.6 m x 3.5 m) with a 2.5 m high ceiling, illuminated by fluorescent lighting, with neither reflective surfaces nor exposure to natural lighting. In both groups, the same computer was used, which was equipped with a AMD Ryzen 7 2700X with a 3.7 GHz CPU, MSI NVIDIA GeForce RTX 2080 graphics card, 16 GB system memory and a Samsung 970 EVO MZ-V7E500BW 500GB SSD. Participants also wore a pair of over-ear headphones to receive audio information and isolate themselves from the noise of the real-life environment. The software packages used for running the virtual environment were UE4 and SteamVR.

5.3.2.2 Setup of the HMD VR

The HTC Vive system was employed for the experiment of the HMD group, which mainly included one HMD, one wireless hand controller and two base stations. Figure 5.3 shows the devices included in the employed system. The HMD has 2160 x 1200 pixels combined resolution (i.e., 1080 X 1200 per eye), a 110-degree field of view and a 90 Hz refresh rate for both screens.

A combination of an open-world navigation solution and a steering locomotion was adopted in the HMD group, which means participants had continuous movement with 'step-by-step' effects in the virtual environment when slowing down. The steering locomotion method was adopted because it generates less motion sickness compared to the teleportation method during the prototype tests. Moreover, this combination provides greater navigational benefits and is more natural to use than walking on a treadmill (Mallaro et al., 2017; Riecke et al., 2010; Ruddle & Péruch, 2004). Participants used one hand controller to move through the virtual environment. By holding the home pad of the controller, the participant moved forward, and by releasing the home pad, the participant stopped moving. The direction of the movement was controlled by the participant's head orientation.

Tracking of the participants' positions and orientations in the virtual environment was achieved by means of the two base stations. These two base stations were placed opposite each other and connected via a sync cable. HTC Vive provides a room-scale technology that allows the user to walk freely, and the HMD features SteamVR Tracking technology which provides 360-degree head-tracking. The participants were tracked within a space of 3.4m x 2.5m in the experimental room.

Figure 5. 3: A participant using the HMD VR during the experiment.

5.3.2.3 Set up of the Desktop VR

The participants of the Desktop group viewed the virtual environment via a 24-inch desktop monitor (AOC G2460PF). The monitor is 565.4 mm long and 393.6 mm high. It has 1920 x 1080 resolution, a refresh rate of 144Hz and 1ms response time. The monitor was placed on top of a rectangular table (90 cm x 150 cm) in the same experimental room as the HMD group (see Figure 5.4). The horizontal distance between the monitor and the participant was approximately 60 cm.

A combination of an open-world navigation solution and a smooth artificial locomotion style was adopted for the Desktop VR. Participants' positions and orientations in the virtual environment were tracked via the virtual camera that represented participants' viewpoints. This combination allows participants to move artificially in the virtual building via the keyboard and mouse (Boletsis & Cedergren, 2019). The participant moved forward by means of the keyboard key (i.e., 'w'), and changed the direction of view and movement by rotating the mouse. As a result of this navigation solution, participants' movement in the virtual building is continuous. Moreover, the setup allowed participants to have 360-degree freedom to move on the horizontal level and 360-degree views on both horizontal and vertical levels.

Figure 5. 4: A participant using the Desktop VR during the experiment.

5.3.3 Experiment design

A single-factor between-subjects experimental design was used for this study to reduce the learning effects because of repetitive exposure. Literature identifies that repetitive exposure to the same environment affects pedestrian wayfinding performance (Lin et al., 2019; Vilar et al., 2013a). Especially in the current study, the experimental environment and tasks are exactly the same for both groups. The VR experiments featured two different experiment settings but the only difference between both setups is the HMD VR versus the Desktop VR. Half of the participants were pseudo-randomly assigned to the HMD group and the other half to the Desktop group to ensure similar gender distributions between the two groups. During the experiment, the participants of both groups were asked to complete four wayfinding tasks during the experiment, including three wayfinding tasks under normal conditions and one wayfinding task under the evacuation condition.

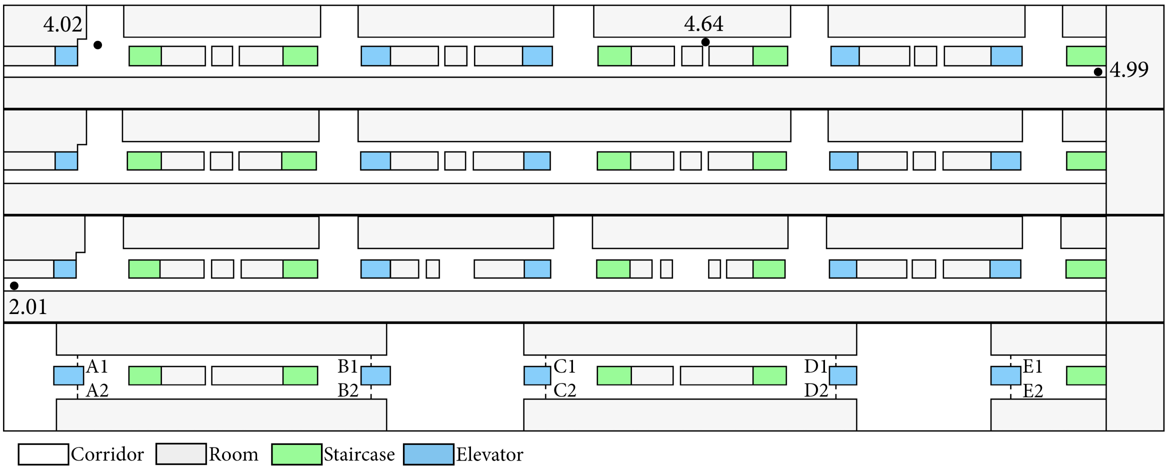


Figure 5. 5: The layout of the virtual environment.

Figure 5.5 shows the abstract layout of the experimental environment. First, pedestrian wayfinding behaviour across the horizontal level was investigated. Participants were initially positioned in front of room 4.02 and were asked to find their way from room 4.02 to room 4.99 (see Figure 5.5), which ensured they need to cross from one main corridor to the other and walk the length of the building. Second, pedestrian wayfinding behaviour (including staircase choice) at the vertical level was investigated. Participants were asked to find their way from room 4.99 to room 2.01. This task required participants to move between floors and walked the length of the building. Third, pedestrian wayfinding behaviour across both the horizontal and vertical levels was investigated. Participants were asked to find their way from room 2.01 to room 4.64, which forced them to switch floors and main corridors. The fourth task of the experiment was to investigate pedestrian wayfinding and evacuation choice during an evacuation scenario. When participants arrived at room 4.64, the evacuation alarm was triggered with a voice message: “Attention, please leave the building using the emergency exits as indicated. Do not use the elevators.”. This evacuation alarm is the same alarm sound that is used during the real-life evacuation procedure at the modelled faculty building. Participants were asked to evacuate and find an exit. Once participants arrived at an exit, the experiment ended.

5.3.4 Experimental procedure

A consistent experimental procedure was used for the HMD group and the Desktop group. The procedure included five major stages:

1. Introduction: When participants arrived at the experimental room, they first read the instruction letter about the experiment, including the usage of the HMD VR or the Desktop VR, the procedure of the experiment and safety measures in case of any discomfort during the experiment. Participants were also informed that they had the right to stop the experiment at any time.

2. Practice: Participants then were instructed to wear the HMD or sit in front of the desktop monitor. During the practice session, participants were asked to find their way from A to B to C in a simple virtual scenario. The purpose of this session was to familiarise participants with using the devices and how to navigate through virtual space. This session ended when participants felt fully confident and comfortable with the devices to start the formal experiment, which generally lasted approximately three minutes. Afterwards, participants were teleported to the virtual building to start the formal experiment.

3. Formal experiment: At the beginning of the formal experiment, participants were initially located in front of room 4.02 in the virtual building. The task information appeared on the screen to instruct participants to begin the first task. Once participants arrived at the task's destination, the next task was depicted. At the beginning of the fourth task, the evacuation alarm sound was automatically triggered. Once the participants reached one of the exits, the formal experiment was terminated and a message popped up showing 'Task complete'.

4. Post-experiment questionnaire: Once the participants completed the formal experiment, they were asked to fill in the post-experiment questionnaire in the same experimental room.

5. Health check: After filling the questionnaire, the experimenter checked with participants whether they felt any discomfort. Participants were only allowed to leave if they had a normal state of health.

5.3.5 Data collection

Two types of data were collected during the experiment, namely the behavioural data pertaining to the participant's movement in the VR environment and questionnaire data pertaining to user experience with the VR system. In order to identify significant differences regarding pedestrian behaviour data and questionnaire data between the two groups, a two-step statistical procedure was applied. First, the Shapiro–Wilk test was conducted to test distribution normality, which is an appropriate normality test for sample sizes that are below 50 (Branzi et al., 2017). Second, if the data was found to be normally distributed, the independent t-test was carried out to determine whether the differences were significant. Otherwise, the nonparametric Mann-Whitney U test was used. For all statistical analyses, the significance level was set at 0.05. Moreover, the effect size was also calculated.

5.3.5.1 Pedestrian behaviour data

Each participant's behaviour in the virtual environment was recorded. Participant's positions, head rotations (i.e., yaw, pitch, and roll), gaze points, together with timestamp were recorded at a frequency of 10 Hz within UE4. According to the identified wayfinding behaviour metrics in literature (Section 5.2.1), these data were translated into three types of metrics regarding participant's wayfinding *behaviour*, namely (1) participant's decision making (e.g., wayfinding strategy, route choice, and exit choice), (2) observation behaviour (e.g., head rotation and gaze point), and (3) wayfinding task performance (i.e., travel time, travel distance, and travel speed). Based on the definition of these metrics in literature, the explanation of each adopted metric for data analysis is listed below:

1. Participant's decision making

(1) *The wayfinding strategy*: The usage of the wayfinding strategy of each participant during each task is analysed. Here, we take the start position, room 4.02 as the well-known parts of the building to distinguish between central point strategy and floor strategy, namely to identify whether participants pass room 4.02 during the current task and the precious task. For instance, if one participant passes room 4.02 during task 2 and accordingly passes 4.02 again during task 3, we record the central point strategy; if one goes directly to the fourth floor and does not pass room 4.02 again during task 3, we record the floor strategy for this participant. Figure 5.6 illustrates the wayfinding strategies that were adopted by one participant during the experiment. This participant used the central point strategy during task 1 (orange trajectory), the direction strategy during task 2 (green trajectory), and the floor strategy during task 3 (blue trajectory) and task 4 (red trajectory).

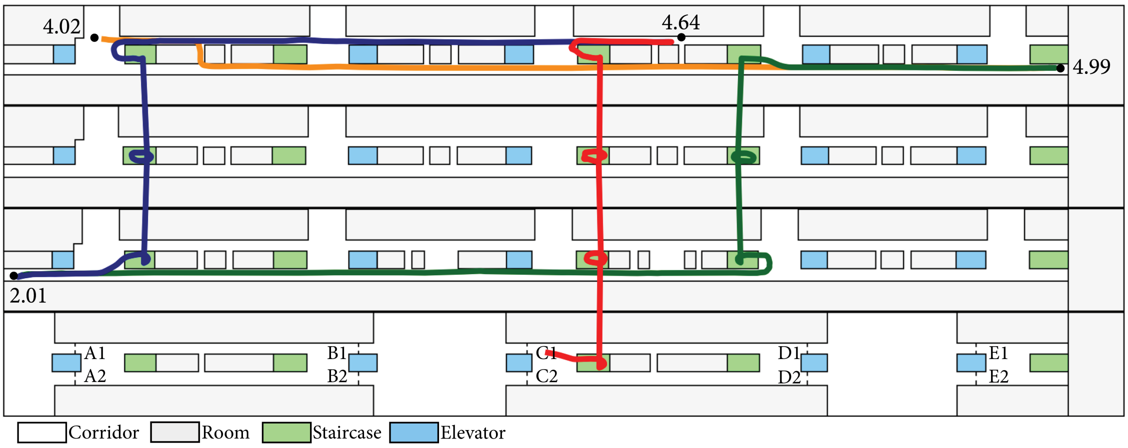


Figure 5. 6: An illustration of different wayfinding strategies adopted by one participant during the experiment.

(2) *The usage of paths*: A path is defined as the smallest section connected by two decision points that located along the two big parallel corridors. The distribution of used paths is analysed.

(3) *The usage of decision points*: Since in the current experiment participants face the same number of decision points, we analyse the distribution of decision points that each

participant used, namely the decision points where a participant decides to cross from one side to another side of the building.

(4) *The usage of staircases*: The distribution of staircases used by participants is analysed. Figure 5.7 shows the distribution of one individual's usage of path, decision point and staircase during task 2.

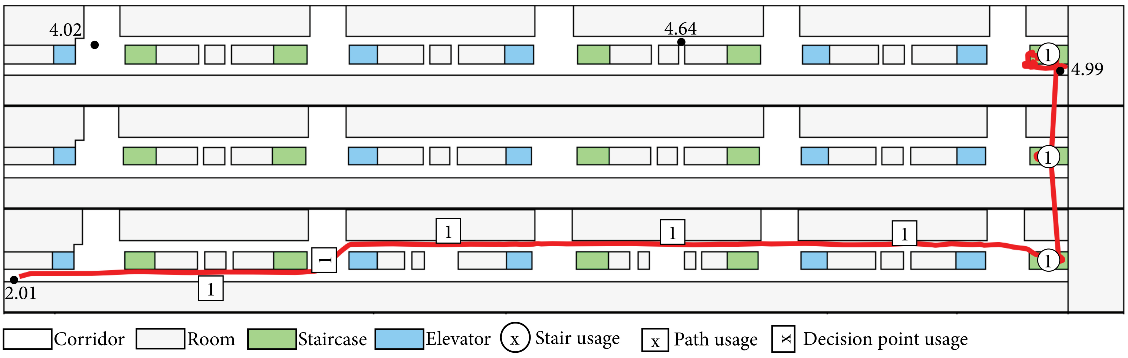


Figure 5. 7: Distribution of one individual's usage of path, decision point and staircase during task 2.

2. Observation behaviour

In order to better understand participant's observation behaviour during wayfinding tasks, both head rotation data and gaze point data is analysed. For the head rotation analysis, in order to limit noise caused by participants who shake their heads while walking (Zhang et al., 2021), we only focus on head rotation data along the Yaw axis. The Yaw movement is the head rotation on the horizontal plane between -180° and 180° (i.e., rotate the head left/right). Participants' average head rotation change $\bar{Y}$ during each task is calculated by Formula 5.1 and 5.2:

$$Y(t) = \min(360 - |Y_{t+dt} - Y_t|, |Y_{t+dt} - Y_t|) \tag{5.1}$$

$$\bar{Y} = \frac{\sum_1^T Y}{T} \tag{5.2}$$

where $Y(t)$ is the instantaneous rotation change, Y_t is the current Yaw coordinate of the participant at t timestep and dt is the timestep interval, T is the travel time of the task.

The point of interest in the virtual environment is determined using a gaze point analysis. Gaze points identify the locations where participants rotate their head and the direction of the head hits the geometry in the environment. Please note, in the current paper, we calculated gaze points based on participants' head directions. We assume that participants always look straight ahead and when participants look at certain objects in the virtual building, the direction of the head hits the geometry in the environment and counts as a gaze point. The density of the dots indicates the number of gaze points and time spent on the AOI (area of interest). The denser the gaze points, the longer participants looked towards that area and the slower the walking speed of participants passing that area. More sparse distribution of the dots indicates that fewer gaze points were created, which means that participants paid less attention to that area and passed by quickly.

3. Wayfinding task performance

Wayfinding task performance is measured in terms of travel time, travel distance, and average speed of each task in both groups.

Travel time is defined as the time participants spent from the starting location to the destination location during each task. It is one of the important criteria to measure the performance of pedestrian wayfinding tasks (Suzer et al., 2018).

Travel distance is defined as the total distance that participants travelled from the starting location to the destination location during each task. The travel distance is the sum of travel distance on the corridor D_c and travel distance on the staircase D_s, which are calculated using Formula 5.3 and 5.4:

$$D_c = \sum_{1}^{T_c} \sqrt{(x_{t+dt} - x_t)^2 + (y_{t+dt} - y_t)^2} \tag{5.3}$$

$$D_s = \sum_{1}^{T_s} \sqrt{(x_{t+dt} - x_t)^2 + (y_{t+dt} - y_t)^2 + (z_{t+dt} - z_t)^2} \tag{5.4}$$

where x_t, y_t, z_t, are the x-coordinate, y-coordinate and z-coordinate of the participant at t timestep, dt is the data recording timestep (0.1s). T_c is the travel time on the horizontal plane and T_s is the travel time on the vertical plane.

The average speed per task is computed for each participant by dividing the total travel distance by the total travel time spent during each task.

5.3.5.2 User experience data

The personal features and experiences of each participant regarding the virtual experiment were collected via the questionnaire. The questionnaire contained five sections: (1) participant's information, which included their socio-demographic information and their experience with VR, computer gaming and the experimental building in real-life, (2) the face validity questionnaire, which assessed whether a simulator measures what it is intended to measure (Kaptein et al., 1996), (3) the Simulator Sickness Questionnaire (Kennedy et al., 1993), which determined if participant's experience sickness throughout the experiment, (4) the System Usability Scale (Brooke, 1996), which assessed the usability of the applied VR systems, and (5) the Presence Questionnaire (Witmer et al., 2005), which measured participant's sense of presence in the virtual environment. This comprehensive questionnaire was used in order to ensure that the authors are able to study and compare user experience in the virtual environment in great detail.

5.3.6 Participant recruitment & characterisation

A priori power analysis was conducted using G*Power 3.1 in order to estimate the required sample size (Faul et al., 2009). The result indicated that a total sample of 68 participants would be needed to detect large effects (d = 0.80) with 90% power using an independent samples t-test between means (two-group). A total sample of 43 participants would be needed to detect large effects (w = 0.50) with 90% power using the Chi-square test. Effect size describes the magnitude of differences found between two groups and larger differences lead to more powerful tests (Gheisari, 2013). In this study, the effect size is chosen based on Cohen's definition of large effect size (Cohen, 1988) and similar studies (Ozcelik & Becerik-Gerber, 2018; Paes et al., 2021) that adopted effect sizes of 0.7 and 0.69, respectively.

Participants were recruited by means of advertisements at the Delft University of Technology (i.e., e-mails, websites, flyers, posters, social media and in-classroom promotions). In this stage, potential participants were told that the purpose of the experiment was to investigate the usage of VR to study pedestrian behaviour. In order to not bias participants' behaviour, no information was provided regarding the actual VR experiment.

The VR experiments were carried out from 27th November 2019 to 18th December 2019. In this study, a total sample of 72 participants joined the experiment, 38 participants took part in the HMD group and 34 took part in the Desktop group. All participants volunteered to take part in the experiment and did not receive compensation for their participation. All participants had normal or corrected-to-normal visions and normal hearing capabilities. Two participants from the HMD group asked to take a break during the experiment and did not finish the whole experiment, so they were excluded from further analysis.

The participants were between 22 and 64 years old (M = 27.85, SD = 6.83) in the Desktop group, and between 17 to 41 years old (M = 28.66, SD = 6.00) in the HMD group. The Mann-Whitney U test showed that there was no significant difference in age between the two groups (U = 486.5.5, p = 0.07, d = 0.13). Table 5.1 presents a summary of the characteristics of the participants in two groups. All participants in both groups had a certain familiarity with the faculty building featuring in the VR experiment. Most of the participants received a Bachelor's degree or higher level of education. More than half of the participants had never or seldom tried VR before; 80.55% in the HMD group and 64.71% in the Desktop group. The familiarity with computer gaming experience was relatively high (i.e., between moderately familiar and very familiar) in the HMD group (66.66%) and the Desktop group (73.54%). Original questions related to 'Familiarity with the faculty building', 'Highest education level', 'Previous experience with VR', and 'Familiarity with any computer gaming' can be found in Appendix C. Chi-square tests showed that there were no significant differences found between two groups regarding gender ($X^2(1, N = 70) = 0.71$, p = 0.399, phi = 0.24), familiarity with the faculty building ($X^2(3, N = 70) = 3.20$, p = 0.361, v = 0.21), the highest level of education ($X^2(3, N = 70) = 7.05$, p = 0.070, , v = 0.32), experience with VR ($X^2(4, N = 70) = 5.71$, p = 0.222, v = 0.29) and familiarity with computer gaming ($X^2(4, N = 70) = 2.36$, p = 0.669, v = 0.18). The Chi-square and Mann-Whitney U tests are statis- tical hypothesis tests that identify whether a statistically significant difference between the participant population of both groups exists. The results indicated that there are no differences in participants' characteristics (i.e., age, gender, familiarity with the faculty building, highest education level, previous experience with VR, and familiarity with any computer gaming) between the two groups. Thus, participants' characteristics do not impact the further comparison of pedestrian way- finding behaviour and user experience between the two groups.

Table 5. 1: The descriptive information of participants.

Descriptive information	Category	HMD	Desktop
Gender	Male	17 (47.22%)	24 (70.59%)
	Female	19 (52.78%)	10 (29.41%)
Familiarity with the faculty building	Not at all familiar	0 (0.00%)	0 (0.00%)
	A-little familiar	1 (2.78%)	5 (14.71%)
	Moderately familiar	5 (13.88%)	4 (11.76%)
	Quite-a-bit familiar	9 (25.00%)	7 (20.59%)
	Very familiar	21 (58.34%	18 (52.94%)
Highest education level	High school or equivalent	5 (13.88%)	0 (0.00%)
	Bachelor degree or equivalent	6 (16.67%)	10 (29.41%)
	Master degree or equivalent	19 (52.78%)	21 (61.77%)
	Doctoral degree or equivalent	6 (16.67%)	3 (8.82%)
Previous experience with VR	Never	11 (30.55%)	7 (20.59%)
	Seldom	18 (50.00%)	15 (44.12%)
	Sometimes	6 (16.67%)	9 (26.47%)
	Often	1 (2.78%)	0 (0.00%)
	Very often	0 (0.00%)	3 (8.82%)
Familiarity with any computer gaming	Not at all familiar	6 (16.67%)	3 (8.82%)
	A-little familiar	6 (16.67%)	6 (17.64%)
	Moderately familiar	8 (22.22%)	5 (14.71%)
	Quite-a-bit familiar	7 (19.44%)	7 (20.59%)
	Very familiar	9 (25.00%)	13 (38.24%)

5.4 Results

This study examined the difference in participants' wayfinding behaviour and user experience as a result of the adoption of HMD VR and Desktop VR. To this end, pedestrian wayfinding behaviour is first analysed and compared in section 5.4.1. Secondly, the user experience of VR is analysed and compared in terms of realism, simulation sickness, feeling of presence, and system usability in section 5.4.2.

5.4.1 Pedestrian behaviour

As mentioned above, pedestrian wayfinding behaviour can be evaluated based on three levels of metrics including decision making, observation behaviour, and wayfinding task performance. Using these metrics, this section presents an analysis of pedestrian behavioural data collected during the VR experiment, namely (1) pedestrian route and evacuation exit choice, (2) observation behaviour, and (3) wayfinding task performance.

5.4.1.1 Route and evacuation exit choice behaviour

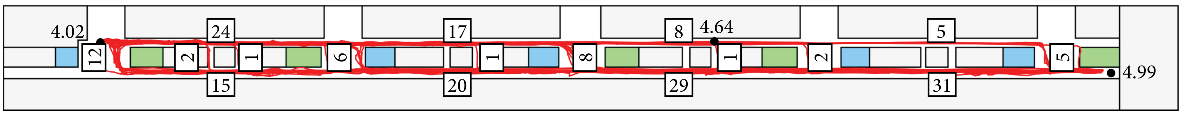
In order to better understand pedestrians' route and exit choice during the wayfinding tasks, this section analyses pedestrian route and exit choice during each task, including (1) the wayfinding strategy, (2) the usage of paths, (3) the usage of decision points, and (4) the usage of staircases.

1. Task 1

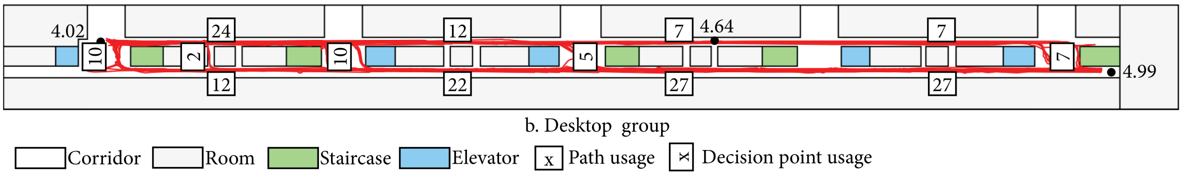
Figure 5.8 shows the aggregated movement trajectories of participants during the first task (room 4.02 – room 4.99), including the usage of paths and decision points. The central point strategy was employed by 24 (66.67%) participants in the HMD group and 24 participants (70.59%) in the Desktop group. These participants first moved along the corridor where their start position was. In the HMD group,12 participants (33.33%) used the direction strategy while 10 participants (29.41%) in the Desktop group used the direction strategy. They first moved in the direction of the target room. There was no significant difference in wayfinding strategies according to the Chi-square test, $X^2(1, N = 70) = 0.125$, $p = 0.98$, $phi = 0.04$.

Regarding the usage of paths, the Chi-square test showed there was no significant difference in the usage of paths between the Desktop group and the HMD group during task 1, $X^2(7, N = 287) = 1.62$, $p = 0.978$, $v = 0.08$.

Fisher exact test showed there was no significant difference in the usage of decision points between the Desktop group and the HMD group during task 1 ($p = 0.626$, $v = 0.31$). In total, the number of used decision points was 38 in the HMD groups and 34 in the Desktop group.



a. HMD group



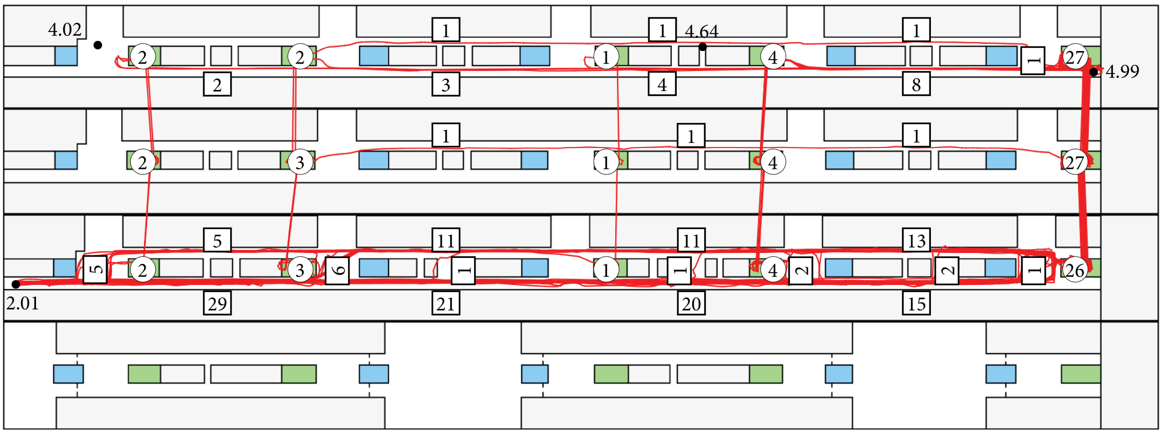
b. Desktop group

Figure 5. 8: Visualisation of the participants' movement trajectories and the frequency of path and decision point usage during task 1.

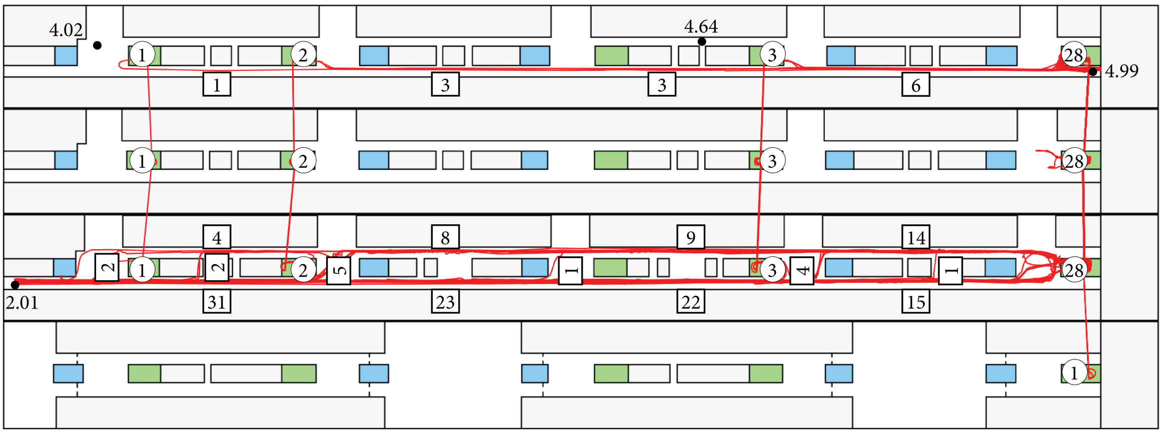
2. Task 2

Figure 5.9 shows the aggregated movement trajectories of participants during the second task (room 4.99 – room 2.01). In the HMD group and the Desktop group, 27 participants (75.00%) and 28 participants (82.35%) employed the floor strategy, respectively. The direction strategy was employed by 9 participants (25.00%) in the HMD group and 6 participants (17.65%) in the Desktop group. There was no significant difference in adopted wayfinding strategy according to the Chi-square test, $X^2(1, N = 70) = 0.561$, $p = 0.454$, $phi = 0.09$.

Fisher exact test revealed that there were no significant differences in the usage of paths ($p = 0.999$, $v = 0.16$), decision points ($p = 0.527$, $v = 0.52$) and staircases ($p = 0.999$, $v = 0.17$) between the Desktop group and the HMD group during task 2.



a. HMD group



b. Desktop group

▭ Corridor ▭ Room 🟩 Staircase 🟦 Elevator ⓧ Stair usage ☐x Path usage ☐x Decision point usage

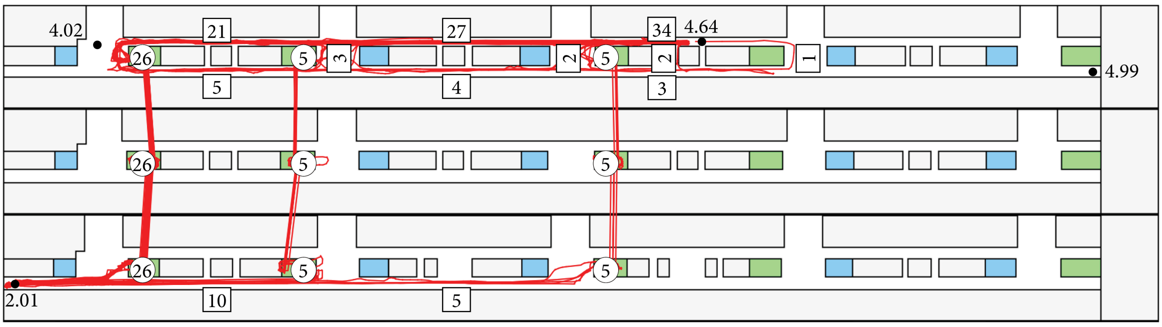
Figure 5. 9: Visualisation of the participants' movement trajectories and the frequency of staircase, path and decision point usage during task 2.

3. Task 3

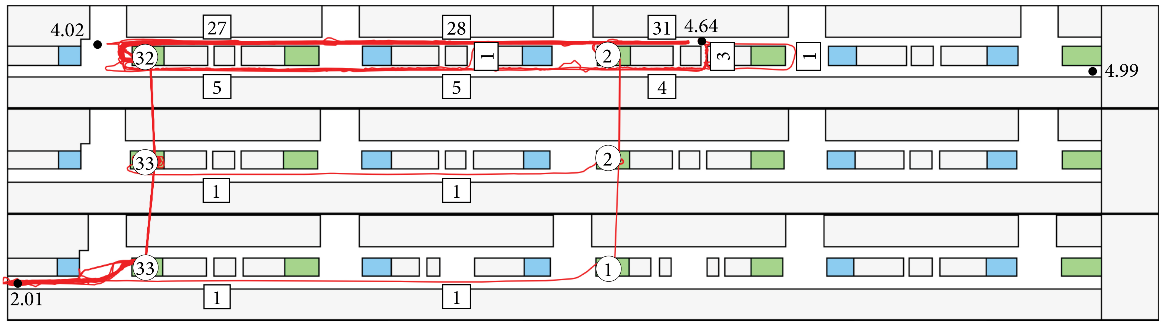
Figure 5.10 shows the aggregated movement trajectories of participants during the third task (room 2.01 – room 4.64). In the HMD group, 26 participants (72.22%) used the floor strategy and 10 participants (27.78%) employed the direction strategy. In the Desktop group, 33 participants (97.06%) employed the floor strategy and 1 participant (2.94%) employed the direction strategy. There was a significant difference in the wayfinding strategy between two groups according to the Chi-square test, $X^2(9, N = 213) = 8.144$, $p = 0.004$, $phi = 0.34$.

Figure 5.10 illustrates the distribution of the usage of paths, decision points, and staircases in both groups. The Fisher exact test revealed that there was no significant difference in the usage of paths ($p = 0.119$, $v = 0.25$) between the Desktop group and the HMD group during task 3. However, there were significant differences in the usage of decision points ($p = 0.021$, $v = 0.92$) and staircases ($p = 0.002$, $v = 0.33$) between the two groups during task 3.

These results indicated that although the usage of paths was similar, the usage of decision points and staircases were significantly different.



a. HMD group



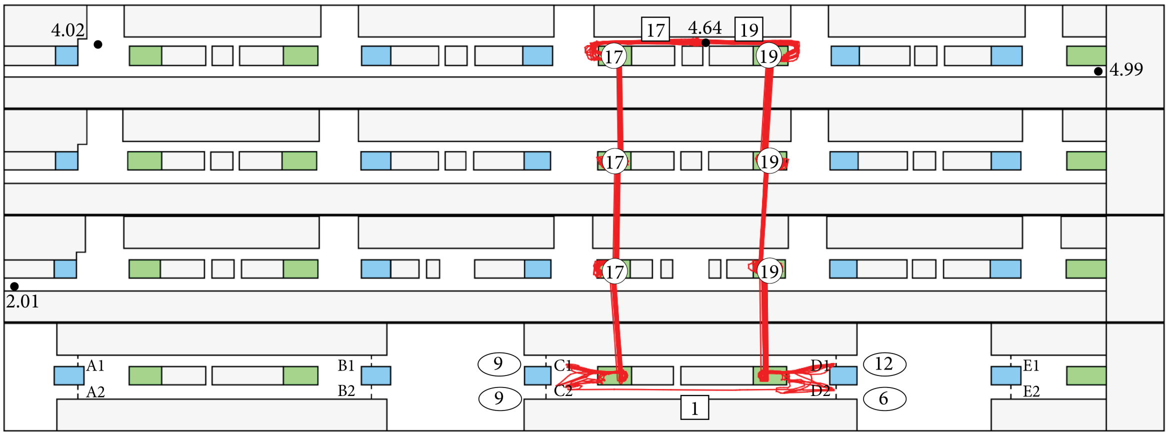
b. Desktop group

Figure 5. 10: Visualisation of the participants' movement trajectories and the frequency of staircase, path and decision point usage during task 3.

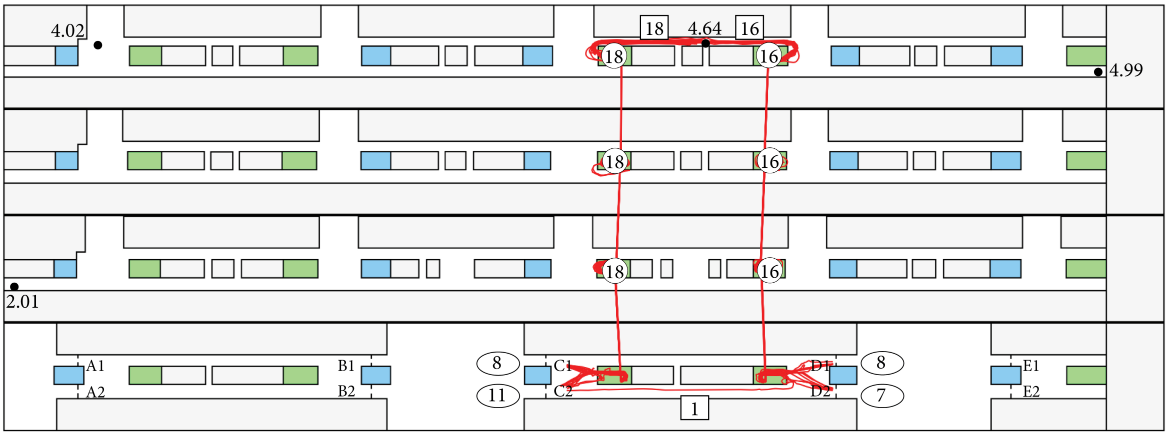
4. Task 4

Figure 5.11 shows the aggregated movement trajectories of participants during the evacuation task (room 4.64 - an exit). Regarding the usage of the wayfinding strategy, all participants chose to go down first, thus the floor strategy was employed by both groups. The Chi-square test showed there were no significant differences in the usage of paths, $X^2(2, N = 72) = 0.230$, $p = 0.891$, $v = 0.06$, and the usage of staircases, $X^2(5, N = 210) = 0.686$, $p = 0.984$, $v = 0.06$.

Even though five main exits were available, only exits C (i.e., C1 and C2) and D (i.e., D1 and D2) were chosen, which are the nearest two exits for the participants. In the HMD group, 9 participants chose exit C1, 9 participants chose exit C2, 12 participants chose exit D1, and 6 participants chose exit D2. In the Desktop group, 8 participants chose exit C1, 11 participants chose exit C2, 8 participants chose exit D1, and 7 participants chose exit D2. There was no significant difference in the exit usage between the two groups using the Chi-square test, $X^2(3, N = 70) = 1.079$, $p = 0.782$, $v = 0.12$.



a. HMD group



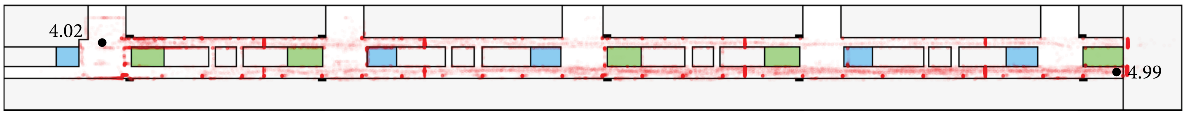
b. Desktop group

☐ Corridor ▨ Room 🟩 Staircase 🟦 Elevator ⓧ Stair usage ☒ Path usage ⬭ Exit choice

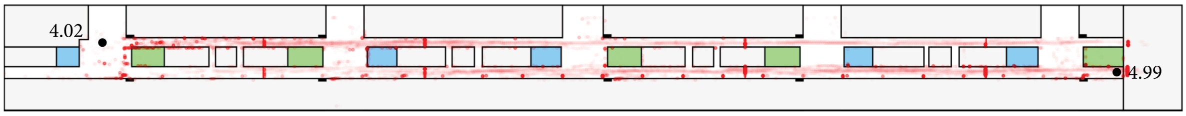
Figure 5. 11: Visualisation of the participants' movement trajectories and the frequency of staircase, path, decision point and evacuation exit usage during task 4.

5.4.1.2 Observation behaviour

For task 1, the distributions of the head rotation change $\bar{Y}$ of both groups were not normally distributed (Shapiro–Wilk test, *p* < .001). Thus, the non-nonparametric Mann-Whitney U test was performed, which showed that there was a significant difference in head rotation change between the two groups (*U* = 372, *p* = 0.002, *d* = 0.44). The average rotation change of HMD group (*M* = 7.38°/s, *SD* = 4.00°/s) was significantly higher than the Desktop group (*M* = 5.55°/s, *SD* = 4.24°/s). Figure 12 shows the aggregated distributions of participants' gaze points during task 1. Here, room numbers (i.e., red dots along with the rooms), fire doors (i.e., red perpendicular in the corridors), and floor plans (i.e., red perpendicular near the floor plans) were the main attractions. Figure 5.12, furthermore, illustrates that participants from the HMD group had denser gaze points near room numbers and fire doors, which indicated that participants had more 'looking around' behaviour and paid more attention to room numbers and fire doors in the HMD group than the Desktop group.



a. HMD group

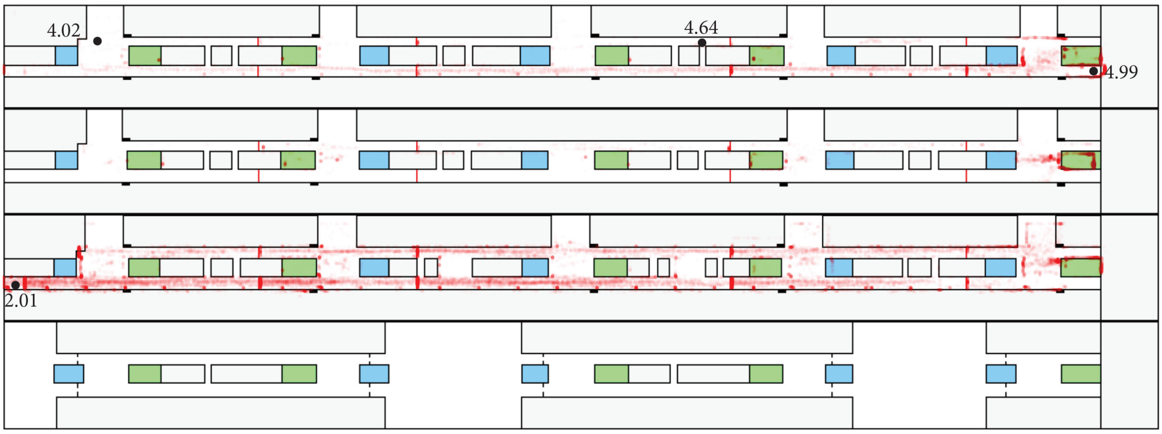


b. Desktop group

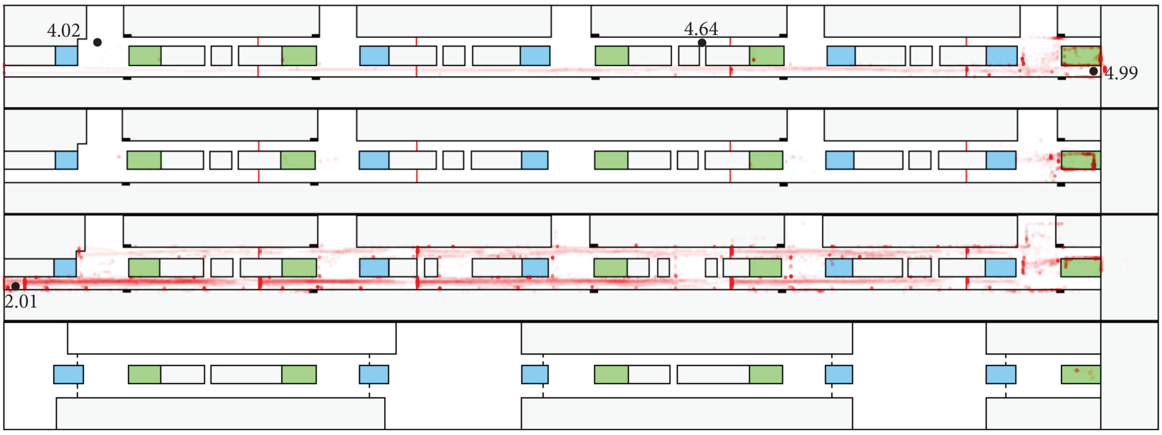
☐ Corridor ☐ Room 🟩 Staircase 🟦 Elevator ▬ Floor plan | Fire door

Figure 5. 12: Distribution of participants' gaze points during task 1.

For task 2, the Shapiro–Wilk test rejected that the head rotation change of both groups followed a normal distribution ($p < .05$). The Mann-Whitney U test showed that there was a significant difference in the head rotation change between the two groups ($U = 461.5$, $p = 0.039$, $d = 0.17$). Participants had significantly higher head rotation change in the HMD group ($M =$ 10.71°/s, $SD = 2.52$°/s) than the Desktop group ($M = 10.17$°/s, $SD = 3.73$°/s). Figure 5.13 shows the aggregated gaze distributions of participants during task 2. The result of head rotation change is further supported by the gaze distributions, which illustrated that the AOI was smaller in the Desktop group than the HMD group. Moreover, the density of the resulting gaze points was higher in the HMD group. Thus, fewer room numbers and fire doors were scanned by the participants in the Desktop group.



a. HMD group

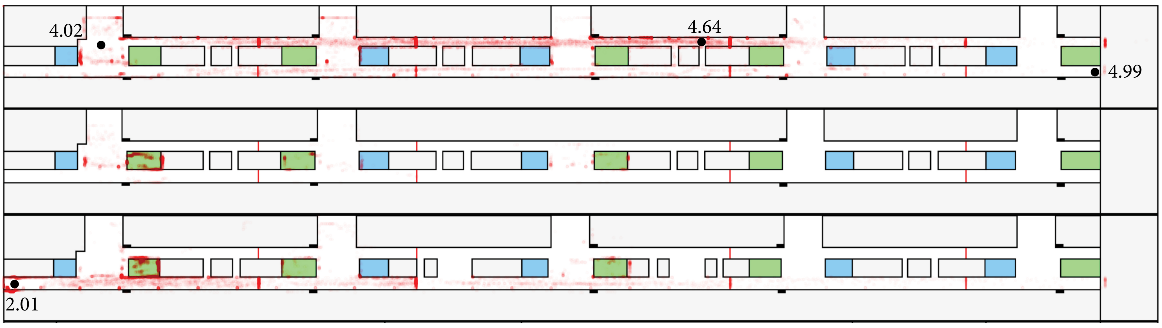


b. Desktop group

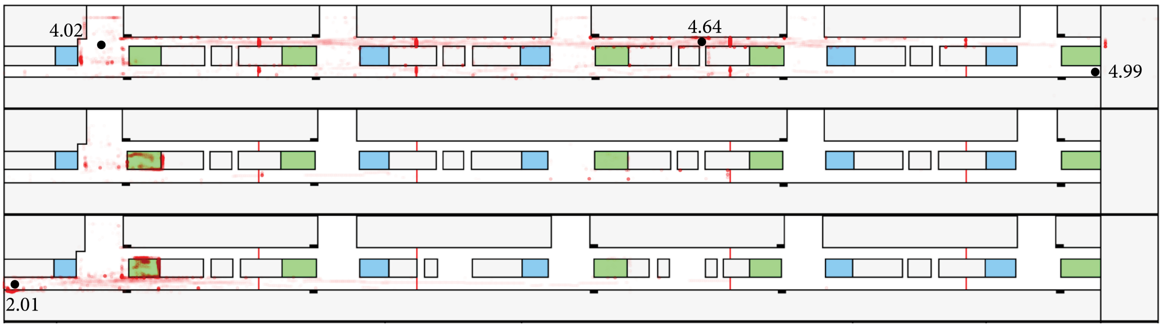
☐ Corridor ☐ Room 🟩 Staircase 🟦 Elevator ▬ Floor plan | Fire door

Figure 5. 13: Distribution of participants' gaze points during task 2.

For task 3, the normal distribution of head rotation change was rejected for both groups (Shapiro–Wilk test, $p < 0.05$). The average head rotation change is 13.61°/s (*SD* = 3.41°/s) and 13.05°/s (*SD* = 3.76°/s) respectively in the HMD group and the Desktop group. The Mann-Whitney U test showed there was no significant difference in head rotation change between the two groups ($U = 538$, $p = 0.194$). Figure 5.13 shows the gaze distributions of participants during task 3. Also in this task, the gaze points of the room number and fire doors were major attractions in the environment for both groups.



a. HMD group

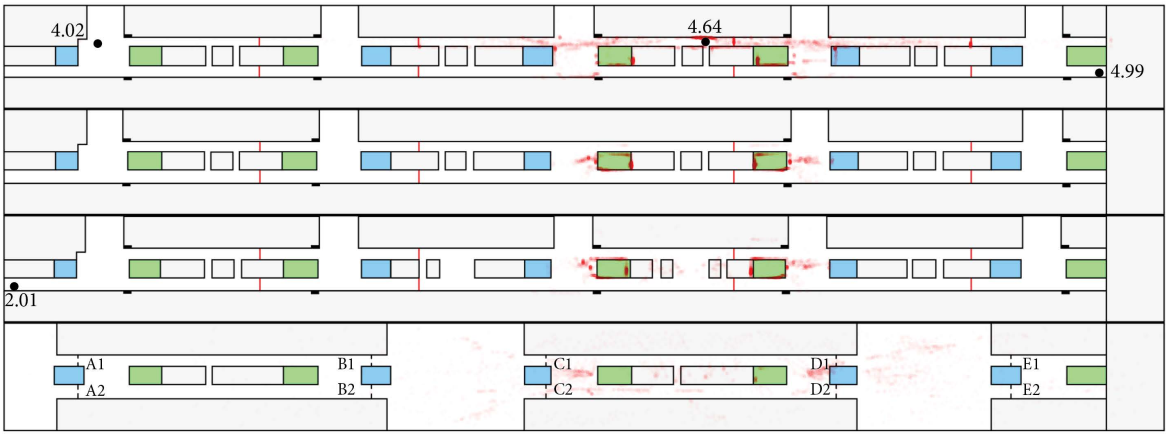


b. Desktop group

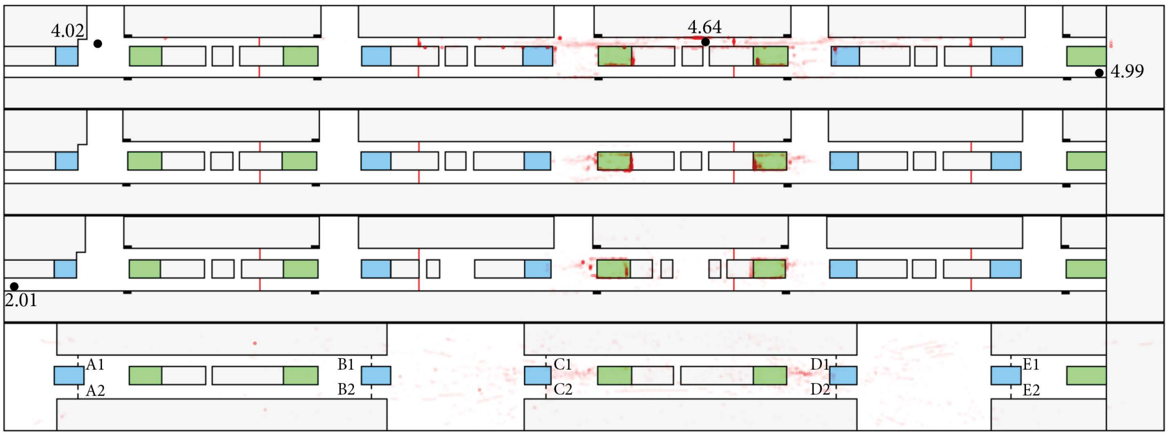
▭ Corridor ▭ Room 🟩 Staircase 🟦 Elevator ■ Floor plan | Fire door

Figure 5. 14: Distribution of participants' gaze points during task 3.

For the evacuation task (task 4), the normal distribution of head rotation change was rejected for the Desktop group (Shapiro–Wilk test, $p < 0.01$) but not for the HMD group (Shapiro–Wilk test, $p = 0.196$). The Mann-Whitney U test showed that there was a significant difference in rotation change between the two groups ($U = 304$, $p < .001$). Participants had significantly higher head rotation change in the Desktop group ($M = 34.26°/s$, $SD = 7.87°/s$) than the HMD group ($M = 27.47°/s$, $SD = 7.06°/s$). Figure 5.14 shows the gaze distributions of participants during task 4, which illustrates that exit signs were the major attractions during the wayfinding task (i.e., the red spheres in the corridor next to the staircases). In both groups, all participants chose to go down using the staircase at the right or left side of room 4.64 after the evacuation alarm triggered. It also showed that participants made a quick decision to go down directly after seeing the exit signs.



a. HMD group



b. Desktop group

Figure 5. 15: Distribution of participants' gaze points during task 4.

5.4.1.3 Wayfinding task performance

Participants' average travel time for each task are summarised in Table 5.2. For both groups, the distribution of travel time was not normally distributed (all $p < .05$). Consequently, the nonparametric Mann-Whitney U test was conducted, which showed significant differences in travel time during task 1 ($U = 215$, $p < 0.01$, $d = 0.97$), task 2 ($U = 203$, $p < .001$, $d = 1.23$), task 3 ($U = 164$, $p < .001$, $d = 1.11$), and evacuation task ($U = 316$, $p < .001$, $d = 0.62$). The tests indicated that participants from the HMD group spent significantly more time during each task than the Desktop group.

Table 5. 2: Means and standard deviations of travel time (s) in each task.

Task number	**HMD group** *Mean (SD)*	**Desktop group** *Mean (SD)*
Task 1	160.79 (20.19)	144.82 (11.12)
Task 2	201.30 (18.30)	179.09 (17.86)
Task 3	140.14 (24.02)	118.59 (12.59)
Task 4	66.67 (11.37)	58.59 (14.50)

The average travel distance of participants during each task is displayed in Table 5.3. The travel distance for both groups was not normally distributed ($p < .05$). Thus, the Mann-Whitney U test was conducted which showed that there were significant differences in travel distance between the HMD and the Desktop group during task 1 ($U = 286$, $p < 0.01$, $d = 0.69$), task 2 ($U = 248$, $p < 0.01$, $d = 0.85$), task 3 ($U = 209$, $p < 0.01$, $d = 0.76$) and evacuation task ($U = 428.5$, $p = 0.016$, $d = 0.34$). The results indicated that participants in the HMD group travelled significantly longer distances than the Desktop group during each task. Even though the difference in travel distance is 4.70 meters on average, this corresponds to a difference in travel time of 16.95 seconds on average.

Table 5. 3: Means and standard deviations of travel distance (m) in each task.

Task number	**HMD group** *Mean (SD)*	**Desktop group** *Mean (SD)*
Task 1	188.68 (4.85)	185.27 (5.10)
Task 2	237.82 (5.52)	232.34 (7.28)
Task 3	163.13 (9.57)	156.05 (8.94)
Task 4	73.34 (8.77)	70.52 (7.80)

The average travel speed of participants during each task is displayed in Table 5.4. The normal distribution of travel speed was rejected for the Desktop group during all tasks and only rejected for the HMD group during task 1 and task 3 (Shapiro–Wilk test, $p < .05$). The result of Mann-Whitney U tests indicated that there were significant differences in average travel speed between two groups during task 1 ($U = 259.5$, $p < 0.01$, $d = 0.97$), task 2 ($U = 220$, $p < 0.01$, $d = 0.82$), task 3 ($U = 177$, $p < 0.01$, $d = 1.27$), and task 4 ($U = 304$, $p < 0.01$, $d = 0.80$). That is, the participants in the HMD group had significantly slower average speed during each task than the Desktop group.

Table 5. 4: Means and standard deviations of travel speed (m/s) in each task.

Task number	**HMD group** *Mean (SD)*	**Desktop group** *Mean (SD)*
Task 1	1.19 (0.11)	1.28 (0.07)
Task 2	1.19 (0.09)	1.32 (0.13)
Task 3	1.18 (0.13)	1.32 (0.08)
Task 4	1.12 (0.15)	1.24 (0.16)

5.4.2 User experience

In order to examine whether technological differences influence the user experience of VR, this section analyses the questionnaire data collected from the HMD group and the Desktop group, namely the face validity, the simulation sickness, the feeling of presence, and the system usability.

5.4.2.1 Face validity

The assessment of face validity included participants' reported answers of four items, namely the realism of the virtual building, the virtual furniture, the movement abilities and the evacuation alarm sound. A 5-point Likert scale ranging from 1 (not at all realistic) to 5 (completely realistic) was used by participants to rate the items, which is a typical scale for Likert response (Jamieson, 2004).

Table 5.5 shows the descriptive results of face validity for both groups. Overall, the average total score of the HMD group and the Desktop group was above 4 out of 5, which suggested the virtual environment had a high level of realism. Meanwhile, seventy-five percent of the participants graded the total score above 4 or higher, which strengthens the face validity results (see Figure 5.16). The total score of the Desktop group was not normally distributed ($p = 0.043$), and the total score of the HMD group was normally distributed ($p = 0.088$). Thus, the non-nonparametric Mann-Whitney U test was performed, which showed that there was no significant difference in the average total score of face validity between the two groups ($U = 587.5$, $p = 0.387$, $d = 0.08$).

In addition, the score of all subscales was not normally distributed (all $p < .001$). The Mann-Whitney U test showed that the 'realism of the movement abilities' is significantly different between the two groups ($U = 458.5$, $p = 0.025$, $d = 0.46$). No significant differences existed related to the items 'realism of the evacuation alarm sound' ($U = 499.5$, $p = 0.054$, $d = 0.45$), 'realism of the virtual building' (U = 503.5, $p = 0.074$, $d = 0.34$), and 'realism of the virtual furniture' ($U = 525$, $p = 0.107$, $d = 0.30$).

Table 5. 5: The mean value and standard deviations of the face validity questionnaire.

Item	**HMD group** *Mean (SD)*	**Desktop group** *Mean (SD)*
Total score of face validity	4.04 (0.36)	4.07 (0.42)
Realism of the virtual building	4.08 (0.60)	4.29 (0.63)
Realism of the virtual furniture	4.17 (0.56)	4.00 (0.55)
Realism of the movement abilities	3.17 (0.65)	3.50 (0.79)
Realism of the evacuation alarm sound	4.75 (0.44)	4.50 (0.66)

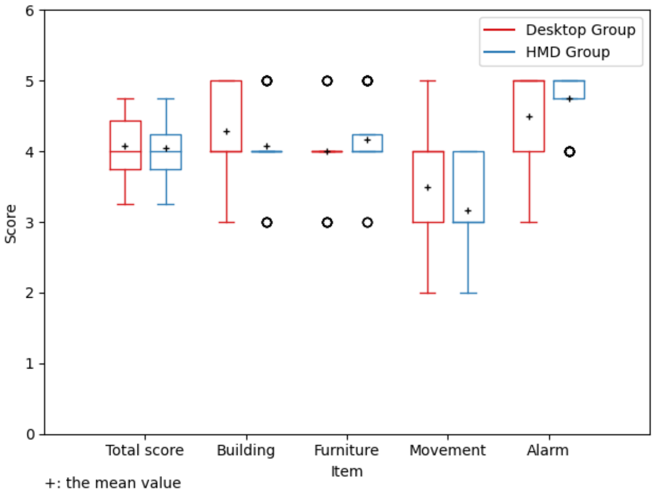


Figure 5. 16: Comparison of the boxplots of the face validity questionnaire for both groups.

5.4.2.2 Simulation sickness

Simulation sickness is generally defined as the discomfort that arises from using simulated environments (Deb et al., 2017). In order to investigate the potential for simulation sickness because of the usage of the VR, the Simulator Sickness Questionnaire (Kennedy et al., 1993) was used. Sixteen symptoms are rated respectively on a 4-point Likert scale from 0 (None) to 3 (Severe). Scores of these symptoms can be grouped into Nausea (N), Oculomotor (O) and Disorientation (D) subscales, as well as a total symptom score.

Table 5.6 shows the mean value and standard deviations of SSQ. For both groups, the distributions of the SSQ score were not normally distributed ($p < .001$). The Mann-Whitney U test showed that there was no significant difference in total SSQ score between the two groups ($U = 559.5$, $p = 0.269$, $d = 0.10$). Moreover, no significant differences in the subscales of Nausea ($U = 591$, $p = 0.397$, $d = 0.11$), Oculomotor ($U = 536.0$, $p = 0.181$, $d = 0.09$), and Disorientation ($U = 603.5$, $p = 0.460$, $d = 0.08$) were found between two groups. The boxplots in Figure 5.17 showed that the Desktop group had more outliers on the higher score. We did not find a particular reason for the outliers (e.g., age, familiarity with VR or the building) and removing the outliers did not change the statistical results ($p > .05$).

Table 5. 6: The mean value and standard deviations of SSQ.

Item	**HMD group**	**Desktop group**
	Mean (SD)	*Mean (SD)*
Total score	15.06 (15.19)	17.27 (26.45)
Nausea	9.80 (14.69)	11.78 (20.07)
Oculomotor	13.69 (12.13)	15.38 (22.35)
Disorientation	16.63 (20.73)	18.83 (32.85)

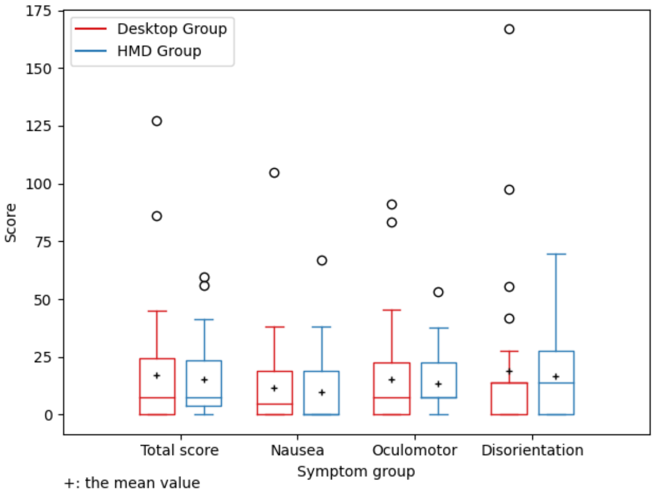


Figure 5. 17: Comparison of the boxplots of the SSQ questionnaire for both groups.

5.4.2.3 Sense of presence

The Presence Questionnaire (PQ) (Witmer et al., 2005) was used to assess participant's feeling of presence in the virtual environment. It includes four subscales, namely involvement, sensory fidelity, immersion and interface quality. The PQ consists of 29 questions and each question was reported from 1 to 7. The total score was counted by summing the reported scores of the 29 items.

Table 5.7 shows the statistical results of PQ for both groups. In the current study, the mean score of PQ was 146.00 (SD = 13.63) for the HMD group and 148.50 (SD = 17.86) for the Desktop group. The total score of PQ of the HMD group (p = 0.44) and the Desktop group (p = 0.618) was normally distributed. Therefore, the independent t-test was performed, which showed there was no significant difference in the total score of PQ between the HMD group and the Desktop group (t = 0.661, p = 0.511, d = 0.16).

All the sub-scale followed a normal distribution (all p > .05). Thus, the independent t-test was performed, which showed that there were no significant differences in the four subscales between the two groups. The statistics results of the t-test for both groups are shown in Table 5.7.

Table 5. 7: Subscales of PQ: Means and standard deviations (range from 1 to 7).

Item	**HMD group** *Mean (SD)*	**Desktop group** *Mean (SD)*	***t*-value, *p*-value, *d***
Involvement	4.81 (0.62)	5.08 (0.83)	1.531, 0.130, 0.37
Sensory fidelity	4.91 (0.87)	4.89 (0.82)	-0.123, 0.903, 0.02
Immersion	5.78 (0.50)	5.56 (0.68)	-1.625, 0.109, 0.37
Interface quality [a]	4.17 (0.97)	4.59 (1.04)	1.747, 0.085, 0.42

[a] Reversed items

5.4.2.4 Usability

The System Usability Scale (SUS) questionnaire (Brooke, 1996), which is commonly used as a usability questionnaire, was adopted in the current study to assess the usability of both VR technologies. The questionnaire consists of 10 items with responses on a 5-point Likert scale, from strongly disagree (1) to strongly agree (5). The total score of SUS ranges from 0 to 100.

The average total score of SUS was 83.75 (*SD* = 11.92) in the Desktop group and 82.01 (*SD* = 11.10) in the HMD group, which indicated the effective usability of both systems. The total scores of SUS in the HMD group (*p* = .001) and the Desktop group (*p* < .001) were not normally distributed. Accordingly, the Mann-Whitney U test was used to compare the average total score of SUS in both groups, which identified that there was no significant difference between the two groups (*U* = 511.50, *p* = 0.119, *d* = 0.15). Table 5.8 presents the mean scores and standard deviations of ratings for the ten items in the SUS. The first five items were worded positively, and the second five items were worded negatively. The item ‘I thought the system was easy to use’ received the highest average score in both groups; ‘I found the system unnecessarily complex’ and ‘I needed to learn a lot of things before I could get going with this system’ received the lowest score in, respectively the HMD group and the Desktop group. This indicated that both systems were easy and simple to use.

Table 5. 8: Mean scores and standard deviations of the SUS questionnaire.

Item	**HMD group** *Mean (SD)*	**Desktop group** *Mean (SD)*
I thought the system was easy to use	4.39 (0.80)	4.65 (0.65)
I felt very confident using the system	4.33 (0.83)	4.56 (0.75)
I would imagine that most people would learn to use this system very quickly	4.11 (0.92)	4.44 (0.99)
I found the various functions in this system were well integrated	3.92 (0.73)	4.15 (0.61)
I think that I would like to use this system frequently	3.39 (1.15)	3.13 (1.09)
I think that I would need the support of a technical person to be able to use this system	1.56 (0.81)	1.44 (0.99)
I thought there was too much inconsistency in this system	1.56 (0.77)	1.38 (0.60)
I found the system very cumbersome to use	1.53 (0.81)	1.76 (1.10)
I needed to learn a lot of things before I could get going with this system	1.36 (0.80)	1.26 (0.62)
I found the system unnecessarily complex	1.33 (0.53)	1.62 (1.10)

5.5 Discussion

This paper aims to compare the adoption of different VR technologies for pedestrian wayfinding studies, via investigating the difference in pedestrian wayfinding behaviour and user experience. Wayfinding experiments with two groups of participants were conducted using either HMD VR or Desktop VR. Four hypotheses were formulated, namely there are significant differences in (H1) route and exit choice behaviour (i.e., wayfinding strategies, usage of paths, decision points, staircases, and exits), (H2) observation behaviour (i.e., head rotation and gaze point), (H3) wayfinding task performance (i.e., time, speed, and distance), and (H4) user experience (i.e., realism, presence, simulation sickness, and usability) between the participants that used Desktop VR and the HMD VR. This section discusses the experimental results with respect to pedestrian behaviour and user experience to answer the above-mentioned hypotheses in sections 5.1 and 5.2, respectively.

5.5.1 Differences in pedestrian wayfinding behaviour?

This study characterised the pedestrian wayfinding behaviour in the VR environment by means of a selection of metrics, namely route and exit choice behaviour (i.e., wayfinding strategies, usage of paths, decision points, staircases, and exits), observation behaviour (i.e., head rotation and gaze point) and wayfinding task performance (i.e., time, speed, and distance). Underneath, the findings pertaining to each metric are discussed and compared to the literature.

5.5.1.1 Difference in pedestrian route and exit choice behaviour

This study found a limited significant difference in terms of route and exit choice behaviour. Only significant differences pertaining to the detailed behaviour (i.e., wayfinding strategy, usage of staircase and decisions points during task 3) were recorded. Therefore, hypothesis H1: there is a significant difference in route and exit choice behaviour (i.e., wayfinding strategy, paths, decision points, staircases, and evacuation exit choice) between the participants that adopted Desktop VR and HMD VR, was only partially confirmed. In particular, the usage of wayfinding strategies, decision points, and staircases were significantly different in the case where the destination was not clear-cut.

Overall, the frequency of adopting a certain wayfinding strategy was found to be similar during task 1, task 2, and task 4. This study illustrates that floor strategy was employed most in wayfinding tasks involved floor changes. Moreover, the frequency of using the floor strategy increased with the task number. This finding can be explained by literature (e.g., Li et al., 2019; Schwarzkopf et al., 2017), which suggest that when a destination is unclear, the proportion of participants who use the floor strategy increases. In this study, the destinations of task 1 and task 2 (i.e., the destinations were at the end of the corridor) were clearer, more regular and easier to understand than task 3 (room 4.64). Thus, the unclarity of task 3 might have resulted in a higher proportion of participants employing the floor strategy during task 3. Another explanation is that staircases were very visible and easily accessible in the current experimental environment, thus inviting participants to move to the destination floor at their earliest convenience. A significant difference was only found during task 3 regarding the wayfinding strategy. There are no published studies comparing pedestrian wayfinding strategies using different VR technologies. Some literature suggests that users in an immersive virtual environment were more likely to move directly between junctions (Conroy, 2001), namely they like to use the ‘straightest’ route, which explained why participants from the HMD group were more likely to employ the direction strategy.

Considering the usage of paths, participant's behaviour was found to be overall similar between both groups. That is, both groups had a similar distribution of used paths during all tasks. Besides that, this study shows that participants preferred to use the wider and longer corridors for all tasks. In particular, the pedestrians refrained from using the smaller corridors that connected the two parallel main corridors and predominantly used the larger open areas to cross between the two main corridors. This is in accordance with studies of (Frankenstein et al., 2012; Vilar et al., 2013b, 2014b; Wiener et al., 2012) that found participants preferred paths that are wider and with longer lines of sight.

The usage of decision points and staircase were overall similar for task 1, task 2, and task 4 between both groups. A significant difference was only found for task 3 regarding the usage of decision points and staircases. This is because more participants in the HMD group adopted the direction strategy than the Desktop group, which also leads to the different usage of decision points and staircases. Moreover, participants who used Desktop VR have a fixated view and a vantage point to observe the virtual building from the real-life environment, which means that they have a more accurate estimation of the movement direction (Sharples et al., 2008).

Regarding the usage of exits during the evacuation, both groups showed similar choices. Meanwhile, the results show the usage of the exits was asymmetrical. That is, only the nearest four exits were used among ten available exits. This behaviour is in line with other studies that look at exit usage (Duives & Mahmassani, 2012; Feng et al., 2021b; Haghani & Sarvi, 2016b; Liao et al., 2014). Meanwhile, in both groups, participants only chose the closet exits. This result is also consistent with recent findings that suggest pedestrians are overall more likely to choose the nearest exits and shortest routes (Fang et al., 2010; Guo et al., 2012; Haghani & Sarvi, 2016a; Kobes et al., 2010a; Li et al., 2019; Liao et al., 2017; Zhu & Shi, 2016).

5.5.1.2 Difference in observation behaviour

Regarding head rotation change, significant differences in tasks 1, 2, and 4 were found between two groups. Ultimately, hypothesis H2: there is a significant difference in observation behaviour (i.e., head rotation and gaze point) between the participants that adopted Desktop VR and HMD VR, was only partially confirmed.

Generally, room numbers, floor plans, fire doors, and evacuation exit signs were the major attractions for participants to find their way in the virtual environment. This finding is consistent with literature that suggests people pay more attention to salient landmarks and information that aids navigation (Tian et al., 2019; Wiener et al., 2012). More head rotation changes were identified in the HMD group than the Desktop group during tasks 1 and 2. This can be explained by literature, which suggests that viewers use a desktop have a higher degree of expectation regarding the direction in which they are likely to travel (Sharples et al., 2008). The result is consistent with navigation studies that suggest that participants feel the fully immersive VR setting is more natural and intuitive to look around (Ruddle et al., 1999; Santos et al., 2009; Zielasko et al., 2017). Participants in the Desktop group needed to press the mouse to change their view to rotate and their physical view is still fixated on the computer screen in front of them (Li & Giudice, 2013), while participants in the HMD group required fewer efforts and felt more natural to rotate (i.e., simply move their head).

Yet, contrary to our expectation, during the evacuation task, participants from the Desktop group had significantly more head rotation changes than the HMD group. This can be explained by two reasons. Firstly, it might be that participants of the HMD group did already observe the environment more during previous tasks, thus less 'observing' was required in the follow-up tasks due to the learning effect. Secondly, with increasing task complexity (i.e., find an exit during an emergency), the participants from the Desktop group increased their levels of head rotation to acquire the necessary information from the environment in order to evacuate and find the location of exits. Meanwhile, the results show that when tasks get more complex (i.e., tasks 3 and 4), it is generally more intuitive and natural for participants to look around.

5.5.1.3 Difference in wayfinding task performance

With respect to the task performance, the results revealed that significant differences existed in participants' travel time, travel distance, and average travel speed during all tasks. Ultimately, hypothesis H 3: there is a significant difference in wayfinding task performance (i.e., time, speed, and distance) between the participants that adopted Desktop VR and HMD VR, was confirmed.

The results indicate that participants had more efficient task performance in the Desktop group compared to the HMD group. This finding is consistent with studies that reported better navigation efficiency in a Desktop VR than an immersive VR (Li & Giudice, 2013; Santos et al., 2009; Westerman et al., 2001). It problematizes the simple assumption that more immersive VR leads to better performance. This might be explained by three reasons. First, participants in the HMD group used more decision points compared to the Desktop group. As Suzer et al. (2018) stated, if a traveller chooses a longer route, the usage of decision points increases, which also leads to more difficulties in the wayfinding task. Therefore, the increase of decision points can cause an increase in the travel distance and travel time. Second, according to the result of head rotation change and gaze points, participants in the HMD group have more 'observing behaviour' (i.e., higher head rotation change, higher density of gaze points and bigger AOI) than those in the Desktop group which might cause longer travel time. Moreover, the significant difference in travel time is consistent with (Hsieh et al., 2018; Santos et al., 2009), which found participants spend longer time using HMD VR compared to using the Desktop VR in wayfinding tasks. Third, the participants from the Desktop group used a standard computer and had more experience with computer gaming, while most of the participants from the HMD group had never or seldom used VR before. Therefore, participants from the Desktop group operated the system more easily, which might cause a shorter travel time.

5.5.2 Differences in user experience?

This study characterised the user experience of the participants by means of four assessments, namely the face validity, simulation sickness, sense of presence, and usability. Underneath, the results pertaining to each questionnaire are discussed and compared to the literature.

5.5.2.1 Face validity

Regarding the face validity questionnaire (see Appendix D), participants in both groups reported an average score above 4 (total score: 5) which confirmed the face validity of both VR setups. This was also confirmed by comments from participants, for instance, ‘I feel like walking in the faculty’ as well as ‘I feel the urge to get out of this building’ and ‘I want to be out of this building as quick as possible’ for the evacuation task. The realism of movement abilities from the Desktop group was significantly higher than the HMD group. This finding might be caused by the ‘step-by-step’ movements in the HMD VR, which cause participants to experience less continuous movements at low walking speeds compared to the smoother movements in the Desktop VR. The score of the face validity questionnaire of the current study is similar to other pedestrian-related studies that also used HMD VR (e.g., Bourhim & Cherkaoui, 2018; Deb et al., 2017). However, no comparative ‘face validity’ studies addressing different VR technologies for pedestrian studies have been found in the literature.

5.5.2.2 Simulation sickness

With respect to the simulation sickness, the average total score of SSQ in both groups was relatively low considering the maximum total score of the SSQ is 236 (Kennedy et al., 2003). Compared to the study of (Dominic & Robb, 2020; Feng et al., 2021b), participants from the current study had lower SSQ scores although they had longer exposure time in the virtual environment.

Although it is generally assumed that motion sickness increase from Desktop VR to HMD VR (Rebenitsch & Owen, 2016), that is not the case in the current study. We found that there was no significant difference in SSQ between both groups, and participants reported a higher average score in the Desktop group than the HMD group. This surprising finding can be explained by three reasons from the literature. First, according to sensory conflict theory (Reason & Brand, 1975), simulation sickness is a result of conflicts between visual inputs and vestibular inputs. While participants in the Desktop group were moving in the virtual environment, their bodies remained sitting in the real world. Thus, participant’s visual system indicated that they were moving, however, their vestibular system told the body it was stationary. In the HMD group, participants continuously rotated their heads in real life to change the direction of movement in the virtual environment, thus fewer sensory conflicts were expected. Second, participants in the HMD group had more active searching behaviour (indicated by the observation behaviour) than the Desktop group. Literature suggests that active participants may experience fewer symptoms (Sharples et al., 2008). Third, there were more outliers of the SSQ scores of the Desktop group which might cause a, on average, higher SSQ score.

Besides that, in both groups, Disorientation received the highest score, followed by Oculomotor and Nausea. Although the Disorientation subscale is related to vestibular disturbances, such as dizziness and vertigo, high disorientation may be an indicator that participants experienced higher levels of virtual presence (Barfield & Weghorst, 1993). The relatively high disorientation score might result from response lags. The current experiment tasks involved changing floors and some turning movements on the stairs in the virtual building, which are key sources of disorientation about one's heading and position in a building. The relation between disorientation and floor changes was also found in Hölscher et al. (2005).

5.5.2.3 Sense of presence

In terms of the feeling of presence, the results revealed that participants in both groups experienced a similarly high level of presence. Moreover, the PQ scores in the current study are also slightly higher than the studies that also used VR technologies to study pedestrian behaviour (e.g., Deb et al., 2017; Lin et al., 2020a; Zhu et al., 2020a). When studying the subscales of PQ, the subscale 'Immersion' received the highest scores in both groups, which identifies that participants felt enveloped by, included in and interacted realistically with the virtual environment. In literature, generally the Desktop VR is categorised as 'non-immersive' VR and the HMD VR is 'immersive VR'. Yet, although the average score of the sub-scale Immersion was slightly higher in the HMD group in the current study, we did not find significant differences between two groups. This finding indicates that both VR technologies provided a similar immersion effect to participants. Our finding is in agreement with the study of (Lee et al., 2010), which showed that Desktop VR can also provide a good sense of presence to users.

We think there are two potential reasons for the finding that participants from the Desktop group reported similar levels of presence as the HMD group. One explanation is provided by literature, which suggests that when users are more comfortable and less focused on the interaction with VR technology itself (and more with their task), the feeling of presence increases (Soler-Domínguez et al., 2020). In our study, the wayfinding tasks force participants' attention away from the interaction with VR. However, in the HMD group, participants needed to wear a headset all the time and proactively rotate their heads to search for information, while participants in the Desktop group sat comfortably in front of a screen, and simply used a mouse and keyboard to move. It means that participants in the HMD group might be less focused on the wayfinding tasks because they were distracted by the headset. A recent discussion by (Nunez, 2004) provides another potential explanation, namely presence is related to users' expectations. People normally have a lower expectation of fidelity and 'realism' of non-immersive VR systems than immersive VR systems. Thus, the lower expectations on Desktop VR limit the negative reports on the feeling of presence when using Desktop VR.

5.5.2.4 Usability

Participants confirmed the usability of the two systems were both at an 'excellent level', according to the interpretation of the SUS score made by Bangor et al. (2009), which confirmed that both VR setups had good usability. Meanwhile, the SUS score of both groups is higher than the studies of (Boletsis & Cedergren, 2019; Deb et al., 2017; Feng, Duives et al., 2021a; Stigall & Sharma, 2019), which are the only four studies that measured SUS regarding the usage of VR in pedestrian behaviour. In both groups, the item 'I thought the system was easy to use' received the highest score, which indicate that both of the VR setups were easy to use. The slightly higher average score of participants in the Desktop group might be due to their previous experience using a computer, as suggested by literature (Boletsis & Cedergren, 2019). That is, participants were more familiar with the display, mouse and keyboard interface.

To summarise, there were no significant differences in terms of realism, simulation sickness, the feeling of presence, and usability between the two groups. Thus, hypothesis H4: there is a significant difference in user experience (i.e., realism, presence, simulation sickness, and usability) between the participants that adopted Desktop VR and HMD VR, was rejected in this study.

5.5.3 Implications

Based on the key findings of this study, we highlight several theoretical and practical implications that are both relevant for pedestrian wayfinding research and human-computer interaction research.

5.5.3.1 Implications for theory

This study provides several theoretical implications for pedestrian wayfinding behaviour study and human-computer interaction. Firstly, this study provides empirical evidence that VR can be used to collect pedestrian wayfinding data in complex and multi-level buildings. Compared to VR studies featured more simplified environments (e.g., Hsieh et al., 2018; Ruddle & Péruch, 2004; Santos et al., 2009), the current study shows that it is possible to collect adequate behavioural data in complex environments with high experimental control and let participants experience the virtual world in an immersive and engaging way. Secondly, this study identifies that it is possible to collect detailed behavioural data (i.e., movement trajectory, head movement, and gaze points), personal characteristics (e.g., age, gender, and familiarity with VR) and user experience (i.e., realism, simulation sickness, feeling of presence, and usability) using a VR research tool in combination with questionnaires, which is difficult to achieve under real-world conditions. This provides proof that pedestrian researchers can collect comprehensive data sets featuring multi-dimensional behaviour data simultaneously and provide researchers with new perspectives to understand pedestrian wayfinding behaviour. Moreover, this study provides exemplars of designing VR experiments regarding the experimental set-up that combines the usage of VR technology and questionnaire to study pedestrian wayfinding behaviour and human-computer interaction. Thirdly, this study shows that when applying VR to study pedestrian behaviour, it is also worthy and important to quantitatively investigate the interaction between people and technologies. Human performance in the virtual environment is influenced by the interaction between the individual and the virtual environment (e.g., presence, usability, realism, and simulation sickens) (Stanney et al., 1998; Witmer & Singer, 1998). For previous studies that investigated the interaction between people and VR technologies, some were qualitative or exploratory, or they only considered limited perspectives. The current study combines four different questionnaires and compares these perspectives quantitatively. In contrast to previous VR comparison studies (e.g., Buttussi & Chittaro, 2018; Rebenitsch & Owen, 2016; Sharples et al., 2008), the realism, simulation sickness, presence, and usability in the current study was overall similar between the HMD and the Desktop group. When applying VR, researchers should take extra caution when making assumptions about the interaction between people and VR technologies in various contexts.

This study identifies significant differences in wayfinding task performance between the HMD and the Desktop group. Participants of the Desktop group navigated more quickly and efficiently during all wayfinding tasks. Meanwhile, pedestrian route and exit choice behaviour (i.e., usage of wayfinding strategy, path, decision points, staircase, and exit) were found to be overall similar during the first two and the evacuation tasks. Our study shows that for 'simpler' wayfinding tasks in multi-level buildings, pedestrian route and exit choice behaviour can be measured effectively using a more simple and less expensive Desktop VR. It indicates that for large-scale virtual environments, the benefits gained from increasing immersion may not be as prevalent as suggested in the literature (e.g., Buttussi & Chittaro, 2018; Santos et al., 2009). Furthermore, the user experience (i.e., realism, simulation sickness, presence, and usability) was overall similar between the two groups. These findings imply that studies that investigate pedestrian route and exit choice behaviour of 'simple' wayfinding tasks (i.e., requires less spatial understanding) do not need to be limited to using immersive VR. Researchers can choose the best practice between HMD VR and Desktop VR base on their budget, existing equipment, and technical supports.

However, the findings regarding the comparison of the wayfinding strategy and observation behaviour imply that differences can appear, especially when (more complex) searching behaviour is triggered. In particular, there were differences in route choice (i.e., wayfinding strategy, decision point, and staircase) during the task where the location of the destination was not clear-cut. Meanwhile, participants who used HMD VR had more head rotation changes and observation behaviour during the first two tasks, while participants in the Desktop group had higher head rotation changes during the evacuation task. Thus, in cases where the wayfinding task become more complex and searching behaviour are important factors that aid wayfinding, there may still be advantages to use immersive VR. One is advised to carefully consider the differences in behavioural outcomes between both VR technologies when investigating wayfinding behaviour for more 'complex' wayfinding tasks (i.e., requires more spatial understanding). The findings highlight that if one wants to investigate pedestrian wayfinding and observation behaviour in complex environments, a more intuitive and natural VR setting (HMD VR in our case) needs to be ensured in order to allow natural observation of the environment.

5.5.3.2 Implications for practice

This study provides insights for designing infrastructure and signage to facilitate wayfinding in complex buildings. This study found that room numbers, floor plans, and fire doors were the main attractions for participants to find their way in a multi-level building. This information helps to identify locations where pedestrians search for information and determine what environmental features they look at in order to inform their wayfinding process. These insights could be useful for practitioners who are involved in planning complex buildings to design effective signage in complex and large-scale buildings. Additionally, our study illustrates that floor strategy was employed dominantly in a multi-level building and pedestrians preferred to use the wider corridors over narrow ones. These findings regarding the usage of wayfinding strategies in a multi-level environment provide empirical evidence for professionals to predict and plan the main navigational flow evenly when a complex network of paths and decision points exist.

Moreover, this study provides proof that VR can be used to study pedestrian wayfinding behaviour and collect valid behavioural data in multi-level buildings. The combination of VR, BIM, and digital twin can be used for engineers through their design process to test the interaction between pedestrians and the built environment that is either too complex to test in real life (e.g., evacuation intervention) or hypothetical scenarios that do not exist today (e.g., new building designs) (Feng et al., 2021a). With the advantages provided by VR, such as the flexibility to simulate a variety of contexts and repeatability to conduct experiments with similar settings, it helps engineers deal with the increasing complexity of the modern engineering systems (Hartmann & Trappey, 2020) and evaluate the design, which can be used to improve the design in an early stage of the design process before it is finally implemented. Therefore provide engineers benefits of shortening development times, lowering construction costs and construction risks.

5.6 Conclusion and future work

This study investigated differences in pedestrian wayfinding behaviour in a multi-level building and user experience of the VR technology in order to compare the adoption of HMD VR and Desktop VR for pedestrian wayfinding studies. In particular, pedestrian behavioural data (i.e., pedestrian route and exit choice behaviour, observation behaviour, and wayfinding task performance) and user experience data (i.e., realism, simulation sickness, presence, and usability) were compared between two groups of participants, where one group used the HMD VR and another group used the Desktop VR.

This study provides the first direct comparison between VR technologies regarding the differences in behavioural outcomes of pedestrians in a multi-level building and user experience between the adoption of different VR technologies. It provides the first solid empirical evidence of direct comparison between HMD VR and Desktop VR on the resulting wayfinding behaviour in a multi-level building, which can have an important implication for future investigation of pedestrian wayfinding and evacuation behaviour in complex buildings. The comparison between HMD VR and Desktop VR implies studies that investigate pedestrian route and exit choice behaviour of ‘simple’ wayfinding tasks (i.e., requires less spatial understanding) do not need to be limited to using immersive VR. However, if one wants to investigate pedestrian wayfinding and observation behaviour in complex environments, a more intuitive and natural VR setting (e.g., HMD VR) is recommended in order to allow natural observation of the environment.

Based on the key findings, we highlight several contributions of the current study. Firstly, this study applies emerging technologies to study pedestrian wayfinding behaviour. Our findings show that one can study pedestrian wayfinding behaviour in complex environments (even in emergency situations) using VR with high experimental control and still collect comprehensive data (i.e., movement trajectory, head rotation, gaze point, and user experience). This supports researchers and engineers to leverage their understanding of pedestrian behaviour in complex environments with new possibilities and perspectives. Secondly, the current study provides a quantitative and comprehensive comparison of pedestrian wayfinding behaviour and user experience as a result of the adoption of different VR technologies. It offers both theoretical underpinnings of the similarities and differences in pedestrian wayfinding behaviour using different VR technologies and practical suggestions for researchers who are interested in applying VR. Thirdly, this study provides clear Desktop VR and HMD VR use-cases of designing VR experiments regarding the experimental set-up, which combines the usage of VR technology and questionnaire to study pedestrian wayfinding behaviour and user experience. The combination may assist researchers in associating between pedestrian behaviour and human-computer interaction in order to better understand the usage of VR in the pedestrian field and formalize complex engineering knowledge.

Yet, there are several limitations of the current study. Firstly, in order to quantitatively measure the advantage of using HMD VR for complex wayfinding tasks, future studies should directly compare pedestrian behaviour in real and virtual environments. Due to COVID-19, it has until now been impossible to conduct the field experiment with an identical setting as the VR experiment in the faculty building. Secondly, comments made by the participants during the experiment reveal that additional elements can potentially make the current virtual experience more realistic, such as the presence of other pedestrians and the interaction with other people. In the present study, the virtual environment did not include other agents. Thus, it would be interesting to investigate the impact of VR technology on pedestrian wayfinding behaviour, while including the interaction with other pedestrians. Thirdly, the gazing behaviour of participants was only studied qualitatively in this study and was based on head rotations alone. In future studies, incorporation of precise eye-tracking technologies would allow for a more in-depth (quantitative) analysis of gazing behaviour, such as gaze time, gaze quantity and gaze sequences. This would improve our understanding pertaining to pedestrians' virtual attention in the environment and pedestrians' decision-making process during wayfinding tasks. Moreover, the combination of behavioural data and physiological data may provide additional insights and new perspectives for wayfinding behaviour. For instance, integrating VR technologies with physiological sensing technologies (e.g., heart rate, electroencephalogram sensors, and biosensors) enables researchers to study participant's wayfinding behaviour in combination with their mental and physical states in the virtual environments with stimuli (e.g., light, sound, signals, and text messages). Lastly, although no differences in personal characteristics were found between the two groups, literature does suggest personal characteristics could influence wayfinding behaviour (e.g., Kinateder et al., 2018a; Lin et al., 2020a). Therefore, future work should explore the impact of individual differences (e.g., familiarity with the environment, gender, and age) on pedestrian wayfinding behaviour in a complex multi-level building to gain a better understanding of individuals performing wayfinding tasks.

Chapter 6

Discussions, Conclusions and Recommendations

This chapter discusses the key findings, presents the conclusions and proposes the directions for future research. This thesis aims to understand ‘To what extent VR technologies can be used to study pedestrian wayfinding behaviour in buildings’. The research in this thesis focused on using VR to study pedestrian wayfinding behaviour in buildings during both normal and emergency situations. In particular, various empirical datasets were collected through different VR technologies in order to understand the usage of VR to investigate pedestrian behaviour and generate new insights into pedestrian wayfinding behaviour in buildings.

This chapter is structured as follows. Section 6.1 discusses the key findings and presents the answers to the research questions that are resulting from the research in this thesis. Subsequently, the overall conclusions are presented in section 6.2. Building on the key findings and conclusions, Section 6.3 highlights their implications for research and practice. Finally, Section 6.4 discusses the limitations in this thesis and directions for future research.

6.1 Key findings and discussions

In this section, the answers to the research questions in Chapter 1 (see 1.2) are provided and key findings are discussed.

1. What are the most essential gaps of contemporary data collection methods for collecting pedestrian behavioural data and what are the possibilities and challenges of using VR to (partly) fill in these gaps?

To answer this research question, ***Chapter 2*** provided a systemic review of studies featuring pedestrian behaviour with respect to using different experimental methods to identify the research gaps and opportunities for new technologies (e.g., VR) to complement the current data collection methods.

The review finds that there is an imbalance in the number of studies that feature: (1) pedestrian behaviour in large complex scenarios, and (2) pedestrian behaviour during new types of high-risk situations. Additionally, three issues are identified regarding current pedestrian behaviour studies, namely (3) little comprehensive data sets featuring multi-dimensional behaviour data simultaneously, (4) generalizability of most collected data sets is limited, and (5) costs of pedestrian behaviour experiments are relatively high.

This review pinpointed three opportunities for VR to (partially) bridge these gaps. Firstly, VR can be used to collect pedestrian behavioural data in large complex and realistic scenarios with great experimental control. Meanwhile, VR provides the opportunity to study pedestrian behaviour in a variety of dangerous situations, such as building fires, earthquakes, or crowd motion during massive events (Haghani et al., 2016). At the same time, with the ability to simulate a variety of contexts, VR allows researchers to investigate pedestrian behaviour in hypothetical scenarios (e.g., new building designs and new transportation systems). It helps researchers understand the interaction between pedestrians and scenarios that do not exist today and also helps planners through dilemmas when designing future infrastructure (Maheshwari et al., 2016). Secondly, once the VR system is set up, it allows researchers to conduct the same experiment repeatedly and even in a physically different location while the settings of the experiment remain the same. It ensures that experimental conditions are similar for all participants, which helps to gain insights into how various external factors or personal characteristics affect behaviour in certain conditions. At the same time, it allows researchers to collect a multitude of pedestrian data with much flexibility and heterogeneity. Thirdly, precise tracking technology (e.g., full-body tracking, eye tracking), which is incorporated in most VR technologies, allows researchers to collect and accurately analyse various aspects of pedestrian behaviour in great detail. Brief actions can also be captured, such as small steps, hesitations, or glances, that would be difficult to observe in the real world (Vilar et al., 2014a). In combination with questionnaire data, VR also provides opportunities to acquire complementary information to further our understanding of the decision-making processes.

At the same time, the review highlights several challenges of using VR to study pedestrian behaviour. Firstly, to ensure VR technologies can be used as a valid research tool to study pedestrian behaviour, more thorough insights with respect to the comparison of pedestrian behaviour in virtual and real-world environments is needed. In particular, research should establish under which conditions and for which pedestrian behaviours, pedestrian behavioural data collected by VR technologies is valid. Secondly, researchers should continue to work on solving the ethical (i.e., mental and physical load of VR experiments for participants) and methodological (i.e., pre-selection effects) limitations of applying VR technologies. VR experiments using some VR devices (i.e., HMDs, desktop displays) can be conducted at different locations and different times (Cosma et al., 2016), which increase the heterogeneity of sampling. However, the potential pre-selection effects might influence the representativeness of the results, for instance, elders or people who have issues with dizziness might not be included in the sample, participants who are more familiar with new technologies might perform more smoothly. Thirdly, researchers have to balance between the level of realism, the scale of the virtual environments and the computational load of VR simulations.

2. How valid are the behavioural results generated by VR for use in pedestrian wayfinding behaviour study?

As mentioned above, one of the challenges of using VR to study pedestrian behaviour is to ensure the collected pedestrian behavioural data is valid. In order to do establish data validity, this thesis conducted VR and field experiments in combination with the questionnaire to establish different aspects of validity, namely the ecological validity, face validity, content validity and construct validity of the usage of VR to study pedestrian wayfinding behaviour.

Chapter 3 compares pedestrians' exit choice in a real-life evacuation drill and an identical virtual environment, preliminary steps are taken to validate the Mobile VR (smartphone-based HMD and 360° video) to study pedestrian exit choice behaviour during evacuations. The results show that the pedestrians' exit choice during the evacuation is overall similar in the field experiment and the VR experiment. Up to this point, only a few studies validated pedestrian evacuation behaviour collected by means of VR experiments, most of which used projection VR (e.g., Kobes et al., 2010a) or HMDs with a simulated virtual environment (e.g., Kinateder & Warren, 2016). The current validation study is complementary to studies showing that results regarding pedestrian exit choice behaviour are valid through different types of VR equipment. Besides that, In agreement with previous work (Helbing et al., 2000; Lovreglio et al., 2016; Moussaïd et al., 2016), herding behaviour was found in both the field experiment and VR experiment. These findings illustrate that the methodological differences between the two experiments do not result in significant differences regarding the pedestrians' exit choice. Additionally, the impact of different types of information strategies (i.e., exit signs, directional signs, presence of people) was investigated using the validated VR experiment method. It was found that the presence of other people and information pertaining to the direction of the exits has a significant influence on pedestrian exit choice. Besides that, pedestrians' exit choice was found to be asymmetrical, especially in the scenario involving other pedestrians. Together it provides preliminary proof of the ecological validity of the VR simulator to study pedestrian exit choice behaviour during evacuations. Moreover, it demonstrates that the combination of smartphone-based HMD and 360° video can be used to conduct controlled evacuation experiments, which allows researchers to control specific variables of interest systematically and to test pedestrian exit choice behaviour in well-specified scenarios.

In ***Chapter 4***, WayR, a VR research tool that aims to study pedestrian wayfinding behaviour in a multi-story building was developed. WayR has distinct features compared to the above-mentioned VR simulator (smartphone-based HMD and 360° video). It represents a multi-story and large-scale building, supports natural navigation through the entire building and collects pedestrian walking trajectories, head movements and gaze points automatically. A preliminary evaluation of WayR's validity (i.e., face validity, content validity, construct validity) for pedestrian wayfinding behaviour study was provided. The validity of WayR is evaluated using objective measures (e.g., route choice, evacuation exit choice, wayfinding performance, observation behaviour) and subjective measures (i.e., face validity questionnaire).

Face validity is established based on the results of the face validity questionnaire. The average score of the face validity questionnaire is 4.04 (out of 5), indicating that WayR has a relatively high degree of realism and the assignments were engaging. Content validity is established by showing WayR includes all the items that are essential to measuring pedestrian wayfinding behaviour. Participant's positions, head rotations, gaze points, timestamps were recorded, and the analysis of these behavioural data shows that the collected data can reflect pedestrian wayfinding behaviour from different perspectives (e.g., choice of path, decision point, wayfinding strategy, wayfinding performance, observation behaviour) and allows the meaning of the data to be readily comprehended.

The construct validity of WayR is evaluated pertaining to pedestrian wayfinding behaviour with other studies in literature and the difference of wayfinding behaviour in relation to assignment complexity. Importantly, by comparing the results of WayR with other studies, similarities in results are an important indicator of the construct validity of WayR. Firstly, from the decision-making perspective of pedestrian wayfinding behaviour, our findings show that the floor strategy was predominantly adopted in a multi-story building and the wayfinding assignment instruction strongly affect pedestrian's wayfinding strategy, as suggested by (Hölscher et al., 2006). Moreover, we found that participants prefer to use paths that are wide and with longer lines of sight, which was also indicated by (Frankenstein et al., 2012; Vilar et al., 2013b, 2014b; Wiener et al., 2012). Besides that, our finding shows that participants were more likely to choose the nearest exits and shortest routes during evacuations, as also indicated by the studies of (Guo et al., 2012; Kobes et al., 2010a; Li et al., 2019; Liao et al., 2017). Secondly, regarding pedestrian wayfinding performance, our findings suggest that level changes make navigation more difficult, which is in line with the findings of (Hölscher et al., 2006; Kuliga et al., 2019), which found level change is a key source of disorientation in a multi-story building. Moreover, in agreement with (Cao et al., 2019; Lin et al., 2019; Meng & Zhang, 2014), we found participants had worse way-finding performance during emergencies compare to normal conditions. Thirdly, regarding the results of observation behaviour, the current study shows that participants had the most head rotations during evacuations (Zhang et al., 2021). Moreover, we found that hesitations were more often made at locations with high levels of information provided or confusion aroused, which is in line with the findings of (Conroy, 2001; Ewart & Johnson, 2021; Orellana & Al Sayed, 2013; Zhang et al., 2021). Additionally, we also found that room numbers, floor plans, fire doors and exit signs were the major attractors during wayfinding. This finding is consistent with previous literature on pedestrian wayfinding behaviour in buildings (Bode et al., 2014; Büchner et al., 2007; Dogu & Erkip, 2000; Duarte et al., 2014; Hessam & Debajyoti, 2018; Hölscher et al., 2013; Kobes et al., 2010b; Montello & Sas, 2006; Pati et al., 2015; Schrom-Feiertag et al., 2017). Lastly, the results show that, in general, participants behaved significantly different across four assignments, which aligns with what we would expect based on our experimental design and what would be expected in the real world. Our findings show that with the increased complexity of the four assignments (i.e., from within-floor assignment to between-floor assignments, from normal wayfinding assignments to evacuation assignment), overall, participants travelled longer distances, travelled at a slower speed, hesitated more often and had more head rotations. Furthermore, the learning effect is also observed as participants made fewer turns and adopted a more effective wayfinding strategy. Similar results pertaining to wayfinding behaviour in relation to assignment complexity have been described in the studies of (Cao et al., 2019; Lin et al., 2019; Meng & Zhang, 2014).

In ***Chapter 5***, the face validity of WayR was further assessed by comparing the usage of Desktop-version WayR and HMD-version VR to study pedestrian wayfinding behaviour. Overall, there were no significant differences in terms of realism. In both cases, participants reported an average score above 4 (total score: 5) which confirmed the face validity of both VR setups. This was also confirmed by comments from participants, for instance, ‘I feel like walking in the faculty’, ‘I feel the urge to get out of this building’, and ‘I want to be out of this building as quick as possible’ for the evacuation task. Overall, the high score of the face validity questionnaire further demonstrated the face validity of WayR.

To summarise, this thesis established the ecological validity of using Mobile VR to study pedestrian exit choice behaviour during evacuations; the face validity, the content validity and the construct validity of WayR to study pedestrian wayfinding behaviour in a complex a multi-level building under normal and evacuation conditions.

3. What are the functional requirements and procedures of developing a VR research tool to study pedestrian wayfinding behaviour in complex buildings?

The development process of a VR research tool considers four steps, namely (1) to define the functional requirements of the VR research tool, (2) to choose the virtual environment, (3) to construct the virtual environment and (4) to implement the interactive elements in the virtual environment. Chapter 4 details the steps one by one.

Based on the research goal of the VR research tool and review of previous studies pertaining to experimental designs to study pedestrian wayfinding behaviour, ***Chapter 4*** defines five key requirements for the development of the new VR research tool. Firstly, in order to study pedestrian wayfinding behaviour across horizontal and vertical levels, the VR research tool needs to allow users to perform wayfinding in multi-story buildings. Secondly, in order to allow for the validation of the VR tool, the virtual environment should feature a scenario that can be reproduced in reality, including all its intricacies. Thirdly, in order to ensure the validity of the VR research tool, the interaction between users and the virtual environment should be natural so that the participant can behave and react to events (e.g., evacuation) similarly to their real-life behaviour. Fourthly, the VR research tool is particularly designed to perform experiments, therefore, the VR tool should be able to track participant's movements, choice and observation behaviour (e.g., walking trajectory, timestamp, head rotation, gaze point). Lastly, the VR tool should be easy and comfortable to use for the participants and the researcher.

Based on the defined functional requirements, ***Chapter 4*** also showcased how to achieve the above-mentioned requirements and the development process of the VR research tool. Firstly, the choice of the virtual environment was to recreate an existing real-life multi-story building in VR at a high level of detail, which enable participants to perform wayfinding across floors and the possibilities to compare the results generated from WayR and the real world. Secondly, the 3D model of the building was developed and the virtual environment was developed based on the 3D model. The virtual building was modelled in 3D using the combined information from different sources featuring the major characteristics of the building and additional environmental elements were added to the 3D model to improve the accuracy of the building's representation and increase its realism. Afterwards, the 3D model was accordingly used to render the virtual environment, which including textures, shadow, lighting, reflection, transparency. Lastly, the VR research tool should support user interaction and provide an immersive environment to perform experiments. Thus, it is necessary to integrate navigation, viewpoint, trigger, soundscape, and data recording. In the end, WayR, a VR tool that represents a real-life multi-level building was built which supports free navigation and collects pedestrian walking trajectories, head rotations and gaze points automatically. Although there is an increasing interest in using VR to study pedestrian behaviour, the current study is one of the few studies (see Lovreglio et al., 2018) that presented requirements and the development process of the VR application to study pedestrian behaviour.

In ***Chapter 5***, the usability of the WayR is assessed based on user experience (e.g., the simulation sickness, feeling of presence, system usability). In order to evaluate the usability of WayR, VR experiments applying Desktop-version WayR and HMD-version WayR have been designed and conducted. Overall, there were no significant differences in terms of simulation sickness, the feeling of presence and usability between the two versions of WayR. With respect to the simulation sickness, the average total score of the Simulation Sickness Questionnaire (SSQ) in both groups was relatively low considering the maximum total score of the SSQ is 236 (Kennedy et al., 2003). In terms of the feeling of presence, the results revealed that participants in both groups experienced a high level of presence. The Presence Questionnaire (PQ) score of the current study is slightly higher than the studies that also used VR to study pedestrian behaviour (e.g., Deb et al., 2017; Lin et al., 2020a; Zhu et al., 2020b). Participants confirmed the usability of the two systems were both at an 'excellent level', according to the interpretation of the System Usability Scale (SUS) score made by (Bangor et al., 2009), which confirmed that both VR setups had good usability. Based on the results, we establish the usability of WayR by showing it offers a high immersive feeling, high usability, and low simulator sickness incidence.

4. What are the behavioural and perceptual similarities and differences of using different VR technologies to study pedestrian wayfinding behaviour?

Although VR has been applied increasingly to study pedestrian behaviour, it has remained unclear how different VR technology would affect behavioural outcomes. In this thesis, the usage of different VR technologies to study pedestrian behaviour is both quantitatively and qualitatively compared.

Chapter 5 directly compared pedestrian wayfinding behaviour in a multi-level building and user experience using different VR technologies. Wayfinding experiments with two groups of participants were conducted using HMD VR or Desktop VR. In particular, pedestrian behavioural data (i.e., pedestrian route and exit choice behaviour, observation behaviour, wayfinding task performance) and user experience data (i.e., realism, simulation sickness, presence, usability) were compared between two groups of participants, where one group used the HMD VR and another group used the Desktop VR. We found significant differences in wayfinding task performance between the HMD and the Desktop group. Participants of the Desktop group navigated more quickly and efficiently during all wayfinding tasks. Meanwhile, pedestrian route and exit choice behaviour (i.e., usage of wayfinding strategy, path, decision points, staircase) were found to be overall similar during the first two and the evacuation tasks.

Our study shows that for ‘simpler’ wayfinding tasks in multi-level buildings, pedestrian route and exit choice behaviour can be measured effectively using a more simple and less expensive Desktop VR. It indicated that for large-scale virtual environments, the benefits gained from increasing immersion may not be as prevalent as suggested in the literature (e.g., Santos et al., 2009; Buttussi & Chittaro, 2018). Furthermore, in contrast to previous VR comparison studies (e.g., Sharples et al., 2008; Rebenitsch & Owen, 2016; Buttussi & Chittaro, 2018), the realism, simulation sickness, presence, usability in the current study was overall similar between the HMD and the Desktop group. These findings imply that studies that investigate pedestrian route and exit choice behaviour of ‘simple’ wayfinding tasks (i.e., requires less spatial understanding) do not need to be limited to using immersive VR. Researchers can choose the best practice between HMD VR and Desktop VR base on their budget, existing equipment, and technical supports.

However, especially when more complex searching behaviour is triggered, the findings regarding the comparison of the wayfinding strategy and observation behaviour imply that differences can appear. In particular, there were differences in route choice (i.e., wayfinding strategy, decision point, staircase) during the task where the location of the destination was not clear-cut. Meanwhile, participants who used HMD had more head rotation change and observation behaviour during the first two tasks, while participants in the Desktop group had higher head rotation change during the evacuation task. Thus, in cases where the wayfinding task become more complex and searching behaviour are important factors that aid wayfinding, there may still be advantages to use immersive VR. One is advised to carefully consider the differences in behavioural outcomes between both VR technologies when investigating wayfinding behaviour for more ‘complex’ wayfinding tasks (i.e., requires more spatial understanding). The findings highlight that if one wants to investigate pedestrian wayfinding and observation behaviour in complex environments, a more intuitive and natural VR setting

(HMD VR in our case) needs to be ensured in order to allow natural observation of the environment.

Across the studies in ***Chapter 3*** and ***Chapter 5***, the usage of three different VR technologies can be qualitatively compared, namely Mobile VR, HMD VR and Desktop VR. Regarding pedestrian behaviour, we can see some similarities in pedestrian exit choice behaviour during evacuations. That is, in all experimental settings, the usage of the exits was asymmetrical. Within three experimental studies, only the nearest exits were chosen by the participants as the evacuation exits amongst all available exits. This behaviour is in line with other studies that find pedestrians were overall more likely to choose the nearest exits (Guo et al., 2012; Haghani & Sarvi, 2016a; Kobes et al., 2010a; Li et al., 2019; Liao et al., 2017). However, due to the technological limitation of the adopted Mobile VR and different research goals of three experimental studies, it is not possible to compare other perspectives of pedestrian behaviour across these studies (e.g., route choice, head rotation, gaze point).

Regarding user experience, it is interesting to notice that overall the Desktop VR and HMD VR had better scores than the Mobile VR with respect to simulation sickness, feeling of presence, and usability. We found that the studies used Desktop VR and HMD VR reported lower simulation sickness score than the Mobile-VR study, although participants were exposed longer to the VR environment in the multi-level wayfinding studies using Desktop VR and HMD VR. It might be explained by literature that suggests active participants may experience fewer symptoms (Sharples et al., 2008). That is, participants from the VR tool studies are able to move in the virtual environment and have more active searching behaviour (i.e., looking around) than in the Mobile VR study which participants were not able to move in the virtual environment but only observe the virtual environment. Moreover, although the Desktop VR is generally categorised as 'non-immersive' VR and the Mobile VR and HMD VR are 'immersive VR', Desktop VR and HMD VR reported higher scores than Mobile VR regarding the sub-scales of the Presence Questionnaire, such as Involvement and Immersion. Furthermore, although the score of the System Usability Scale questionnaire of all the VR studies indicated good usability, the SUS score of the VR tool studies is higher than the Mobile-VR study. It shows that the increased complexity of a VR system does not necessarily decrease usability.

6.2 Conclusions

The main research objective of this thesis is to understand '***To what extent VR technologies can be used to study pedestrian wayfinding behaviour in buildings***'. This thesis shows that different VR technologies (i.e., Mobile VR, HMD VR, Desktop VR) can collect valid behavioural data and study pedestrian wayfinding behaviour in various contexts. Based on the presented findings and discussions, we can draw the following conclusions:

1. VR can collect valid pedestrian data featuring exit choice behaviour in simple scenarios. Direct comparisons of pedestrian exit behaviour in real world and VR shows pedestrian behaved similarly in both cases, which shows that Mobile VR (smartphone-based HMD and

360° video) can be used to study pedestrian exit choice behaviour during evacuations in simple scenarios.

2. VR can collect valid pedestrian data featuring wayfinding behaviour in large-scale and complex scenarios. Applying WayR, wayfinding experiments consists of different wayfinding assignments in a multi-story building were conducted. The face validity is established based on participants' high score of the realism of the virtual environment and the consistency of their experience in the virtual building and real world. The content validity is demonstrated by showing the behavioural data collected by VR can reflect pedestrian wayfinding behaviour from ten relevant and complementary metrics identified by literature (e.g., decision making, wayfinding performance, observation behaviour) and allows the meaning of the data to be readily comprehended. The construct validity is determined by showing participants' wayfinding behaviour is consistent with pedestrian wayfinding behaviour studies in the literature and their behaviour is overall different amongst assignments with various complexity.

3. VR allows researchers to collect comprehensive data and accurately analyse numerous aspects of pedestrian behaviour in minute detail. This thesis shows that HMD VR and Desktop VR can collect comprehensive behavioural data simultaneously and these data can be transferred into decision making (e.g., choice of decision point, path, wayfinding strategy), wayfinding performance (e.g., travel speed, travel time, travel distance) and observation behaviour (e.g., head rotation, gaze point, hesitation). It provides opportunities to not only study pedestrian wayfinding behaviour from strategic and tactical levels but also operational level, which can help researchers acquire complementary information to further understanding the decision-making processes of pedestrian behaviour.

4. The technological differences of VR might cause differences in certain pedestrian wayfinding behaviour and participant's perception of the virtual environment. Quantitative comparison of HMD VR and Desktop VR shows that technological differences have a significant impact on wayfinding task performance, route choice and head rotation but not on participant's perception of the virtual environment. Qualitative comparison of Mobile VR, HMD VR and Desktop VR shows that different VR systems can cause different perceptions of the virtual environment regarding simulation sickness, feeling of presence and usability.

5. Pedestrian wayfinding behaviour is different between simple scenarios and complex scenarios. The comparison of pedestrian wayfinding behaviour during the four assignments with different complexity (i.e., from within-floor assignment to between-floor assignments, from normal wayfinding assignments to evacuation assignment) shows that, overall, participants travelled longer distances, travelled at a slower speed, hesitated more often and had more head rotations. Thus, in general, participants behaved significantly different between simple scenarios and more complex scenarios.

6.3 Implications for research and practice

Based on the key findings and conclusions of this thesis, we highlight several implications that are relevant for researchers and practitioners interest in the usage of VR to study pedestrian behaviour.

6.3.1 Implications for research

The findings in this thesis provide implications for research regarding the usage of VR and pedestrian wayfinding behaviour research.

1. VR technologies can be a valuable addition to the current experimental methods to study pedestrian behaviour.

First, this thesis validates the usage of VR to collect pedestrian wayfinding behavioural data in various contexts. Most importantly, this thesis found that pedestrians behaved similarly in virtual environments and the real world. This provides evidence for researchers that are interested in applying VR to study pedestrian wayfinding behaviour but are concerned about the validity issue of VR. Second, this thesis shows that researchers can create environments suitable for their research objectives with high experimental control and let participants experience the virtual world in an immersive and engaging way. Complex and stressful environments and a number of possible factors that potentially influence pedestrian wayfinding behaviour can easily be created and modified in VR, which ensure researchers still collect adequate behavioural data. Compared to other data collection methods, this thesis shows that compares to traditional data collection methods, using VR provides more opportunities for collecting pedestrian behavioural data accurately and automatically. It means that VR can provide researchers with easier and quicker access to the collected behavioural data. Third, this thesis shows that using VR, it is possible to collect detailed behavioural data (i.e., movement trajectory, head movement, gaze points), personal characteristics (e.g., age, gender, familiarity with VR) and user experience (i.e., realism, simulation sickness, feeling of presence, usability) in combination with questionnaires, which is almost impossible to achieve under real-world conditions. This finding provides proof that pedestrian researchers can collect comprehensive data sets featuring multi-dimensional behaviour data simultaneously and help researchers have new perspectives to understand pedestrian wayfinding behaviour. However, the types of collected data also depend on the VR setups, including both hardware and software capabilities. Moreover, it is worthy to note that the investments associated with the development and purchase of different VR setups for research purposes vary greatly.

2. Researchers should take the difference of VR technologies into account when making the choice of VR technology.

A key choice for studying pedestrian behaviour is which VR technology to use. When choosing among different VR technologies, this thesis suggests that researchers do not have to limit their options to HMD VR. This thesis shows the effectiveness of using Mobile-VR, Desktop VR and HMD VR to study pedestrian behaviour in various contexts. The quantitative and qualitative comparison of the above-mentioned VR technologies provide researchers empirical evidence to identify suitable choices regarding the usage of VR technologies for pedestrian wayfinding behaviour study. The findings suggest that the choice of suitable VR devices may depend more on the behavioural data researchers want to collect than the sophistication of the VR equipment.

Comparing Mobile VR to Desktop VR and HMD VR, choosing Mobile VR provides a low-cost solution but limits the type of data that can be collected. Our findings suggest that when a lack of clarity exists regarding which external variables should be included in the comprehensive pedestrian behaviour study, a preliminary pilot study featuring the combination of 360◦ video and smartphone-based HMD can allow researchers to get more grip on the actual set of influential factors.

The comparison between HMD VR and Desktop VR implies studies that investigate pedestrian route and exit choice behaviour of ‘simple’ wayfinding tasks (i.e., requires less spatial understanding) do not need to be limited to using immersive VR. Researchers can choose the best practice between HMD VR and Desktop VR base on their budget, existing equipment and technical supports. However, if one wants to investigate pedestrian wayfinding and observation behaviour in complex environments, a more intuitive and natural VR setting (HMD VR in our case) needs to be ensured in order to allow natural observation of the environment.

3. Guidance of developing VR research tool and exemplars of conducting VR experiments.

Besides choosing appropriate VR technologies, researchers face the challenge of developing suitable VR applications to meet their research objectives. This thesis provides a detailed description of developing a VR research tool to study pedestrian wayfinding behaviour, as exemplars to emulate for researchers who are interested in developing their own VR applications. Moreover, this thesis provides exemplars of designing VR experiments regarding the experimental set-up that combines the usage of VR technology and questionnaire to study pedestrian wayfinding behaviour and user experience. Human performance in the virtual environment is generally influenced by the interaction between the individual and the virtual environment. The combination may assist researchers in associating between pedestrian behaviour and human-computer interaction in order to better understand the usage of VR in the pedestrian field. The guidance of developing the VR research tool and exemplars of conducting VR experiments could help standardize the field in the future regarding the usage of VR for pedestrian research. Moreover, they can be applied not only for the usage of VR in pedestrian field but for other transport modes as well.

4. Behavioural findings pertaining to simplified scenarios cannot be directly generalised to complex scenarios.

This thesis shows that pedestrians behaved significantly different between simple scenarios and complex scenarios. This finding implies that when pedestrian researchers design experiments featuring pedestrian wayfinding behaviour in complex scenarios, experimental scenarios should mimic complex scenarios realistically and experimental setups should retain the capability of collecting pedestrian behaviour data. Moreover, researchers should take extra caution when generalizing behavioural findings pertaining to simplified environments to complex scenarios and vice versa.

6.3.2 Implications for practice

This thesis provides insights serval practical implications for architects, designers, and safety managers to improve pedestrian wayfinding efficiency in buildings.

1. Insights for evacuation management officials develop strategies to facilitate efficient evacuation.

The findings in this thesis regarding pedestrian evacuation behaviour provide insights to evacuation management officials to develop strategies to facilitate efficient evacuation. This thesis (***Chapter 3***) shows that pedestrians were more likely to recognise exits during evacuations when additional information was provided in the environment. Especially increasing the visibility of the exit sign allows pedestrians to, on average, recognise more exits. Moreover, increased visibility of the exit sign is also found to ensure a more symmetrical usage of the exits. Meanwhile, the results show pedestrians prefer to choose the nearest exits and shortest routes. Therefore, when evacuation management officials develop strategies to facilitate efficient evacuation, they can take these insights into account in order to utilize evacuation exits evenly and avoid crowd in front of exits.

2. Insights of pedestrian wayfinding behaviour for designing infrastructure and signage to facilitate wayfinding in public buildings.

This thesis found that room numbers, floor plans, fire doors, starting position and destinations were the main attractions for participants to find their way in a mulita-level building (***Chapter 5***). Moreover, it is found that hesitations were more often made at locations with high levels of information provided or confusion aroused. These information help to identify locations where pedestrians search for information and determine what environmental features they need or look at in order to inform their wayfinding process. Furthermore, it is found that level change is a key source of disorientation in a multi-level building. Therefore, these insights could be useful for practitioners that involve in planning complex buildings to producing effective signage in complex and large-scale buildings. Additionally, our study illustrates that floor strategy was employed dominantly in a multi-level building and pedestrians preferred to use the wider corridors over narrow ones. These findings regarding the usage of wayfinding strategies in a multi-level environment provide empirical evidence for professionals to predict and plan the main navigational flow even when a complex network of paths and decision points exist.

3. A ready-to-use VR research tool to test the impact of evacuation interventions.

The findings in this thesis show that WayR is capable to collect valid behavioural data in both normal and emergency situations (***Chapter 4***). Meanwhile, WayR provides an immersive environment to perform high-fidelity experiments and offers the possibility to simulate virtual objects (e.g., smoke, route indicators, emergency lights) in dangerous situations (e.g., building fire, earthquakes). Moreover, the virtual building of WayR was built based on the building of the Civil Engineering and Geoscience Faculty of the Delft University of Technology. Thus, WayR provides the chance to train the evacuation and safety staff from the local community to better manage and organize the evacuation process; and test the impact of evacuation interventions before its implementation, such as escape route indicators, evacuation escape planning, and evacuation information strategies.

6.4 Future research directions

Several limitations exist in the current study and need to be addressed in future work. In this section, we formulate several recommendations for directions of future research that can build on the work presented in this thesis. These research directions are divided into four topics, namely further validation study, improve the realism of VR, test impacts of interventions, and combine VR with new types of technology.

1. Further validation of behavioural data generated by WayR.

Although face validity, content validity and construct validity of WayR are established (***Chapter 4***), further validation of WayR still needs to be determined. That is whether the pedestrian wayfinding behaviour in the virtual building is also similar to pedestrians' behaviour in the identical real-world building. It was our intention to conduct a large-scale validation experiment which is one of the motivations of creating a real-life based virtual scenario. Due to COVID-19, directional and physical distancing signage signifying flow were placed in the building, which made it is impossible to conduct the field experiment with an identical setting as the VR experiment. Thus, when the conditions allow, empirical data in real life needs to be collected in order to compare pedestrian behaviour collected in the virtual building and behavioural results collected in the real world, particularly to perform the same set of wayfinding tasks in a similar setting. Moreover, this comparison will allow us to quantitatively measure the advantage of using HMD VR for complex wayfinding tasks compare to Desktop VR.

2. Improve the social realism and environmental realism of VR

For the sake of validation purposes, this thesis mainly investigated pedestrian behaviour in normal scenarios and typical emergency scenarios (i.e., evacuation drills) that can be reproduced in the real building. Elements such as fire and smoke that can potentially contribute to a more realistic experience were not included in the scenarios. Future studies should continue working on improving the realism of experience in VR. This can be achieved on two aspects, namely social realism, and environmental realism. Regarding social realism, it is found the presence of other people and their interaction might influence pedestrian wayfinding behaviour. The Mobile-VR study (***Chapter 3***) shows that herding behaviour can have a significant influence on pedestrian exit choice during evacuations. Comments made by the participants from the WayR experiment (***Chapter 4***) also reveal that elements, such as the presence of other pedestrians and the interaction with other people, can potentially make the current virtual experience more realistic. In WayR, no other agents or socially relevant variables were added at this stage because the goal is to evaluate the validity and usability of WayR. Thus, it would be interesting to add multiple users in the environment simultaneously and investigate the impact of the interaction with other virtual pedestrians on pedestrian wayfinding behaviour, especially in multi-level buildings. Regarding environmental realism, some realistic characteristics such as noise in normal conditions and smoke and fire during evacuations were not considered in this thesis. With the ability to simulate a variety of contexts with high experimental control, it is possible to integrate these elements in VR and investigate how pedestrians behave in these scenarios.

3. Test impacts of interventions and personal characteristics on pedestrian wayfinding behaviour in VR.

Besides understanding how pedestrians interact with existing conditions, there is a need to investigate the impacts of different interventions on wayfinding behaviour in VR that mean to improve pedestrian wayfinding and evacuation efficiency. One of the advantages of VR is the ability to rapidly change the scenario and add new elements to the scenario. Moreover, this thesis shows that it is possible to conduct VR experiments with various conditions but in an almost identical setting. Based on the evidence that VR is able to collect valid behavioural data, it is possible to systematically determine the impact of interventions in high-risk scenarios (e.g., fire evacuations, earthquakes) and hypothetic scenarios (e.g., dynamic signage, floorplans in case of Covid-19) on pedestrian wayfinding behaviour. This could help researchers to gain insights on how various external factors affect pedestrian behaviour which helps researchers understand the interaction between pedestrians and scenarios that do not exist today and also helps planners through dilemmas when designing future interventions. Besides testing the effectiveness of interventions, it is possible to use VR as a training tool to test whether evacuation training in VR can improve pedestrian evacuation behaviour. VR offers an appealing alternative that trains pedestrians in virtual environments without being exposed to real danger.

Moreover, individual differences were not investigated in this thesis, such as age, gender, familiarity with the building. Future works could explore the impact of individual differences on pedestrian wayfinding behaviour in order to gain a better understanding of how heterogeneous individuals behave while accomplishing wayfinding tasks.

4. Incorporate new technologies with VR to study pedestrian wayfinding behaviour.

This thesis only applied VR to study pedestrian wayfinding behaviour in entire virtual environments. Augmented reality (AR) technology is another addition to the set of VR technologies. AR superimposes synthetic three-dimensional stimuli (e.g. people, vehicles, signs) on objects in the real world (Sherman & Craig, 2003). It can interactively and accurately align real and virtual objects with each other in real-time (Azuma, 1997), which would allow researchers to investigate pedestrian instant interactions with real world during the wayfinding process.

This thesis shows that the combination of traditional measures of pedestrian wayfinding behaviour and observation behaviour can be useful analysis to further our understanding of the decision-making process. With this combination, researchers can not only determine where people travelled for how long but also where they stopped and where do they look at and searched for information. It is worthy to note that this thesis has analysed pedestrian observation behaviour in a virtual building based on head-tracking technologies and gazing behaviour was only studied qualitatively in this study. It could be improved by further quantitative analysis of gazing behaviour, such as gaze time, gaze quantity and gaze sequences. Moreover, with the rapid development of tracking technologies, such as eye-tracking, body-tracking, it is possible to incorporate these technologies with VR to gather more advanced and accurate behavioural data. Furthermore, VR can be integrated with sensing technologies (e.g., heart rate, electroencephalogram sensors, biosensors) that can reflect participant’s mental and physical states instantaneously. The combination of behavioural data and physiological data may provide additional insights and new perspectives for wayfinding behaviour.

Appendix

Appendix A. Summary of reviewed studies (Chapter 2)

Table A. 1: Studies based on field observations using traditional techniques and monitoring techniques.

	Experimental Set-Up				**Pedestrian behaviour**														
					Strategic			Tactical						Operational					
								Route choice				Exit choice					Interaction with pedestrians		
Article	Sample size	Sample type	Condition	Equipment	Activity choice	Destination choice	Activity scheduling	Interaction with spaces	Interaction with information	Interaction with objects	Interaction with pedestrians	Interaction with information	Interaction with pedestrians	Movement through spaces	Interaction with objects	Interaction with information	Following behaviour	Group behaviour	Collision avoidance behaviour
Shields & Boyce (2000)	2,072	customer, staff	store	video	·	·	✓	·	✓	·	·	✓	·	·	·	·	·	·	·

Article	Experimental Set-Up				Pedestrian behaviour														
					Strategic			Tactical						Operational					
								Route choice				Exit choice					Interaction with pedestrians		
	Sample size	Sample type	Condition	Equipment	Activity choice	Destination choice	Activity scheduling	Interaction with spaces	Interaction with information	Interaction with objects	Interaction with pedestrians	Interaction with information	Interaction with pedestrians	Movement through spaces	Interaction with objects	Interaction with information	Following behaviour	Group behaviour	Collision avoidance behaviour
Yang et al. (2012)	?	student	teaching building	video	·	·	·	·	·	·	·	·	·	✓	·	·	·	✓	·
Galea et al. (2017)	1,200	audience	theatre	video	·	·	✓	·	·	·	·	·	·	·	·	·	·	·	·
Nilsson & Johansson (2009)	135	audience	cinema	video	·	·	✓	·	·	·	·	·	·	·	·	·	·	·	·
Fruin (1971)	?	commuter	walkway in a bus terminal	photography	·	·	·	·	·	·	·	·	·	✓	·	·	·	·	·
Corbetta et al. (2016)	80,000	passenger	main walkway of the train station	Microsoft Kinect TM sensors	·	·	·	·	·	·	·	·	·	✓	·	·	·	·	·
Lam et al. (1995)	?	pedestrian	stairway, walkway, etc.	video and manual count	·	·	·	·	·	·	·	·	·	✓	·	·	·	·	·
Virkler & Elayadath (1992)	?	pedestrian	walkway	video, stopwatch	·	·	·	·	·	·	·	·	·	✓	·	·	·	·	·
Al-azzawi & Raeside (2007)	7,535	pedestrian	sidewalk	video	·	·	·	·	·	·	·	·	·	✓	·	·	·	·	·

Article	**Experimental Set-Up**				**Pedestrian behaviour**															
					Strategic			Tactical						Operational						
								Route choice				Exit choice					Interaction with pedestrians			
	Sample size	Sample type	Condition	Equipment	Activity choice	Destination choice	Activity scheduling	Interaction with spaces	Interaction with information	Interaction with objects	Interaction with pedestrians	Interaction with information	Interaction with pedestrians	Movement through spaces	Interaction with objects	Interaction with information	Following behaviour	Group behaviour	Collision avoidance behaviour
Tanaboriboon et al. (1986)	519	pedestrian	sidewalk, walkway	video recorder	·	·	·	·	·	·	·	·	·	✓	·	·	·	·	·
Shah et al. (2013)	?	passenger	stairway	video	·	·	·	·	·	·	·	·	·	✓	·	·	·	·	·
Tanaboriboon & Guyano (1991)	?	pedestrian	stairway	video	·	·	·	·	·	·	·	·	·	✓	·	·	·	·	·
Moussaïd et al. (2010)	1,500	group	public place; commercial walkway	video	·	·	·	·	·	·	·	·	·	·	·	·	·	✓	·
Duives et al. (2014)	712	group	corridor	video	·	·	·	·	·	·	·	·	·	✓	·	·	·	✓	·
Gorrini et al. (2015)	1,645	group	commercial walkway	video	·	·	·	·	·	·	·	·	·	·	·	·	·	✓	·
Do et al. (2016)	50	group	train station	video	·	·	·	·	·	·	·	·	·	✓	·	·	·	✓	·
Feng & Li (2017, 2016)	300;830	group	campus; metro station	video	·	·	·	·	·	·	·	·	·	·	·	·	·	✓	·
Duives (2012)	?	visitor	festival	drone	·	·	·	·	·	·	·	·	·	✓	·	·	·	·	·

Article	Experimental Set-Up				Pedestrian behaviour															
					Strategic			Tactical						Operational						
								Route choice				Exit choice		Movement through spaces	Interaction with objects	Interaction with information	Interaction with pedestrians		
	Sample size	Sample type	Condition	Equipment	Activity choice	Destination choice	Activity scheduling	Interaction with spaces	Interaction with information	Interaction with objects	Interaction with pedestrians	Interaction with information	Interaction with pedestrians				Following behaviour	Group behaviour	Collision avoidance behaviour
Zhang et al. (2013)	30,000	visitor	festival	video, infrared counter	·	·	·	·	·	·	·	·	·	✓	·	·	·	·	·
Helbing et al. (2007)	?	visitor	festival	video	·	·	·	·	·	·	·	·	·	✓	·	·	·	·	·
Johansson et al. (2008)	?	visitor	festival	video	·	·	·	·	·	·	·	·	·	✓	·	·	·	·	·
Ma et al. (2013)	?	visitor	festival	video	·	·	·	·	·	·	·	·	·	✓	·	·	·	·	·
Larsson et al. (2020)	?	visitor	public events	video footage	·	·	·	·	·	·	·	·	·	✓	·	·	·	·	·
Wang et al. (2019)	?	pedestrian	terrorist attack	recorded video	·	·	·	·	·	·	·	·	·	✓	·	·	·	✓	·
Favaretto et al. (2017)	?	crowd	multi-crowded scenes	video	·	·	·	·	·	·	·	·	·	✓	·	·	·	·	·
Wang et al. (2012)	?	pedestrian	normal, abnormal scene	video	·	·	·	·	·	·	·	·	·	✓	·	·	·	·	·
Duives (2016)	?	visitor	festival	video	·	·	·	·	·	·	·	·	·	✓	·	·	·	·	·
Li et al. (2020)	?	crowd	road intersectio	video	·	·	·	·	·	·	·	·	·	✓	·	·	·	·	·

Article	Experimental Set-Up				Pedestrian behaviour														
					Strategic			Tactical						Operational					
								Route choice				Exit choice					Interaction with pedestrians		
	Sample size	Sample type	Condition	Equipment	Activity choice	Destination choice	Activity scheduling	Interaction with spaces	Interaction with information	Interaction with objects	Interaction with pedestrians	Interaction with information	Interaction with pedestrians	Movement through spaces	Interaction with objects	Interaction with information	Following behaviour	Group behaviour	Collision avoidance behaviour
			n area; festival																
Centorrino et al. (2019)	900	visitor	museum	Bluetooth	·	·	✓	·	·	·	·	·	·	·	·	·	·	·	·
Danalet et al. (2016)	5,902	employee, student	campus	Wi-Fi	·	✓	✓	·	·	·	·	·	·	·	·	·	·	·	·
Ton et al. (2015)	240,949	passenger	train station	Wi-Fi, Bluetooth	·	✓	✓	✓	·	·	·	·	·	·	·	·	·	·	·
Versichele et al. (2012)	80,828	visitor	festival	Bluetooth	·	·	·	·	·	·	·	·	·	✓	·	·	·	·	·
Yoshimura et al. (2014)	24, 452	visitor	museum	Bluetooth	✓	✓	✓	·	·	·	·	·	·	·	·	·	·	·	·
Yoshimura et al. (2017)	105,597	visitor	museum	Bluetooth	✓	✓	✓	·	·	·	·	·	·	·	·	·	·	·	·
Bonne et al. (2013)	29,296; 16,486	visitor	festival; university campus	Wi-Fi	·	✓	·	·	·	·	·	·	·	·	·	·	·	·	·
Duives et al. (2018)	659	visitor	festival	Wi-Fi, camera	·	✓	·	·	·	·	·	·	·	·	·	·	·	·	·
Gioia et al. (2019)	7623	visitor	public event	Wi-Fi	·	·	·	·	·	·	·	·	·	✓	·	·	·	·	·

Article	Experimental Set-Up				Pedestrian behaviour														
					Strategic			Tactical						Operational					
								Route choice				Exit choice					Interaction with pedestrians		
	Sample size	Sample type	Condition	Equipment	Activity choice	Destination choice	Activity scheduling	Interaction with spaces	Interaction with information	Interaction with objects	Interaction with pedestrians	Interaction with information	Interaction with pedestrians	Movement through spaces	Interaction with objects	Interaction with information	Following behaviour	Group behaviour	Collision avoidance behaviour
Wirz et al. (2012)	800	visitor	festival	GPS, Wi-Fi	·	·	·	·	·	·	·	·	·	✓	·	·	·	·	·
Farooq et al. (2015)	156,789	pedestrian	festival	Wi-Fi, infrared sensors	·	✓	✓	✓	·	·	·	·	·	·	·	·	·	·	·
Daamen et al. (2016)	?	visitor	festival	camera, Wi-Fi, GPS	·	·	·	·	·	·	·	·	·	✓	·	·	·	·	·
van der Spek (2008)	80;150;130	pedestrian	city centre	GPS	✓	✓	·	·	·	·	·	·	·	·	·	·	·	·	·
Galama (2015)	155	visitor	festival	GPS	·	·	·	✓	✓	✓	✓	·	·	·	·	·	·	·	·
Daamen et al. (2017)	109	visitor	festival	GPS	·	✓	·	·	✓	✓	✓	·	·	·	·	·	·	·	·
Blanke et al. (2014)	29,000	visitor	festival	GPS	✓	✓	·	·	·	·	·	·	·	✓	·	·	·	·	·
Duives et al. (2019)	9,748	visitor	festival	GPS	·	✓	·	✓	·	·	·	·	·	·	·	·	·	·	·
Gao (2015)	74,000,000	mobile phone caller/receiver	city	mobile phone	✓	✓	·	·	·	·	·	·	·	·	·	·	·	·	·
Keij (2014)	?	SMS sender/caller	city corridor	mobile phone	·	·	✓	·	·	·	·	·	·	·	·	·	·	·	·

Article	Experimental Set-Up				Pedestrian behaviour														
					Strategic			Tactical						Operational					
								Route choice				Exit choice					Interaction with pedestrians		
	Sample size	Sample type	Condition	Equipment	Activity choice	Destination choice	Activity scheduling	Interaction with spaces	Interaction with information	Interaction with objects	Interaction with pedestrians	Interaction with information	Interaction with pedestrians	Movement through spaces	Interaction with objects	Interaction with information	Following behaviour	Group behaviour	Collision avoidance behaviour
Calabrese et al. (2011)	30, 000	mobile phone caller	public transport	mobile phone	✓	✓	·	✓	·	·	·	·	·	·	·	·	·	·	·
Zhang et al., 2017)	?	mobile phone caller	CBD	mobile phone	·	✓	·	·	·	·	·	·	·	·	·	·	·	·	·
Botta et al. (2015)	?	social media user	city	social media	·	✓	·	·	·	·	·	·	·	·	·	·	·	·	·
Yang et al. (2019)	70,000	social media user	city	social media	✓	✓	✓	·	·	·	·	·	·	·	·	·	·	·	·
Gong et al. (2020, 2018)	?; 378	social media user	festival	social media	·	✓	·	·	·	·	·	·	·	·	·	·	·	·	·
Yang et al. (2019)	3757	social media user	university	social media	✓	✓	·	·	·	·	·	·	·	·	·	·	·	·	·
Alkhatib et al. (2019)	?	social media user	incident	social media	·	✓	·	·	·	·	·	·	·	·	·	·	·	·	·

Note: ✓ This article studied this type of behaviour.
? The article did not mention this information explicitly.
· This behaviour is not included in the scope of this study.

Table A. 2: Studies based on controlled experiments under normal and emergency conditions.

Article	Experiment Set-Up				Pedestrian behaviour														
					Strategic			Tactical						Operational					
								Route choice				Exit choice					Interaction with pedestrians		
	Sample size	Sample type	Condition	Equipment	Activity choice	Destination choice	Activity scheduling	Interaction with spaces	Interaction with information	Interaction with objects	Interaction with pedestrians	Interaction with information	Interaction with pedestrians	Movement through spaces	Interaction with objects	Interaction with information	Following behaviour	Group behaviour	Collision avoidance behaviour
Bukáček et al. (2018)	76	student	bottleneck	camera	·	·	·	·	·	·	·	·	·	✓	·	·	·	·	·
Daamen & Hoogendoorn (2003a)	80	?	bottleneck	camera	·	·	·	·	·	·	·	·	·	✓	·	·	·	·	·
Helbing et al. (2005)	100	student	bottleneck	camera	·	·	·	·	·	·	·	·	·	✓	·	·	·	·	·
Hoogendoorn & Daamen (2005)	60-90	?	bottleneck	camera	·	·	·	·	·	·	·	·	·	✓	·	·	·	·	·
Kretz et al. (2006)	94	student	bottleneck	camera	·	·	·	·	·	·	·	·	·	✓	·	·	·	·	·
Liao et al. (2014a)	350	student	bottleneck	camera	·	·	·	·	·	·	·	·	·	✓	·	·	·	·	·
Seyfried et al. (2009)	20,40,60	student, staff	bottleneck	camera	·	·	·	·	·	·	·	·	·	✓	·	·	·	·	·
Seyfried et al. (2010,)	250	soldier	bottleneck	camera	·	·	·	·	·	·	·	·	·	✓	·	·	·	·	·
Zhang & Seyfried (2014)	400	?	bottleneck	camera	·	·	·	·	·	·	·	·	·	✓	·	·	·	·	·
Seyfried et al. (2005)	1;15;20;25;30; 34	student, staff	corridor	camera	·	·	·	·	·	·	·	·	·	✓	·	·	·	·	·

	Experiment Set-Up				**Pedestrian behaviour**														
					Strategic			Tactical						Operational					
								Route choice				Exit choice					Interaction with pedestrians		
Article	Sample size	Sample type	Condition	Equipment	Activity choice	Destination choice	Activity scheduling	Interaction with spaces	Interaction with information	Interaction with objects	Interaction with pedestrians	Interaction with information	Interaction with pedestrians	Movement through spaces	Interaction with objects	Interaction with information	Following behaviour	Group behaviour	Collision avoidance behaviour
Chattaraj et al. (2009)	1;15;20;25;30;34	student	corridor	camera	·	·	·	·	·	·	·	·	·	✓	·	·	·	·	·
Liu et al. (2009)	1;15;20;25;30;34	student, staff, local resident	corridor	camera	·	·	·	·	·	·	·	·	·	✓	·	·	·	·	·
Boltes et al. (2011)	350	student	corridor, T-junction	camera	·	·	·	·	·	·	·	·	·	✓	·	·	·	·	·
Zhang & Seyfried (2013)	400	mostly student	straight corridor	stereo camera	·	·	·	·	·	·	·	·	·	✓	·	·	·	·	·
Wong et al. (2010)	24-90	student	walkway with angles	camera	·	·	·	·	·	·	·	·	·	✓	·	·	·	·	·
Zhang & Seyfried (2014)	350; 46	student	corridor; intersection with pillar and staircase	camera	·	·	·	·	·	·	·	·	·	✓	·	·	·	·	·
Shiwakoti et al. (2015)	22	student	merging corridor	camera	·	·	·	·	·	·	·	·	·	✓	·	·	·	·	·

Article	**Experiment Set-Up**				**Pedestrian behaviour**														
					Strategic			Tactical						Operational					
								Route choice				Exit choice					Interaction with pedestrians		
	Sample size	Sample type	Condition	Equipment	Activity choice	Destination choice	Activity scheduling	Interaction with spaces	Interaction with information	Interaction with objects	Interaction with pedestrians	Interaction with information	Interaction with pedestrians	Movement through spaces	Interaction with objects	Interaction with information	Following behaviour	Group behaviour	Collision avoidance behaviour
Lian et al. (2017)	295	student	angled channel	video	·	·	·	·	·	·	·	·	·	✓	·	·	·	·	·
Gorrini et al. (2013)	68	?	room with corridor	camera	·	·	·	·	·	·	·	·	·	✓	·	·	·	✓	·
Dias et al. (2014)	16	?	corridors with turning angels	camera	·	·	·	·	·	·	·	·	·	✓	·	·	·	·	·
Rahman et al. (2019)	60	undergraduate student	angled corridor	GoPro 5 camera	·	·	·	·	·	·	·	·	·	✓	·	·	·	·	·
Ziemer et al. (2016)	1,000	student	ring corridor	camera	·	·	·	·	·	·	·	·	·	✓	·	·	·	·	·
Huang et al. (2018)	25	student	seat with aisle	camera	·	·	·	·	·	·	·	·	·	·	✓	·	·	·	✓
Cao et al. (2019b)	30	?	ring corridor	camera	·	·	·	·	·	·	·	·	·	✓	·	·	·	·	·
Hu et al. (2019)	72	student	circle	camera	·	·	·	·	·	·	·	·	·	·	·	·	·	·	✓
Xiao et al. (2019)	64	university student	circle	camera	·	·	·	·	·	·	·	✓	·	✓	·	·	·	·	·

Article	**Experiment Set-Up**				**Pedestrian behaviour**														
					Strategic			Tactical						Operational					
								Route choice				Exit choice					Interaction with pedestrians		
	Sample size	Sample type	Condition	Equipment	Activity choice	Destination choice	Activity scheduling	Interaction with spaces	Interaction with information	Interaction with objects	Interaction with pedestrians	Interaction with information	Interaction with pedestrians	Movement through spaces	Interaction with objects	Interaction with information	Following behaviour	Group behaviour	Collision avoidance behaviour
Paris et al. (2007)	6;24	?	a square area visible	motion capture system	·	·	·	·	·	·	·	·	·	·	·	·	·	·	✓
Moussaïd et al. (2009)	40	?	hospital	camera, tracking system	·	·	·	·	·	·	·	·	·	·	·	·	·	·	✓
Versluis (2010)	12	?	educational building	camera, tracking system	·	·	·	·	·	·	·	·	·	·	·	·	·	·	✓
Moussaïd et al. (2012)	119	?	a ring-shaped corridor	motion capture system	·	·	·	·	·	·	·	·	·	·	·	·	·	·	✓
Huber et al. (2014)	10	?	middle of a room	video, tracking system	·	·	·	·	·	·	·	·	·	·	·	·	·	·	✓
Parisi et al. (2016)	20	?	parking lot	GoPro 3 camera	·	·	·	·	·	·	·	·	·	·	·	·	·	·	✓
Liu et al. (2016)	40	student	rectangular room	camera	·	·	·	·	·	·	·	·	·	·	·	·	·	·	✓
Li et al. (2019)	233	visitor	hall with obstacles	camera	·	·	·	·	·	✓	·	·	·	·	·	·	·	·	·

Article	Experiment Set-Up				Pedestrian behaviour														
					Strategic			Tactical						Operational					
								Route choice				Exit choice					Interaction with pedestrians		
	Sample size	Sample type	Condition	Equipment	Activity choice	Destination choice	Activity scheduling	Interaction with spaces	Interaction with information	Interaction with objects	Interaction with pedestrians	Interaction with information	Interaction with pedestrians	Movement through spaces	Interaction with objects	Interaction with information	Following behaviour	Group behaviour	Collision avoidance behaviour
Daamen & Hoogendoorn (2010)	90-150	children, adult, elder	emergency door	video	·	·	·	·	·	·	·	·	·	✓	·	·	·	·	·
Tian et al. (2012)	62	student	bottleneck	video	·	·	·	·	·	·	·	·	·	✓	·	·	·	·	·
Jo et al. (2014)	56	?	room connect to corridor	video	·	·	·	·	·	·	·	·	·	✓	·	·	·	·	·
Huo et al., 2016)	73	college student	high-rise building.	video	·	·	·	·	·	·	✓	·	✓	✓	·	·	·	·	·
Shahhoseini et al. (2017)	150	?	merging corridor	video	·	·	·	·	·	·	·	·	·	✓	·	·	·	·	·
Cao et al. (2018)	65	?	supermarket	video	·	·	·	·	·	·	✓	·	✓	·	·	·	·	·	·
Zhao et al. (2020)	80	college student	room with obstacles	video	·	·	·	·	·	·	·	·	·	·	✓	·	·	·	·
Ding et al. (2020)	52	college student	room with obstacles	video	·	·	·	·	·	·	·	·	·	·	✓	·	·	·	·
Fang et al. (2010a)	294	?	educational hall with two exits and stairs	video	·	·	·	·	·	·	✓	·	·	✓	·	·	·	·	·

Article	**Experiment Set-Up**				**Pedestrian behaviour**														
					Strategic			Tactical						Operational					
								Route choice				Exit choice					Interaction with pedestrians		
	Sample size	Sample type	Condition	Equipment	Activity choice	Destination choice	Activity scheduling	Interaction with spaces	Interaction with information	Interaction with objects	Interaction with pedestrians	Interaction with information	Interaction with pedestrians	Movement through spaces	Interaction with objects	Interaction with information	Following behaviour	Group behaviour	Collision avoidance behaviour
Jeon et al. (2011)	125	citizen	transportation building	recorder	·	·	·	·	✓	·	·	·	·	·	·	✓	·	·	·
Guo et al. (2012)	78	?	classroom with obstacles and desks	video	·	·	·	·	✓	✓	✓	·	✓	·	·	·	·	·	·
Zhu & Shi (2016)	102	?	teaching building	video	·	·	·	✓	✓	·	✓	✓	✓	·	·	·	·	·	·
Fridolf et al. (2013)	100	?	tunnel with artificial cold smoke and acetic acid	video	·	·	·	·	·	·	·	✓	·	✓	·	·	·	·	·
Galea et al. (2017)	700	?	rail station platform	video	·	·	·	·	·	·	·	✓	·	·	·	·	·	·	·
D’Orazio et al. (2016)	113	?	theatre	video	·	·	·	·	·	·	·	·	·	·	·	✓	·	·	·
Ronchi et al. (2018)	66	?	road tunnel	thermal imaging camera	·	·	·	·	·	·	·	✓	·	✓	·	✓	·	·	·

Article	Experiment Set-Up				Pedestrian behaviour														
	Sample size	Sample type	Condition	Equipment	Strategic			Tactical						Operational					
								Route choice				Exit choice					Interaction with pedestrians		
					Activity choice	Destination choice	Activity scheduling	Interaction with spaces	Interaction with information	Interaction with objects	Interaction with pedestrians	Interaction with information	Interaction with pedestrians	Movement through spaces	Interaction with objects	Interaction with information	Following behaviour	Group behaviour	Collision avoidance behaviour
Porzycki et al. (2018)	28;50	tunnel professional; student	road tunnel	video, infrared cameras	·	·	·	·	·	·	·	·	·	·	·	✓	·	·	·
Cao et al. (2019a)	30	graduate student	rectangle room	video	·	·	·	·	·	·	·	·	·	✓	·	·	·	·	·
Heliövaara et al. (2012)	54	student	a corridor with two exits	video	·	·	·	·	·	·	✓	·	✓	·	·	·	·	·	·
von Krüchten & Schadschneider (2017)	32–46	student	built room	video	·	·	·	·	·	·	·	·	·	·	·	·	·	✓	·
Haghani & Sarvi (2017)	150	?	room with multiple exits	video	·	·	·	·	·	·	·	·	·	·	·	·	✓	·	·
Xie et al. (2020)	36	college student	rectangle steel structure room	video	·	·	·	·	·	·	·	·	·	✓	·	·	✓	·	·

Note: ✓ This article studied this type of behaviour.
? The article did not mention this information explicitly.
· This behaviour is not included in the scope of this study.

Table A. 3: VR studies related to pedestrian behaviour.

Article	Experiment Set-up				Pedestrian behaviour														
					Strategic			Tactical						Operational					
								Route choice				Exit choice		Movement through spaces	Interaction with objects	Interaction with information	Interaction with pedestrians		
	Sample size	Sample type	Scenario	VR/AR equipment	Activity choice	Destination choice	Activity scheduling	Interaction with spaces	Interaction with information	Interaction with objects	Interaction with pedestrians	Interaction with information	Interaction with pedestrians				Following behaviour	Group behaviour	Collision avoidance behaviour
Tan et al. (2006)	?	?	city scene	video-based	✓	✓	✓	·	·	·	·	·	·	·	·	·	·	·	·
Natapov & Fisher-Gewirtzman (2016)	40	students, researcher, staff	city district	HMD, joystick	✓	✓	·	·	·	·	·	·	·	·	·	·	·	·	·
Feng et al. (2020a)	16	?	multilevel building	HMD	·	·	·	✓	·	·	·	·	·	·	·	·	·	·	·
Fink et al. (2007)	10	?	room with obstacle	HMD; bicycle helmet	·	·	·	·	·	·	·	·	·	·	✓	·	·	·	·
Sanz et al. (2015)	17	student or professional	room with obstacle	shutter glasses, CAVE-like environment	·	·	·	·	·	·	·	·	·	·	✓	·	·	·	·

Article	Experiment Set-up				Pedestrian behaviour														
					Strategic			Tactical						Operational					
								Route choice				Exit choice					Interaction with pedestrians		
	Sample size	Sample type	Scenario	VR/AR equipment	Activity choice	Destination choice	Activity scheduling	Interaction with spaces	Interaction with information	Interaction with objects	Interaction with pedestrians	Interaction with information	Interaction with pedestrians	Movement through spaces	Interaction with objects	Interaction with information	Following behaviour	Group behaviour	Collision avoidance behaviour
Li et al. (2019)	146	mostly student	hall with obstacles	computer-based	·	·	·	·	✓	·	·	·	·	·	·	·	·	·	·
Bruneau et al. (2015)	13	?	street-like	CAVE	·	·	·	·	·	·	·	·	·	·	·	·	·	·	✓
Kinateder et al. (2014a)	40	mainly student	road tunnel	two video projectors, powerwall, polarized glasses	·	✓	✓	·	·	·	·	·	·	·	·	·	·	·	·
Kinateder et al. (2014b)	42	mainly student	road tunnel	CAVE	·	✓	✓	·	·	·	✓	·	·	·	·	·	·	·	·
Kinateder & Warren (2016)	150	?	room with exits	HMD	·	·	·	·	·	·	·	✓	·	·	·	·	·	·	·
Bode et al. (2015)	464	?	a central room and two corridors	computer-based	·	·	·	·	·	·	✓	·	✓	·	·	·	·	·	·

Article	**Experiment Set-up**				**Pedestrian behaviour**														
					Strategic			Tactical						Operational					
								Route choice				Exit choice					Interaction with pedestrians		
	Sample size	Sample type	Scenario	VR/AR equipment	Activity choice	Destination choice	Activity scheduling	Interaction with spaces	Interaction with information	Interaction with objects	Interaction with pedestrians	Interaction with information	Interaction with pedestrians	Movement through spaces	Interaction with objects	Interaction with information	Following behaviour	Group behaviour	Collision avoidance behaviour
van den Berg (2016)	378	student, mixed population	island	computer-based	✓	✓	✓	·	✓	·	✓	·	·	·	·	·	·	·	·
Moussaïd et al. (2016b)	36	?	corridor; bottleneck	computer-based	·	·	·	·	·	·	✓	·	·	·	·	·	·	·	·
Kinateder et al. (2018a)	40	mostly student	a museum room with two exits	HMD	·	·	·	·	·	·	·	·	✓	·	·	·	·	·	·
Lin et al. (2020a)	169	?	metro station	HMD	·	·	·	·	·	·	✓	·	·	·	·	·	·	·	·
Tang et al. (2009)	107	student, employee, firefighter, etc.	single floor with rooms and corridors	video-based	·	·	·	·	✓	·	·	✓	·	·	·	·	·	·	·
Kobes et al. (2010a)	153	?	one floor of a hotel	video-based	·	·	✓	·	✓	·	·	✓	·	·	·	·	·	·	·

Article	**Experiment Set-up**				**Pedestrian behaviour**														
					Strategic			Tactical						Operational					
								Route choice				Exit choice					Interaction with pedestrians		
	Sample size	Sample type	Scenario	VR/AR equipment	Activity choice	Destination choice	Activity scheduling	Interaction with spaces	Interaction with information	Interaction with objects	Interaction with pedestrians	Interaction with information	Interaction with pedestrians	Movement through spaces	Interaction with objects	Interaction with information	Following behaviour	Group behaviour	Collision avoidance behaviour
Ahn & Han (2012, 2011)	179; 162	?	an indoor building	AR evacuation system, phone	·	·	·	·	✓	·	·	✓	·	·	·	·	·	·	·
Silva et al. (2013)	20	mainly student	hospital	serious game	·	·	·	·	·	·	·	✓	·	·	·	·	·	·	·
Duarte et al. (2014)	90	student	company headquarters with rooms and corridors	HMD	·	·	✓	·	·	·	·	✓	·	·	·	·	·	·	·
Cosma et al. (2016)	60	student	tunnel	HMD	·	·	·	·	✓	·	·	·	·	·	·	·	·	·	·
Kinateder et al. (2019)	24	?	room with two exits	HMD	·	·	·	·	·	·	·	✓	·	·	·	·	·	·	·
Cao et al. (2019a)	64	undergraduate or graduate student	museum	HMD	·	·	·	·	✓	·	·	✓	·	·	·	·	·	·	·

Article	**Experiment Set-up**				**Pedestrian behaviour**														
					Strategic			Tactical						Operational					
								Route choice				Exit choice					Interaction with pedestrians		
	Sample size	Sample type	Scenario	VR/AR equipment	Activity choice	Destination choice	Activity scheduling	Interaction with spaces	Interaction with information	Interaction with objects	Interaction with pedestrians	Interaction with information	Interaction with pedestrians	Movement through spaces	Interaction with objects	Interaction with information	Following behaviour	Group behaviour	Collision avoidance behaviour
Zhu et al. (2020b)	226	?	metro station	HMD	·	·	·	·	✓	·	·	·	·	·	·	·	✓	·	✓
Feng et al. (2019)	24;95	?	room with multiple exits	HMD	·	·	·	·	·	·	·	✓	·	·	·	·	·	·	·

Note: ✓ This article studied this type of behaviour.
? The article did not mention this information explicitly.
· This behaviour is not included in the scope of this study

Table A. 4: Studies based on survey methods.

Article	Experiment Set-up				Pedestrian behaviour														
					Strategic			Tactical						Operational					
								Route choice				Exit choice					Interaction with pedestrians		
	Sample size	Sample type	Condition	Questionnaire	Activity choice	Destination choice	Activity scheduling	Interaction with spaces	Interaction with information	Interaction with objects	Interaction with pedestrians	Interaction with information	Interaction with pedestrians	Movement through spaces	Interaction with objects	Interaction with information	Following behaviour	Group behaviour	Collision avoidance behaviour
Duives & Mahmassani (2012)	117	?	evacuation at a shopping mall	online questionnaire (SP)	·	·	·	·	·	·	✓	✓	✓	·	·	·	✓	·	·
Lovreglio et al. (2014)	191	?	two emergency exits in a closed environment	online questionnaire (SP)	·	·	·	·	·	·	✓	·	✓	·	·	·	·	·	·
Haghani & Sarvi (2016b)	167	pedestrian, student	a floor of an educational building	interview (SP)	·	·	·	·	·	·	·	✓	✓	·	·	·	·	·	·
Olander et al. (2017)	46	student, worker	emergency signage	questionnaire (RP)	·	·	·	·	✓	·	·	✓	·	·	·	·	·	·	·
Chen et al. (2018)	173	children	a classroom with desks, chairs and two exits	questionnaire (RP)	·	·	·	·	✓	·	✓	·	·	·	·	·	·	✓	·
Aleksandrov et al. (2018)	566	student, resident	75-story building	online questionnaire (SP)	·	·	·	✓	✓	·	✓	·	·	·	·	·	·	·	·

Article	**Experiment Set-up**				**Pedestrian behaviour**														
					Strategic			Tactical						Operational					
								Route choice				Exit choice					Interaction with pedestrians		
	Sample size	Sample type	Condition	Questionnaire	Activity choice	Destination choice	Activity scheduling	Interaction with spaces	Interaction with information	Interaction with objects	Interaction with pedestrians	Interaction with information	Interaction with pedestrians	Movement through spaces	Interaction with objects	Interaction with information	Following behaviour	Group behaviour	Collision avoidance behaviour
Do et al. (2016)	50	passenger	train station	interview (SP)	·	·	·	·	·	·	·	·	·	·	·	·	·	✓	·
Haghani & Sarvi (2016a)	110	passenger	train station with six exits	interview (RP)	·	·	·	·	·	·	·	·	✓	·	·	·	·	·	·
D'Orazio et al. (2016)	113	?	theatre	questionnaire (RP)	·	·	·	·	·	·	·	·	✓	·	·	·	·	·	·
Daamen et al. (2017)	88	?	festival	questionnaire (RP)	·	·	·	·	✓	✓	✓	·	·	·	·	·	·	·	·

Note: ✓ This article studied this type of behaviour.
? The article did not mention this information explicitly.
· This behaviour is not included in the scope of this study.

Appendix B. Gaze points of pedestrians during different assignments (Chapter 4)

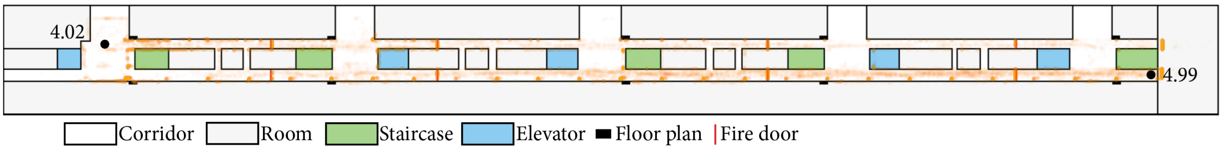


Figure B. 1: Spatial distribution of participants’ gaze points during assignment 1

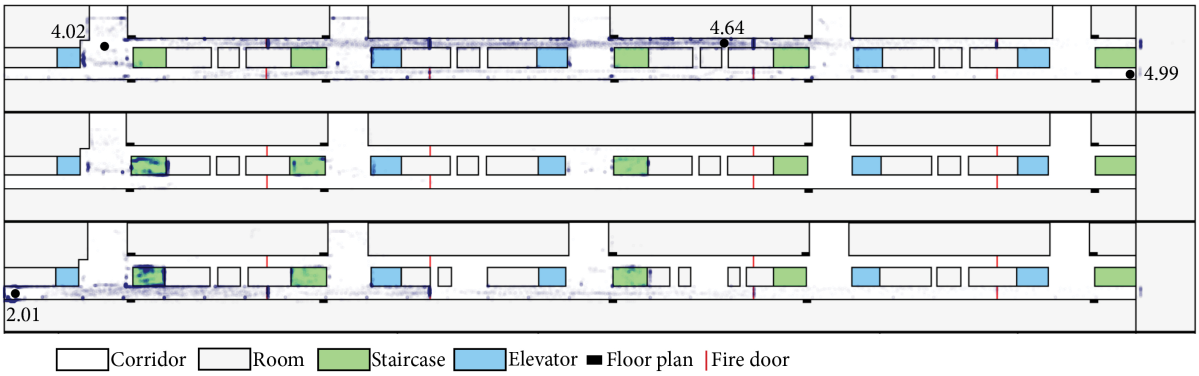


Figure B. 2: Spatial distribution of participants’ gaze points during assignment 3

Appendix C. List of questions related to participant's characteristics (Chapter 4, 5)

Are you familiar with the building of the Civil engineering and geosciences Faculty?

The highest education level you achieved.

Are you familiar with any computer gaming?

How often do you experience a virtual reality environment (e.g., gaming, training, entertainment)?

Appendix D. Face validity questionnaire (Chapter 4, 5)

Instruction: Please characterize your experience in the virtual environment with a 5-point scale. Please consider the entire scale when making your responses, as the intermediate levels may apply.

1. How realistic is the virtual building? *

2. How realistic is the virtual furniture (chairs, doors, etc.)? *

3. How realistic is the visual experience of the movement abilities? *

4. How realistic is the evacuation alarm sound? *

* Answer: 1 is Not at all realistic, and 5 is Completely realistic

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Summary

This study aims to understand ***to what extent Virtual Reality (VR) technologies can be used to study pedestrian wayfinding behaviour in buildings***. Pedestrians perform wayfinding behaviour in buildings on a daily basis. VR provides the possibility to collect behavioural data with high experimental control in various scenarios to understand this behavioural process. Although there is an increasing interest in using VR to study pedestrian behaviour, it is currently unclear under what circumstances VR can be used to study pedestrian wayfinding behaviour. In order to clarify this, three major challenges exist in the context of using VR to study pedestrian wayfinding behaviour, including lack of validation data, lack of wayfinding studies in complex and realistic scenarios, and lack of comparison between different VR technologies.

The research in this thesis focuses on using VR to study pedestrian wayfinding behaviour under normal and emergency conditions, from simple scenarios to complex scenarios. In particular, various empirical datasets featuring pedestrian wayfinding behaviour were collected using different VR technologies in order to understand the usage of VR to investigate pedestrian behaviour and thereby generate new insights into pedestrian wayfinding behaviour in buildings. In this summary, the main achievements and conclusions of this thesis are presented.

Chapter 2 conducts a systematic review to identify the research gaps in the current data collection methods for studying pedestrian behaviour and determines the potential of VR technology to (partially) fill in these gaps. The literature review discerns five main research gaps, namely: (1) the impossibility to study pedestrian behaviour under vast complex scenarios, (2) the lack of comprehensive methods to capture all essential behavioural data simultaneously, (3) the current difficulties to study new types of high-risk scenarios and (4) the lack of comparisons of pedestrian behaviour data among different data collection methods to represent pedestrian behaviour in real life, and (5) the relatively high costs of most experimental methods. Meanwhile, the review shows that VR technologies could potentially address these research gaps in three ways, namely (1) study pedestrian behaviour in environments that are difficult or cannot be mimicked in real-life, (2) conduct the same experiments repeatedly to explore the effects of various factors on pedestrian behaviour, and (3) gain more accurate behavioural data and deep understanding of the decision-making process of pedestrian behaviour.

One of the challenges of using VR to study pedestrian wayfinding behaviour is to ensure the collected pedestrian behavioural data is valid. ***Chapter 3*** validates the usage of Mobile-VR (smartphone-based HMD and 360° video) to study pedestrian exit choice behaviour during evacuations. Pedestrians' exit choice during an evacuation drill in real world and an identical virtual environment were directly compared. The results show that the pedestrians' exit choice during the evacuation is overall similar in the field experiment and the VR experiment. Moreover, herding behaviour was found in both the field experiment and VR experiment. These findings illustrate that the methodological differences between the two experiments do not result in significant differences regarding the pedestrians' exit choice. Additionally, the impact of different types of information strategies (i.e., exit signs, directional signs, presence of people) was investigated using this particular Mobile VR technology. It was found that the presence of other people and information pertaining to the direction of the exits has a significant influence on pedestrian exit choice. Taken together, it provides preliminary proof of the ecological validity of the VR simulator to study pedestrian exit choice behaviour during evacuations.

In ***Chapter 4***, a new VR research tool (WayR) was developed to systemically investigate pedestrian wayfinding behaviour in a multi-story building under both normal and emergency situations. Existing studies have largely used VR to study pedestrian behaviour in simplified environments, studies featuring pedestrian wayfinding behaviour in complex multi-story buildings are much needed. WayR supports free navigation and collects pedestrian walking trajectories, head movements and gaze points automatically. Chapter 4 details the development process of a VR research tool, including four steps, namely (1) to define the functional requirements of the VR research tool, (2) to choose the virtual environment, (3) to construct the virtual environment and (4) to implement the interactive elements in the virtual environment.

To evaluate the validity and usability of WayR, VR experiments consist of four wayfinding assignments with increasing complexity (i.e., from within-floor assignment to between-floor assignments, from normal wayfinding assignments to evacuation assignment) were conducted. Objective measures (i.e., route choice, evacuation exit choice, wayfinding performance, observation behaviour) and subjective measures (i.e., realism, feeling of presence, system usability, simulation sickness) were analysed. Face validity refers to the degree to a simulator's realism compares to the real situation (Deb et al., 2017). The face validity of WayR is established based on participants' high score of the realism of the virtual environment and the consistency of their experience in the virtual building and real world. Content validity refers to the extent to which a tool/method adequately includes the items that are essential to measure what it means to measure (Westen & Rosenthal, 2003). The content validity of WayR is demonstrated by showing the behavioural data collected by VR can reflect pedestrian wayfinding behaviour from ten relevant and complementary metrics identified by literature (e.g., decision making, wayfinding performance, observation behaviour) and allows the meaning of the data to be readily comprehended. Construct validity refers to the extent to which the tool, in this case, WayR, adequately assesses what it claims to measure (Deb et al., 2017). The construct validity of WayR is determined by showing participants' wayfinding behaviour is consistent with pedestrian wayfinding behaviour studies in the literature and their behaviour is overall different amongst assignments with various complexity. Moreover, the usability is determined based on the high score of realism, immersion, usability and the low score of sickness. Taken together, the findings confirm that WayR is capable of collecting valid pedestrian wayfinding behavioural data in a complex multi-story building.

Another challenge of using VR to study pedestrian wayfinding behaviour is choosing which VR technologies to use. VR technologies have different characteristics and may cause people to interact and perceive the virtual environment differently (Santos et al., 2009). Applying WayR, ***Chapter 5*** directly compares the usage of HMD VR and Desktop VR regarding pedestrian wayfinding behaviour (i.e., pedestrian route and exit choice behaviour, observation behaviour, wayfinding task performance) and user experience (i.e., realism, simulation sickness, presence, usability). The same set of wayfinding experiments in Chapter 4 were conducted. Significant differences in wayfinding task performance between the HMD and the Desktop group were found. Meanwhile, pedestrian route and exit choice behaviour (i.e., usage of wayfinding strategy, path, decision points, staircase) were found to be overall similar during the first two and the evacuation assignments. The findings show that for 'simpler' wayfinding tasks in multi-level buildings, pedestrian route and exit choice behaviour can be measured effectively using a more simple and less expensive Desktop VR. However, the findings regarding the comparison of the wayfinding strategy and observation behaviour imply that differences can appear, especially when (more complex) searching behaviour is triggered. In particular, there were differences in route choice (i.e., wayfinding strategy, decision point, staircase) during the task where the location of the destination was not clear-cut. Meanwhile, participants who used HMD had more head rotation change and observation behaviour during the first two tasks, while participants in the Desktop group had higher head rotation change during the evacuation task. Thus, in cases where the wayfinding task become more complex and searching behaviour are important factors that aid wayfinding, there may still be advantages to use immersive VR. Furthermore, user experience (i.e., feeling of presence, realism, simulation sickness, usability) in the current study was found overall similar between the two technologies.

In sum, this thesis provides empirical evidence that different VR technologies (i.e., Mobile VR, HMD VR, Desktop VR) can collect valid behavioural data and study pedestrian wayfinding behaviour in various contexts. More specifically, this thesis shows that (1) VR can collect valid pedestrian data featuring exit choice behaviour in simple scenarios (***Chapter 3***), (2) VR can collect valid pedestrian data featuring wayfinding behaviour in large-scale and complex scenarios (***Chapter 4, Chapter 5***), (3) VR allows researchers to collect comprehensive data and accurately analyse numerous aspects of pedestrian behaviour in minute detail (***Chapter 4, Chapter 5***), (4) the technological differences of VR might cause differences in certain pedestrian wayfinding behaviour and participant's perception of the virtual environment (***Chapter 3***, ***Chapter 5***), and (5) pedestrian wayfinding behaviour is different between simple scenarios and complex scenarios (***Chapter 5***).

Based on the key findings of this thesis, there are several implications that are relevant for researchers and practitioners interest in the usage of VR to study pedestrian behaviour. Most importantly, this thesis shows that VR technologies can be a valuable complement to the current experimental methods to study pedestrian behaviour. This thesis provides evidence that VR can collect valid data and study pedestrian behaviour. Moreover, this thesis suggests researchers should take the difference of VR technologies into account when making the choice of VR technology. The choice of suitable VR devices may depend more on the behavioural data researchers want to collect than the sophistication of the VR equipment. Additionally, the finding implies that behavioural findings pertaining to simplified scenarios cannot be directly generalised to complex scenarios and vice versa. Furthermore, the behavioural findings can be used for architects, designers and safety planners to improve pedestrian wayfinding efficiency in buildings, such as develop strategies to facilitate efficient evacuation, design infrastructure and signage to facilitate wayfinding in public buildings.

Build on the work presented in this thesis, several recommendations for directions of future research are formulated. First of all, the study of comparing pedestrian wayfinding behaviour in the virtual building with pedestrians' behaviour in the identical real-world building is needed in order to further validate WayR. Second of all, future studies should continue working on improving the realism of experience in VR, including social realism and environmental realism. Last, using WayR, there is a need to investigate the impacts of different interventions on wayfinding behaviour in VR that mean to improve pedestrian wayfinding and evacuation efficiency. Lastly, incorporating VR with new technologies, such as AR, tracking technologies, sensing technologies, will allow researchers not only to collect comprehensive behavioural data but also physiological data, which can provide additional insights and new perspectives for wayfinding behaviour.

Samenvatting

Deze studie verkent in welke mate Virtual Reality (VR) technologieën gebruikt kunnen worden om het wayfinding gedrag van voetgangers in gebouwen te bestuderen. Voetgangers voeren dagelijks wayfinding-gedrag uit in gebouwen. VR biedt de mogelijkheid om gedragsgegevens te verzamelen met een hoge experimentele controle in verschillende scenario's om dit gedragsproces te begrijpen. Hoewel er een toenemende belangstelling is voor het gebruik van VR om voetgangersgedrag te bestuderen, is het momenteel onduidelijk onder welke omstandigheden VR kan worden gebruikt om het wegwijsgedrag van voetgangers te bestuderen. Om dit te verduidelijken, bestaan er drie grote uitdagingen in de context van het gebruik van VR om het gedrag van voetgangers te bestuderen, waaronder een gebrek aan validatiegegevens, een gebrek aan studies naar wayfinding in complexe en realistische scenario's, en een gebrek aan vergelijking tussen verschillende VR-technologieën.

Het onderzoek in dit proefschrift richt zich op het gebruik van VR om het gedrag van voetgangers te bestuderen onder normale omstandigheden en in noodsituaties, van eenvoudige scenario's tot complexe scenario's. In het bijzonder werden verschillende empirische datasets met wegwijsgedrag van voetgangers verzameld met behulp van verschillende VR-technologieën om het gebruik van VR voor het onderzoeken van voetgangersgedrag te begrijpen en zo nieuwe inzichten te genereren in wegwijsgedrag van voetgangers in gebouwen. In deze samenvatting worden de belangrijkste resultaten en conclusies van dit proefschrift gepresenteerd.

Hoofdstuk 2 voert een systematische review uit om de onderzoeksgaten in de huidige dataverzamelingsmethoden voor het bestuderen van voetgangersgedrag te identificeren en bepaalt het potentieel van VR technologie om deze leemten (gedeeltelijk) op te vullen. De literatuurstudie onderscheidt vijf belangrijke hiaten in onderzoek, namelijk: (1) de onmogelijkheid om het gedrag van voetgangers te bestuderen onder complexe scenario's, (2) het gebrek aan alomvattende methoden om alle essentiële gedragsgegevens tegelijkertijd vast te leggen, (3) de huidige moeilijkheden om nieuwe soorten risicoscenario's te bestuderen en, (4) het gebrek aan vergelijkingen van gegevens over het gedrag van voetgangers tussen verschillende gegevensverzamelingsmethoden om het gedrag van voetgangers in het echte leven weer te geven, en (5) de relatief hoge kosten van de meeste experimentele methoden. Ondertussen toont de review aan dat VR-technologieën deze onderzoekshiaten potentieel op drie manieren kunnen aanpakken, namelijk (1) het gedrag van voetgangers bestuderen in omgevingen die moeilijk of niet in het echte leven kunnen worden nagebootst, (2) experimenten herhaaldelijk uitvoeren om de effecten van verschillende factoren op het gedrag van voetgangers te onderzoeken, en (3) meer accurate gedragsgegevens en een diepgaand begrip van het besluitvormingsproces van het gedrag van voetgangers verwerven.

Een van de uitdagingen van het gebruik van VR om het gedrag van voetgangers te bestuderen is ervoor te zorgen dat de verzamelde gegevens over het gedrag van voetgangers valide zijn. Hoofdstuk 3 valideert het gebruik van Mobile-VR (smartphone-gebaseerde HMD en 360° video) om het exit-keuzegedrag van voetgangers tijdens evacuaties te bestuderen. De exit keuze van voetgangers tijdens een evacuatie oefening in de echte wereld en een identieke virtuele omgeving werden direct vergeleken. De resultaten tonen aan dat de exitkeuzes van voetgangers tijdens de evacuatie globaal gelijk zijn in het veldexperiment en het VR-experiment. Bovendien werd zowel in het veldexperiment als in het VR-experiment kuddegedrag vastgesteld. Deze bevindingen illustreren dat de methodologische verschillen tussen de twee experimenten niet resulteren in significante verschillen met betrekking tot de exit-keuze van de voetgangers. Bovendien werd de impact van verschillende soorten informatiestrategieën (d.w.z. uitritborden, richtingborden, aanwezigheid van mensen) onderzocht met deze specifieke mobiele VR-technologie. Het bleek dat de aanwezigheid van andere mensen en informatie met betrekking tot de richting van de uitgangen een significante invloed heeft op de exit-keuze van voetgangers. Alles bij elkaar levert dit een voorlopig bewijs van de ecologische validiteit van de VR simulator voor het bestuderen van het exit-keuzegedrag van voetgangers tijdens evacuaties.

In hoofdstuk 4 is een nieuw VR onderzoeksinstrument (WayR) ontwikkeld om systematisch het gedrag van voetgangers in een gebouw met meerdere verdiepingen te onderzoeken, zowel onder normale omstandigheden als in noodsituaties. Bestaande studies hebben VR grotendeels gebruikt om het gedrag van voetgangers in vereenvoudigde omgevingen te bestuderen, studies met wegwijsgedrag van voetgangers in complexe gebouwen met meerdere verdiepingen zijn hard nodig. WayR ondersteunt vrije navigatie en verzamelt automatisch voetgangerstrajecten, hoofdbewegingen en oogpunten. Hoofdstuk 4 beschrijft het ontwikkelingsproces van een VR onderzoeksinstrument, inclusief vier stappen, namelijk (1) het definiëren van de functionele eisen van het VR onderzoeksinstrument, (2) het kiezen van de virtuele omgeving, (3) het construeren van de virtuele omgeving en (4) het implementeren van de interactieve elementen in de virtuele omgeving.

Om de validiteit en bruikbaarheid van WayR te evalueren werden VR experimenten uitgevoerd bestaande uit vier wayfinding opdrachten met toenemende complexiteit (d.w.z. van opdrachten binnen de verdieping naar opdrachten tussen verdiepingen, van normale wayfinding opdrachten naar evacuatie opdrachten). Objectieve metingen (d.w.z. routekeuze, keuze evacuatie-uitgang, wayfinding prestatie, observatiegedrag) en subjectieve waarnemingen (d.w.z. realisme, gevoel van aanwezigheid, bruikbaarheid van het systeem, simulatieziekte) werden geanalyseerd. Gezichtsvaliditeit verwijst naar de mate waarin het realisme van een simulator zich verhoudt tot de werkelijke situatie (Deb et al., 2017). De gezichtsvaliditeit van WayR is vastgesteld op basis van de hoge score van deelnemers op het realisme van de virtuele omgeving en de consistentie van hun ervaring in het virtuele gebouw en de echte wereld.

Inhoudsvaliditeit verwijst naar de mate waarin een instrument/methode adequaat de items bevat die essentieel zijn om te meten wat het bedoelt te meten (Westen en Rosenthal, 2003). De inhoudsvaliditeit van WayR wordt aangetoond door aan te tonen dat de door VR verzamelde gedragsgegevens het wayfinding gedrag van voetgangers kunnen weergeven aan de hand van tien relevante en complementaire metrieken die in de literatuur zijn geïdentificeerd (bijv. besluitvorming, wayfinding performance, observatiegedrag) en de betekenis van de gegevens gemakkelijk te begrijpen maakt. Constructvaliditeit verwijst naar de mate waarin het instrument, in dit geval WayR, adequaat beoordeelt wat het beweert te meten (Deb et al., 2017). De constructvaliditeit van WayR wordt bepaald door aan te tonen dat het wayfinding-gedrag van deelnemers consistent is met studies naar wayfinding-gedrag van voetgangers in de literatuur en dat hun gedrag over het algemeen verschillend is bij opdrachten met verschillende complexiteit. Bovendien is de bruikbaarheid bepaald op basis van de hoge score van realisme, immersie, bruikbaarheid en de lage score van ziekte. Alles bij elkaar bevestigen de bevindingen dat WayR in staat is om valide gegevens te verzamelen over het gedrag van voetgangers in een complex gebouw met meerdere verdiepingen.

Een andere uitdaging bij het gebruik van VR om het gedrag van voetgangers te bestuderen is de keuze van de te gebruiken VR technologieën. VR technologieën hebben verschillende karakteristieken en kunnen ervoor zorgen dat mensen anders reageren op de virtuele omgeving en deze anders waarnemen (Santos et al., 2009). Door WayR toe te passen, vergelijkt Hoofdstuk 5 direct het gebruik van HMD VR en Desktop VR met betrekking tot voetgangers wayfinding gedrag (i.e., voetgangers route en uitgang keuze gedrag, observatie gedrag, wayfinding taak prestatie) en gebruikers ervaring (i.e., realisme, simulatie ziekte, aanwezigheid, bruikbaarheid). Dezelfde reeks wayfinding experimenten uit hoofdstuk 4 werden uitgevoerd. Significante verschillen in wayfinding taakprestaties tussen de HMD en de Desktop groep werden gevonden. Intussen werd vastgesteld dat het gedrag van voetgangers bij het kiezen van een route en uitgang (d.w.z. gebruik van wayfinding strategie, pad, beslissingspunten, trap) over het algemeen soortgelijk was tijdens de eerste twee en de evacuatie opdrachten. De bevindingen tonen aan dat voor "eenvoudigere" wayfinding-taken in gebouwen met meerdere verdiepingen, het gedrag van voetgangers bij het kiezen van de route en de uitgang doeltreffend kan worden gemeten met behulp van een eenvoudiger en minder duur desktop VR. De bevindingen betreffende de vergelijking van de wayfinding-strategie en het observatiegedrag impliceren echter dat er verschillen kunnen optreden, vooral wanneer (complexer) zoekgedrag wordt uitgelokt. In het bijzonder waren er verschillen in routekeuze (d.w.z., wayfinding strategie, beslissingspunt, trap) tijdens de taak waarbij de locatie van de bestemming niet eenduidig was. Ondertussen hadden deelnemers die HMD gebruikten meer verandering in hoofdrotatie en observatie gedrag tijdens de eerste twee taken, terwijl deelnemers in de Desktop groep een hogere hoofdrotatie verandering hadden tijdens de evacuatie taak. Dus, in gevallen waar de wayfinding taak complexer wordt en zoekgedrag belangrijke factoren zijn die wayfinding helpen, kunnen er nog steeds voordelen zijn om immersieve VR te gebruiken. Verder bleek de gebruikerservaring (d.w.z. gevoel van aanwezigheid, realisme, simulatieziekte, bruikbaarheid) in de huidige studie over het algemeen vergelijkbaar tussen de twee technologieën.

Kortom, deze dissertatie levert empirisch bewijs dat verschillende VR technologieën (d.w.z. Mobiele VR, HMD VR, Desktop VR) valide gedragsgegevens kunnen verzamelen en het wayfinding gedrag van voetgangers in verschillende contexten kunnen bestuderen. Meer specifiek toont dit proefschrift aan dat (1) VR valide gegevens van voetgangers kan verzamelen met exit-keuzegedrag in eenvoudige scenario's (Hoofdstuk 3), (2) VR valide gegevens van voetgangers kan verzamelen met wayfinding-gedrag in grootschalige en complexe scenario's (Hoofdstuk 4, Hoofdstuk 5), (3) VR onderzoekers in staat stelt om uitgebreide gegevens te verzamelen en nauwkeurig talrijke aspecten van voetgangersgedrag te analyseren in minutieus detail (Hoofdstuk 4, Hoofdstuk 5), (4) de technologische verschillen van VR kunnen verschillen veroorzaken in bepaald wegwijsgedrag van voetgangers en de perceptie van de virtuele omgeving door de deelnemers (Hoofdstuk 3, Hoofdstuk 5), en (5) wegwijsgedrag van voetgangers is verschillend tussen eenvoudige scenario's en complexe scenario's (Hoofdstuk 5).

Gebaseerd op de belangrijkste bevindingen van deze dissertatie, zijn er verschillende implicaties die relevant zijn voor onderzoekers en praktijkmensen die geïnteresseerd zijn in het gebruik van VR om voetgangersgedrag te bestuderen. Het belangrijkste is dat deze dissertatie aantoont dat VR technologieën een waardevolle aanvulling kunnen zijn op de huidige experimentele methoden om voetgangersgedrag te bestuderen. Deze dissertatie levert bewijs dat VR valide gegevens kan verzamelen en voetgangersgedrag kan bestuderen. Bovendien suggereert dit proefschrift dat onderzoekers rekening moeten houden met het verschil van VR-technologieën bij het maken van de keuze voor VR-technologie. De keuze van geschikte VR-apparaten kan meer afhangen van de gedragsgegevens die onderzoekers willen verzamelen dan van de geavanceerdheid van de VR-apparatuur. Bovendien impliceert de bevinding dat gedragsbevindingen die betrekking hebben op vereenvoudigde scenario's niet direct kunnen worden gegeneraliseerd naar complexe scenario's en vice versa. Bovendien kunnen de gedragsbevindingen worden gebruikt door architecten, ontwerpers en veiligheidsplanners om de efficiëntie van voetgangersbewegwijzering in gebouwen te verbeteren, zoals het ontwikkelen van strategieën om efficiënte evacuatie te vergemakkelijken, het ontwerpen van infrastructuur en bewegwijzering om de bewegwijzering in openbare gebouwen te vergemakkelijken.

Voortbouwend op het werk dat in deze dissertatie is gepresenteerd, zijn verschillende aanbevelingen geformuleerd voor richtingen van toekomstig onderzoek. Ten eerste is een studie nodig om het gedrag van voetgangers in het virtuele gebouw te vergelijken met het gedrag van voetgangers in een identiek gebouw in de echte wereld, om WayR verder te valideren. Ten tweede, toekomstige studies moeten blijven werken aan het verbeteren van het realisme van de ervaring in VR, inclusief sociaal realisme en omgevingsrealisme. Ten slotte is het nodig om, gebruikmakend van WayR, de impact van verschillende interventies op het wayfinding gedrag in VR te onderzoeken om zo de voetgangers wayfinding en evacuatie efficiëntie te verbeteren. Ten slotte zal de integratie van VR met nieuwe technologieën, zoals AR, tracking technologieën, sensing technologieën, onderzoekers in staat stellen om niet alleen uitgebreide gedragsgegevens te verzamelen, maar ook fysiologische gegevens, die extra inzichten en nieuwe perspectieven kunnen bieden voor het wayfinding gedrag.

About the author

Yan Feng was born in 1993 in Baotou, China. In 2015, she obtained her Bachelor degree in Traffic and Transportation at East China Jiaotong University, China. During her undergraduate study, she received rewards and scholarships, including the National Scholarship Award (Ministry of Education of China), Academic Distinction Scholarship Award, and Student of Distinction Award. For her graduation project, she studied passenger Traffic Volume Sharing Rate of Inter-city Transport Corridor and received the Best Graduation Thesis Award.

After her graduation, she continued her study in transportation and started research on the topic of pedestrian behaviour at Beijing Jiaotong University, China. Her research focused on the social group behaviour of pedestrians. Her graduation thesis was titled "Research on Traffic Characteristics and Simulation Model of Social Groups with Heterogeneity in Metro Station Channel". During her master study, she received the 1st Prize for Academic Scholarship and Excellent Master Student Reward. She obtained her master degree with distinction in 2017.

In October 2017, she continued her research on pedestrians at Department of Transport and Planning of Delft University of Technology where she started as a Doctoral candidate. Her research focuses on using Virtual Reality to study pedestrian wayfinding behaviour in buildings during both normal and emergency situations. During her doctoral studies, she worked as a teaching assistant for "Active Modes: Traffic and Transport". She served as a reviewer for various international journals and conferences.

She works now as a Postdoctoral Researcher at Delft University of Technology. Extending her research on VR& pedestrian behaviour, she continues her work on applying VR/AR to study different modes of mobility in urban spaces, including pedestrian, cyclist and automate vehicles. She is passionate about conducting interdisciplinary research that combines engineering, architecture, design, and computer science. Her research interests include pedestrian behaviour, Virtual Reality, wayfinding behaviour, evacuation behaviour, AV-VRU interaction, human mobility, social behaviour, human-computer interaction.

List of publications

Journal Articles

1. **Feng, Y.**, Duives, D. C., & Hoogendoorn, S. P. (2022). Wayfinding behaviour in a multi-level building: a comparative study of HMD VR and Desktop VR. *Advanced Engineering Informatics*, *51*, 101475.
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1. **Feng, Y.**, Duives, D. C., Daamen, W., & Hoogendoorn, S. P. (2021). Impact of obstacles on pedestrian route and exit choice behaviour in a building. Presented at the *Pedestrian and Evacuation Dynamics 2021*. Melbourne, Australia
2. **Feng, Y.** (2021). Do Different Types of VR Influence Pedestrian Route Choice Behaviour? A Comparison Study of Desktop VR and HMD VR. In *Extended Abstracts*

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Summary

This dissertation is focused on using Virtual Reality to study pedestrian wayfinding behaviour in buildings during both normal and emergency situations, from simple scenarios to complex scenarios. In particular, various empirical datasets featuring pedestrian wayfinding and evacuation behaviour were collected using different VR technologies to understand the usage of VR to investigate pedestrian behaviour and thereby generate new insights into pedestrian wayfinding behaviour in buildings. This thesis shows that different VR technologies (i.e., Mobile VR, HMD VR, Desktop VR) can collect valid behavioural data and study pedestrian wayfinding behaviour in various contexts.

About the Author

Yan Feng is a postdoctoral researcher at Delft University of Technology. She specializes in using Virtual Reality to study mobility behaviour in urban spaces, including pedestrians, cyclists, and automated vehicles. She is passionate about conducting interdisciplinary research that combines transportation engineering, architecture, design, and computer science to understand the interaction among people, space and technology.

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