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

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ABSTRACT

Although understanding wayfinding behaviour in complex buildings is important to ensure pedestrian safety, the state of the art predominantly investigated pedestrian movement in simplified environments. This paper presents a Virtual Reality tool – WayR, that is designed to investigate pedestrian wayfinding behaviour in a multi-story building under both normal and emergency situations. WayR supports free navigation and collects pedestrian walking trajectories, head movements and gaze points automatically. To evaluate WayR, a VR experiment consists of four wayfinding assignments were conducted. The validity and usability of WayR are evaluated 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). Analysis of the objective measures indicates that participants' wayfinding behaviour in VR matches with findings in the literature. Moreover, we found that overall participants behaved significantly different across wayfinding assignments with increasing complexity. Furthermore, the results of subjective measures indicate a high degree of realism, immersion, usability, and low level of sickness of WayR. Overall, the results demonstrated the face validity, content validity, construct validity and usability of WayR as a research tool to study wayfinding behaviour in a complex multi-story building.

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 and 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., 2021b).

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 and Johansson, 2009) or controlled conditions (e.g., Fang et al., 2010; Hölscher et al., 2005; Jeon et al., 2011; Zhu and 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; Galea et al., 2017; Heliövaara et al., 2012; Imanishi and Sano, 2019; Kobes et al., 2010b; Nilsson and Johansson, 2009; Peacock et al., 2012; Rahouti et al., 2020; Zhu and 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

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difficult to control (Feng et al., 2021a; Haghani, 2020). 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 and 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., 2019b; 2019a; 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., 2019b; Fu et al., 2021a; Hsieh et al., 2018; Kinateder et al., 2018; 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 and Zhang, 2014; Orellana and 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 et al., 2014a; Kinateder and Warren, 2016; Kobes et al., 2010a; Ronchi et al., 2014; Vilar et al., 2014a; 2013). Only a few studies attempted to capture and analyse more advanced behavioural data, such as gaze point and head rotation (e.g., Meng and 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., 2019a; Kinateder and 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 and 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 paper contributes to the literature in three ways. Firstly, the paper develops and describes the detailed development process of the VR research tool: WayR. Secondly, the paper 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 the paper establishes the validity and usability of using VR to investigate pedestrian wayfinding behaviour in a complex multi-story building,

The rest of the paper is organised as follows. Section 2 summarises studies that applied VR methods to study pedestrian wayfinding behaviour. Based on the insights of the previous VR study, Section 3 identifies the functional requirements of WayR and details the developing process of WayR. Section 4 details the experiment method applying WayR. The results of this experiment and WayR's validity and usability are discussed in Section 5. The paper ends with preliminary conclusions pertaining to WayR's validity and usability to study pedestrian behaviour and provides directions for future research.

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 and 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 and Giudice (2013) studied pedestrian wayfinding performance in two-story virtual buildings. Meng and 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 (Hengshan Li et al., 2019; Lin et al., 2020; 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., 2013), visual cues (Cao et al., 2019; Zhu et al., 2020a), social influence (Fu et al., 2021a; Kinateder et al., 2014a; Kinateder and Warren, 2016), smoke (Fu et al., 2021b; Kobes et al., 2010a), and personal characteristics (Kinateder et al., 2018; Lin et al., 2020, 2019).

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 and 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 and 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 and 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 and 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., 2014b, 2014a), studies featuring pedestrian wayfinding behaviour in complex multi-story buildings are still rare (e.g., Andree et al., 2015; Hengshan Li et al., 2019). Pedestrian wayfinding behaviour is affected by the layout of the architectural setting and the quality of the environmental information (Dogu and 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 and 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., 2014b). 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., 2019; 2014a; Hengshan Li et al., 2019; Lovreglio et al., 2018; Schrom-Feiertag et al., 2017; Vilar et al., 2014a; Zhu et al., 2020b). 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 and 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.

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

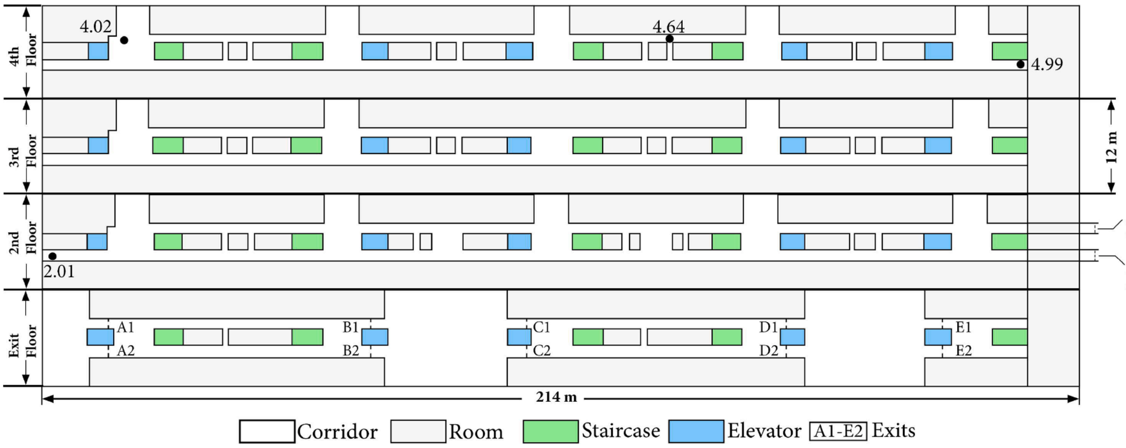


Fig. 1. Floorplan of the virtual building.

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.

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.

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 Fig. 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

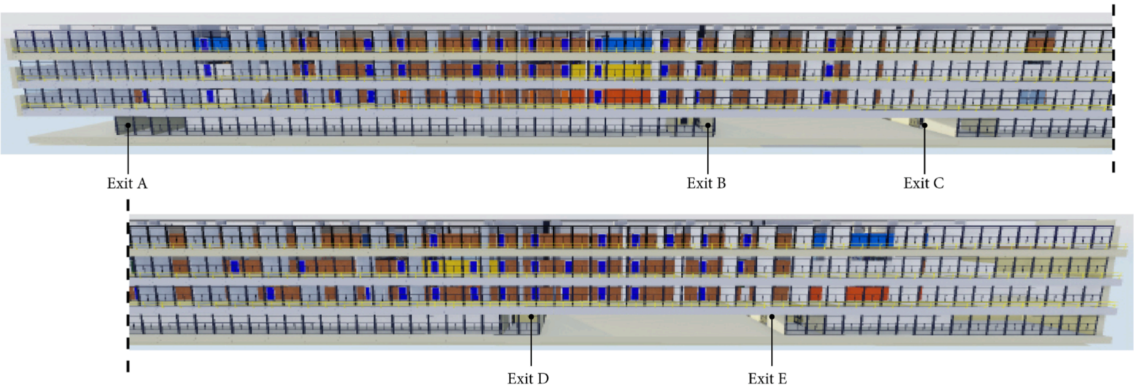
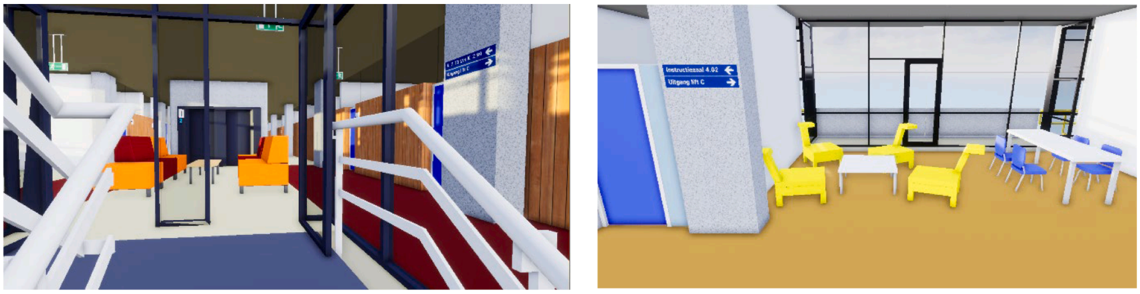
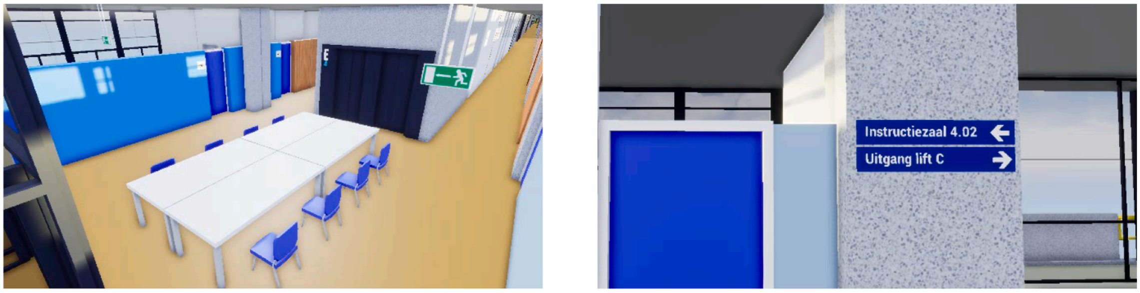


Fig. 2. The overview of the virtual building.



a. glasses window

b. different chairs and tables



c. evacuation sign

d. floor plan

Fig. 3. Samples of four types of features added to the virtual environment.

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.

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. Fig. 2 shows an overview of the comprehensive 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 and 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

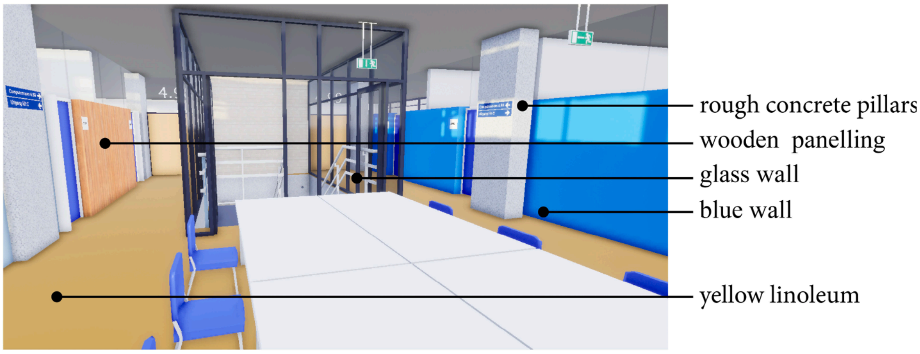


Fig. 4. Illustration of one corridor in the virtual building.

a. virtual building

b. real world view

Fig. 5. Pictures of (a) the virtual building and (b) the real world view.

original position. Fig. 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).

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. Figs. 3 and 4 shows 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

Fig. 6. One example of implemented Navigation Mesh, indicated by green colour.

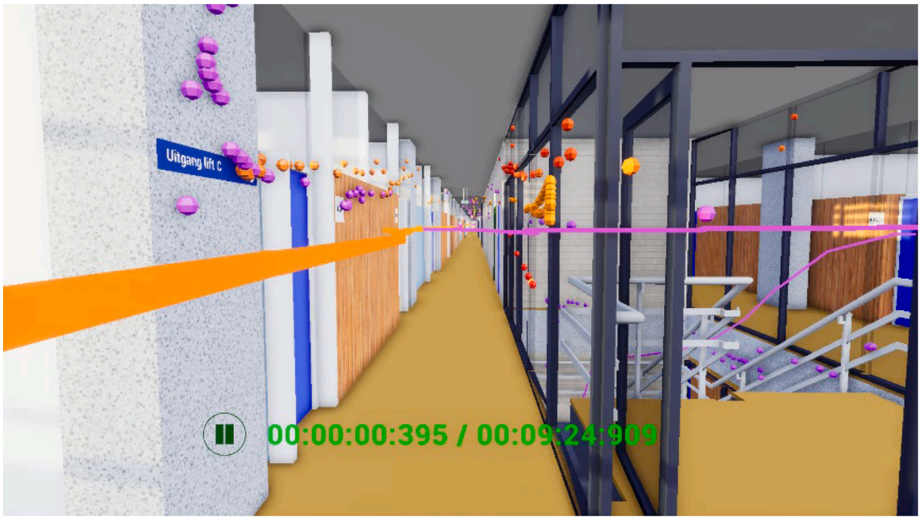


Fig. 7. One example of the distribution of walking trajectories and gaze points in the virtual building.

(Fig. 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. Fig. 5 shows one example of the final rendering of the virtual environment and the real-world view.

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 (Fig. 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.

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 and 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 and 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' locations 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 repeats 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.

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 7 shows the distribution of one user’s walking trajectories (lines) and gaze points (dots) in the virtual building.

4. Evaluation VR experiment

In order to evaluate WayR, a VR experiment was designed and conducted. Section 4.1 first details the experimental design. Next, the adopted apparatus for this study is introduced in section 4.2. Section 4.3 describes the experimental procedure. Accordingly, section 4.4 and section 4.5 detail the data collection by the VR experiment and participant’s characteristics.

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 Fig. 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 assignments 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.

4.2. Experiment apparatus

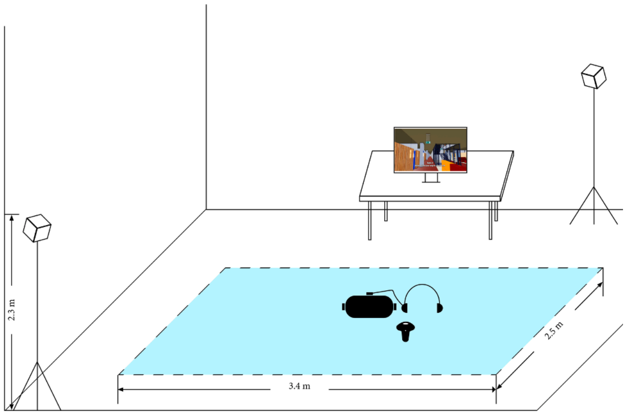


Fig. 8. A simple illustration of the room setup.

Fig. 9. One participant was using the HMD display and hand controller during the VR experiment.

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 and 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 (Fig. 8).

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 and König, 2016). Participants used one hand controller to move in the environment. Fig. 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.

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

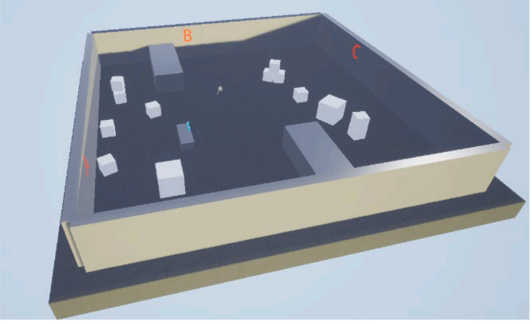


Fig. 10. A screenshot of the test environment.

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.

4.3. 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 (Fig. 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.

3. Performing the assignments. After the familiarisation phase, participants were teleported to the actual virtual building. As stated in section 4.1, the start position is room 4.02 (see Fig. 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 Fig. 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

Fig. 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. 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 hesitation).

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.

4.5. 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

Table 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%)

years ($M = 28.66$, $SD = 6.00$). Table 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.

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 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 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.

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 and 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 5.1.1 details the results pertaining to route and exit choice behaviour. Afterwards, section 5.1.2 presents the wayfinding task performance results, and section 5.1.3 details the result of observation behaviour. Subsequently, the content validity and construct validity of WayR are discussed in section 5.1.4.

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. Figs. 12–15 show the walking trajectories of all participants during four assignments. Pedestrian route choice can be seen as a series of decisions (Hoogendoorn and 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.

5.1.1.1. 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). Fig. 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).

Table 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).

In order to determine whether the identified difference in the employed wayfinding strategies are 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

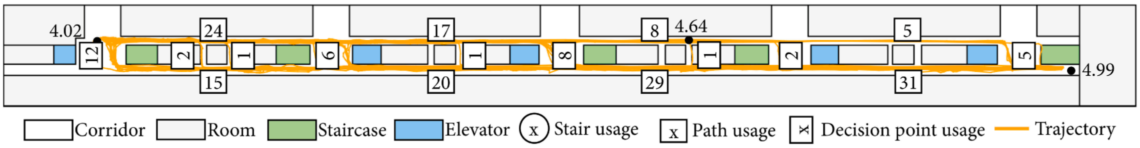


Fig. 12. Participants' trajectories during assignment 1: room 4.02 → room 4.09..

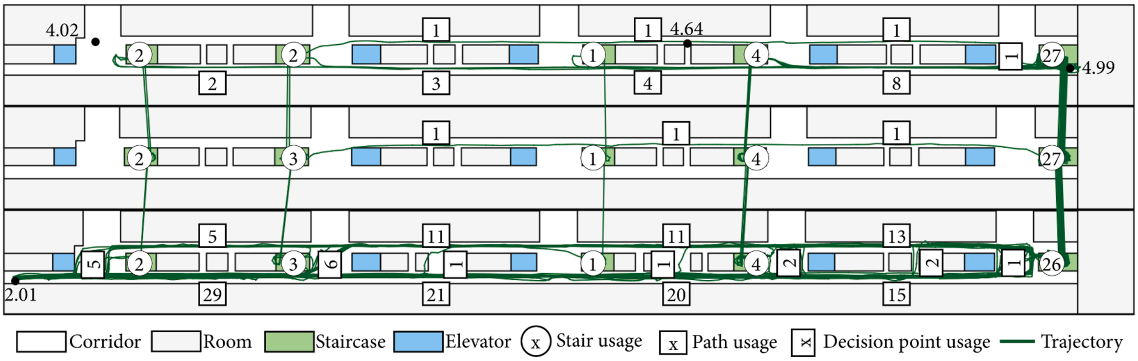


Fig. 13. Participants' trajectories during assignment 2: room 4.99 → room2.01.

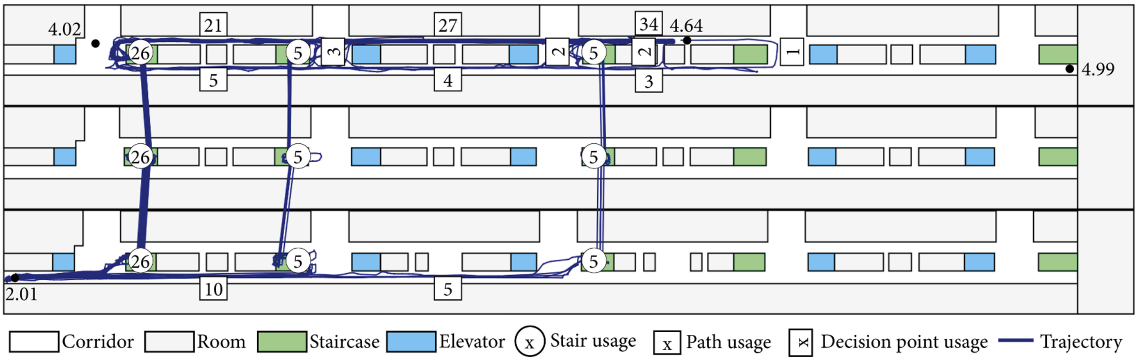


Fig. 14. Participants' trajectories during assignment 3: room 2.01 → room 4.64.

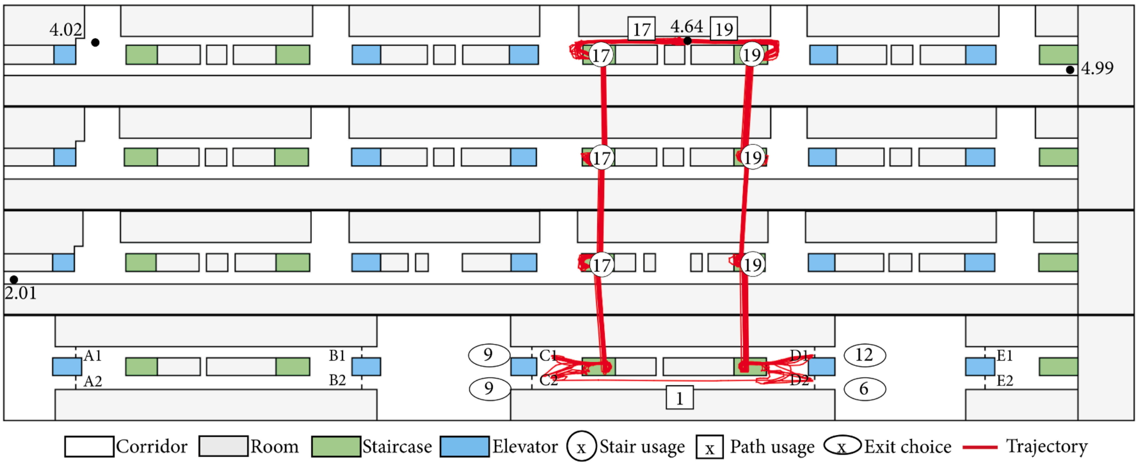


Fig. 15. Participants' trajectories during assignment 4: room 4.64 → an exit.

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.

5.1.1.2. 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 and 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

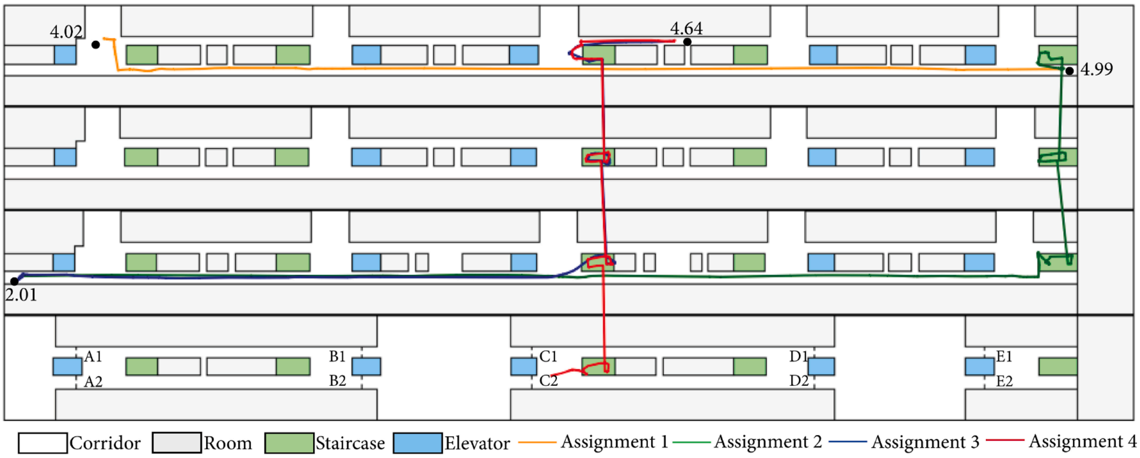


Fig. 16. Trajectories of one participant during all four assignments.

Table 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

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 ($Z = 0.00, p = 0.005$). 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., 2014b, 2013; Wiener et al., 2012). This finding also indicates that participants can realistically perceive the difference in environmental features in the virtual building.

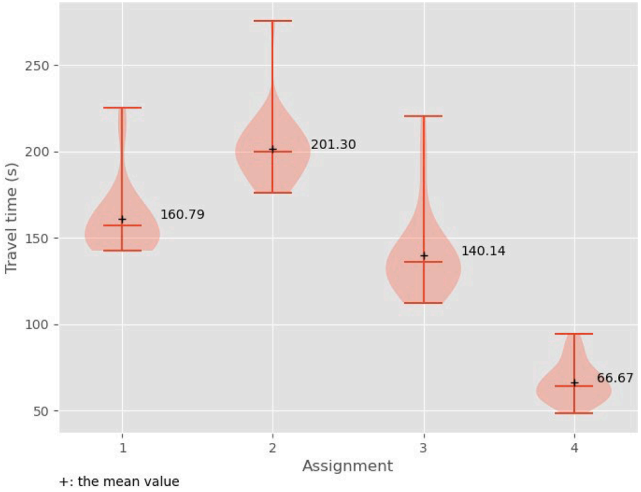


Fig. 17. Violin plot of the time spent by the participants during four assignments.

5.1.1.3. Exit choice. As Fig. 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 and Mahmassani, 2012; Feng et al., 2021b; Liao et al., 2014; Zhu and 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

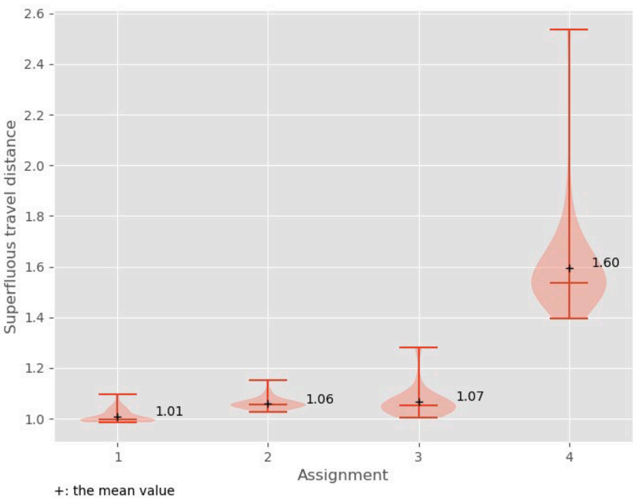


Fig. 18. Violin plot of the superfluous travel distance of all participants during four assignments.

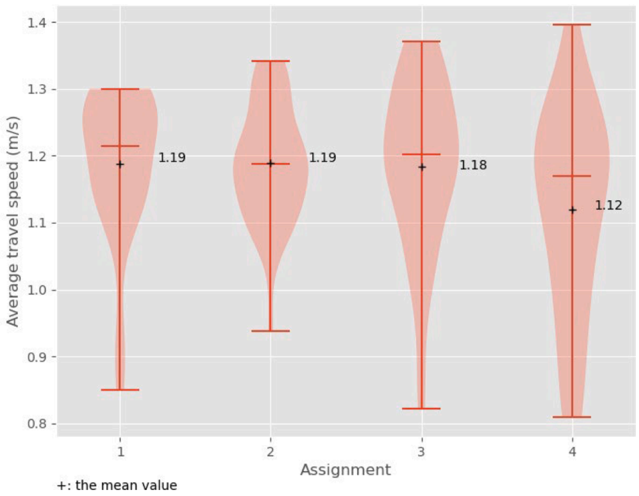


Fig. 19. Violin plot of the average travel speed of all participants during four assignments.

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).

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 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.

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., 2007, 2005; Kuliga et al., 2019). The distribution of superfluous travel distance during each assignment is presented in Fig. 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 ($M_1 = 1.01$, $SD_1 = 0.03$).

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 Fig. 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.

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 wayfinding performance during emergencies than normal conditions (Cao et al., 2019; Lin et al., 2019; Meng and 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.

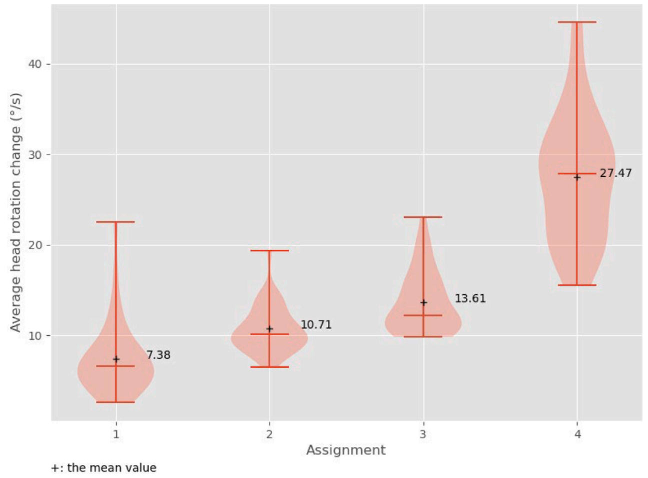


Fig. 20. Violin plot of average head rotation change (Yaw) of all participants during four assignments.

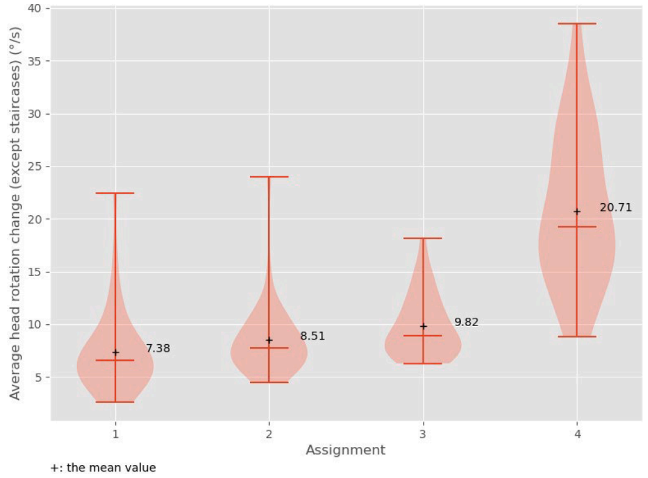


Fig. 21. Violin plot of average head rotation change (except staircases) of all participants during four assignments.

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.

5.1.3.1. 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 $\overline{Y}$ during each assignment is calculated by Formula 1 and 2:

$$Y(t) = min(360 - |Y_{t+dt} - Y_t|, |Y_{t+dt} - Y_t|) \tag{1}$$

$$\overline{Y} = \frac{\sum_1^T Y}{T} \tag{2}$$

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. Fig. 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 ($M_2 = 10.71$ °/s, $SD_2 = 2.52$ °/s) and assignment 1 ($M_1 = 7.38$ °/s, $SD_1 = 4.00$ °/s).

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. Fig. 21 shows the distribution of the average head rotation change (except staircases part) of participants. The Friedman test showed significant differencs 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).

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 changes 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.

5.1.3.2. 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.

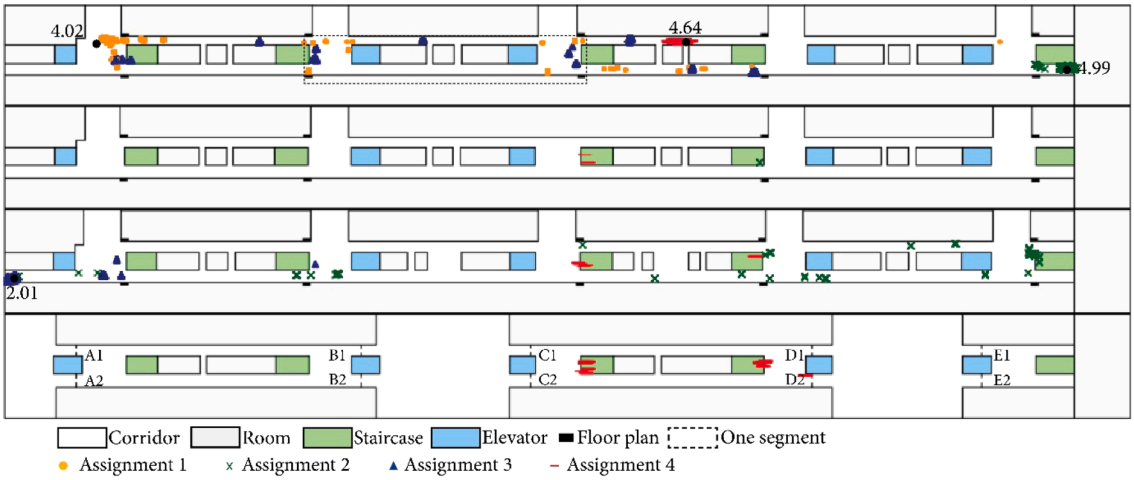


Fig. 22. Spatial distribution of participant's hesitation points in the virtual building during all four assignments.

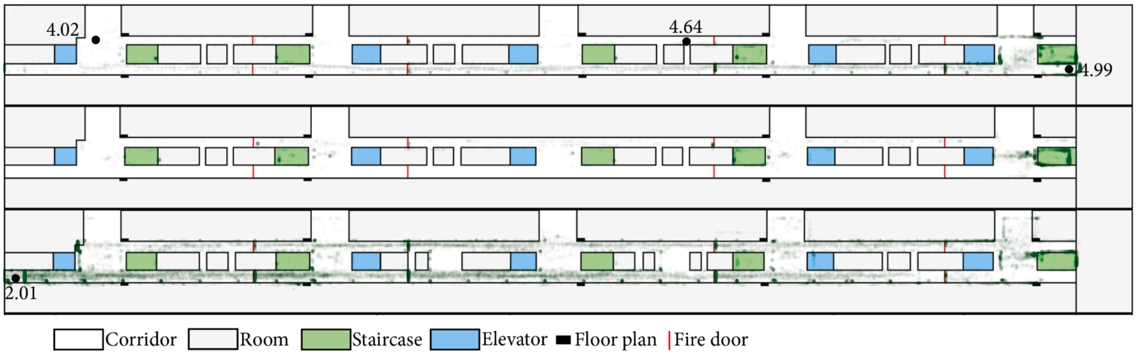


Fig. 23. Spatial distribution of participants' gaze points during assignment 2.

A hesitation point is a location where people stop or pause for a significant amount of time (Conroy, 2001; Ewart and 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. Fig. 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 and 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 Fig. 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.

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 and Johnson, 2021; Orellana and 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 and 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

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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.

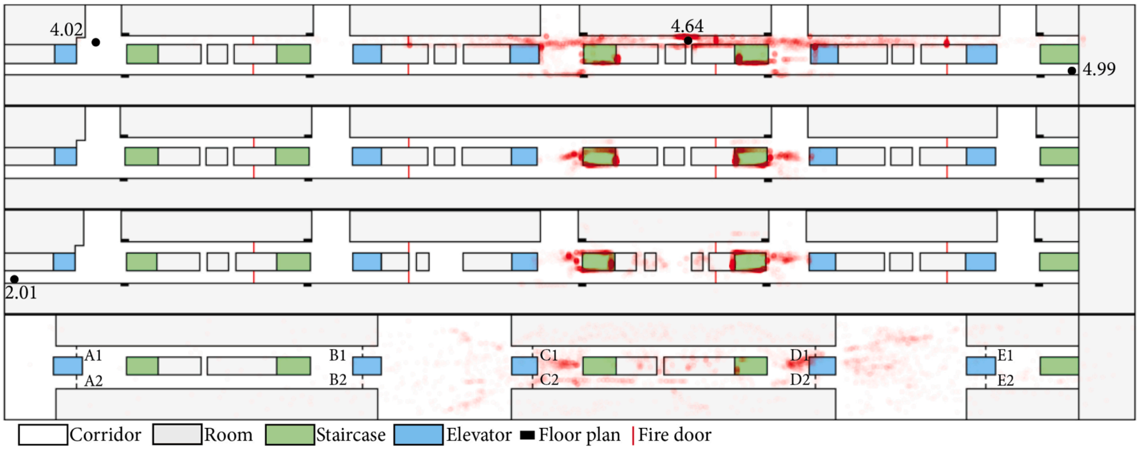

Fig. 24. Spatial distribution of participants' gaze points during assignment 4.

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. Figs. 23 and 24 show the scatter of participants' gaze points during assignment 2 and evacuation assignment. Figs. A1 and A2 in Appendix A 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 and Erkip, 2000; Hessam and Debajyoti, 2018; Hölscher et al., 2013; Montello and 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.

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.

5.1.4.1. 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 and 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 and Mahmassani, 2012; Frankenstein et al., 2012; Liao et al., 2014; Vilar et al., 2014b; Wiener et al., 2012; Zhu and Shi, 2016), wayfinding task performance (e.g., time, distance, and speed) (Cao et al., 2019; Fang et al., 2020; Li and Giudice, 2013; Meng and 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 and Zhang, 2014; Ruddle and 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.

5.1.4.2. 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., 2014b, 2013; 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 with 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 and Zhang, 2014), we found participants had worse wayfinding 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 and Johnson, 2021; Orellana and 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 and Erkip, 2000; Duarte et al., 2014; Hessam and Debajyoti, 2018; Hölscher et al., 2013; Kobes et al., 2010b; Montello and 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 rotations 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 and 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.

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.

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 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 and Cherkaoui, 2020, 2018; Schwebel et al., 2008)

Table 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

Table 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

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 and 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 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

Table 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.

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 and Weghorst, 1993).

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 widely 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 et al., 2020; Zhu et al., 2020a). In addition, the four subscales in the PQ questionnaire are analysed (see Table 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.

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 and Cedergren, 2019; Deb et al., 2017; Feng et al., 2021b; Stigall and Sharma, 2019) that also measured SUS concerning the usage of VR technologies for studying pedestrian behaviour.

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 on 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.

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 and Al Sayed, 2013), and locations of major attractors during wayfinding (Büchner et al., 2007; Dogu and Erkip, 2000; Hessam and Debajyoti, 2018; Hölscher et al., 2013; Kobes et al., 2010; Montello and 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.

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.

CRediT authorship contribution statement

Yan Feng: Conceptualization, Methodology, Investigation, Formal analysis, Writing – original draft. **Dorine C. Duives:** Conceptualization, Writing – review & editing, Supervision. **Serge P. Hoogendoorn:** Supervision, Funding acquisition.

Declaration of Competing Interest

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

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Appendix A. Gaze points of pedestrians during different assignments

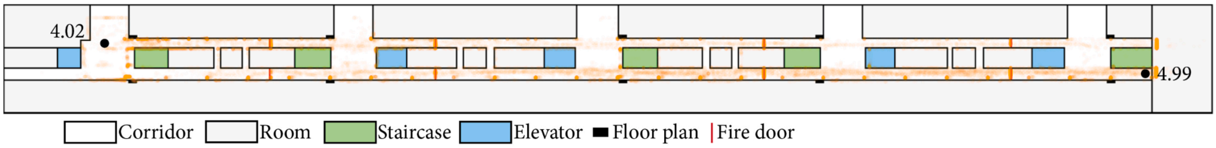

Fig. A1. Spatial distribution of participants’ gaze points during assignment 1.

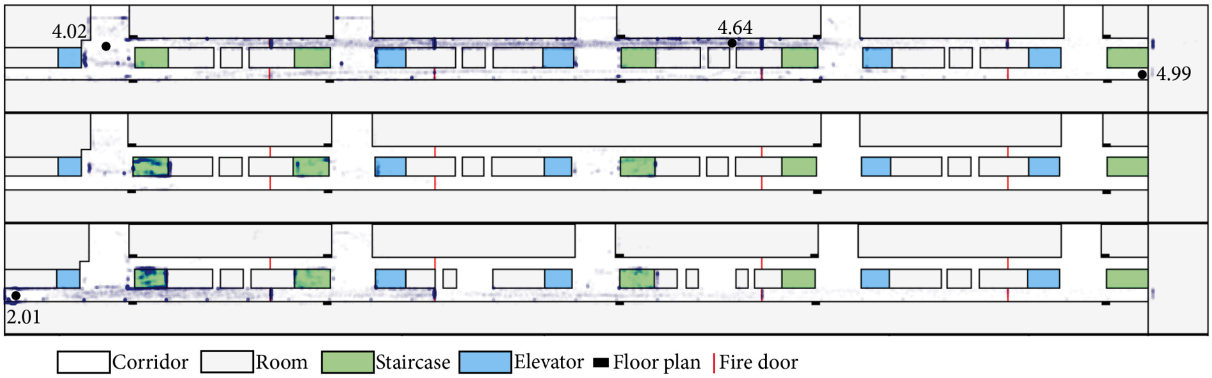

Fig. A2. Spatial distribution of participants' gaze points during assignment 3.

Appendix B. Face validity questionnaire

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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