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Using virtual reality to study pedestrian exit choice behaviour during evacuations

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ABSTRACT

Exit choice is vital to pedestrians' survival during evacuations. This paper presents the results of a VR experiment and a field experiment to study pedestrian exit choice behaviour during evacuations. Primarily, we compared pedestrian exit choice behaviour with a VR experiment and a field experiment to determine the ecological validity of a particular VR simulator (smartphone-based HMD and 360° video) as a research tool to study pedestrian exit choice behaviour. The results showed that the pedestrians' exit choice behaviour during the evacuation is similar in the field experiment and the VR experiment. Furthermore, we investigated whether and to what extent different types of information (i.e., exit signs, directional signs, presence of people) influence pedestrian exit choice during evacuations. The analysis focused on the commonalities and differences in the pedestrians' exit choice behaviour between the scenario without additional information and three scenarios with different types of information. The comparison between scenarios with different types of information illustrated that the presence of other pedestrians and directional signs have a significant influence on the participants' exit choice. Moreover, the results indicated that this VR simulator is applicable to study pedestrian exit choice behaviour during evacuations.

1. Introduction

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

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

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

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generation of realistic evacuation behaviour. Besides that, the answers from participants in surveys may deviate from their actual actions in real situations, especially the case when respondents are required to answer questions regarding unfamiliar situations or are required to recall past experiences.

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

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

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

The outline of the paper is as follows. Section 2 provides an overview of the state of the art of using different experimental methods to study pedestrian exit choice behaviour during evacuations. Section 3 presents the research methodology for the field experiment and the VR experiments. Section 4 focuses on validation results obtained from field observation and VR experiments. Section 5 presents the results featuring the impact of information on pedestrian exit behaviour during evacuations. Section 6 discusses the results of the validation study and the effect of different types of information on pedestrian exit choice behaviour. This paper ends with conclusions, limitations and suggestions for future research.

2. Background

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

2.1. Using field observations to study pedestrian exit choice behaviour during evacuations

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

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

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

2.3. Using VR experiments to study pedestrian exit choice behaviour during evacuations

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

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

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

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

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

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

3. Experimental method

To achieve the first objective of this study, two experiments were carried out to study the exit choice behaviour of pedestrians during evacuation when they face either a real-life environment or a virtual environment. To achieve the second objective, we compared the commonalities and differences in exit choice between scenarios with different types of information in the VR experiments. Underneath these two experiments are further specified. First, the setup of the field experiment is described in Section 3.1. Accordingly, the setup of the VR experiment is detailed in Section 3.2.

3.1. Field evacuation experiment

The video recordings were captured during an unannounced evacuation drill conducted on November 23rd, 2017 as part of the safety training programme of the emergency response services of the faculty of Architecture of the Delft University of Technology. The subsequent analysis mentioned in this paper was conducted as part of this training exercise to evaluate the student's and safety officer's response to the alarm. As such, no Human Research Ethics Committee (HREC) examination was required for the evacuation drill. The subsequent usage of the video for the VR experiment was assessed by the HREC as part of the evaluation of the VR experiment protocols. See Section 3.2 for the details pertaining to this assessment. Underneath the experimental layout, experiment setup and procedures of this field evacuation experiment are further elaborated upon.

3.1.1. Experiment area layout

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

At the time of the evacuation drill, twenty-four students were present. Students were standing/sitting next to the tables doing their assignments individually, their locations are identified by the black circles in Fig. 1. While working in this space, students could see all exits from their current location. We do not know the used entrance of each student, but most students generally walk in via Exit A and C, as these exits

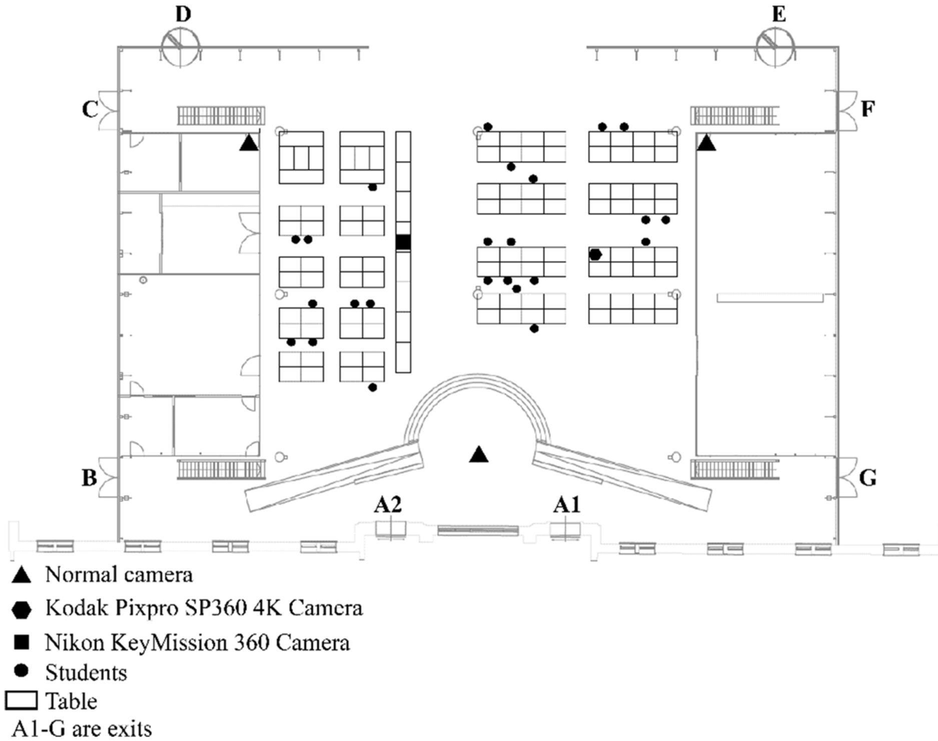


Fig. 1. A schematic illustration of the experimental area.

are the major exits of the workshop space.

3.1.2. *Experiment setup*

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

A combination of normal cameras and 360 cameras was used, namely two 360° cameras (i.e., Nikon KeyMission 360 Camera and Kodak Pixpro SP360 4 K Camera) and three normal cameras (i.e., CarCamDoo camera). Their positions in the workshop space are identified by icons in Fig. 1. Two of the three 'normal' cameras were placed at the second level of the workshop space, and the third one was placed on a balcony overseeing the workshop space (Fig. 2). These normal cameras had a higher and wider view, which ensured capturing the evacuation process of each individual. In order to identify every person clearly, the two 360 cameras were placed at the height of 1.8 m above the ground to capture the overall movement of the participants from an aerial view (Fig. 3). The setup of the field experiment ensured the behaviour of all students could easily be observed throughout the whole evacuation process without the observation being invaded or disturbing their natural behaviour.

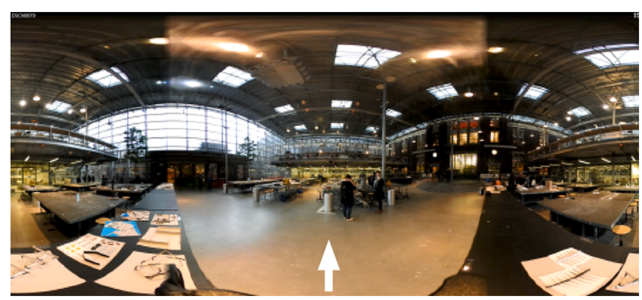
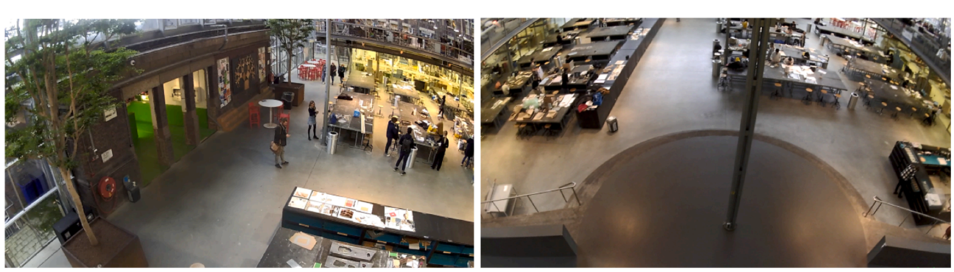


Fig. 3. A screenshot of 360° view of the workshop space by the Nikon 360 Camera.

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

3.1.3. *Experiment procedure of the evacuation drill*

The full-scale unannounced evacuation drill of the Architecture



(a) (b)

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

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

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

3.2. Evacuation experiment in the virtual environment

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

3.2.1. Experimental design

A single-factor between-subjects experimental design was used for this study to reduce the learning effects due to repetitive exposure. In order to determine the effect of various types of information on pedestrian exit choice behaviour, four different scenarios were carried out: one scenario to validate the tool and three experimental scenarios (i.e., no additional information, exit sign scenario, direction scenario). Each scenario used the 360° video-recording of the abovementioned full-scale unannounced evacuation drill as the benchmark. In essence, participants were immersed in a 360° visual environment, which was the video-recording from the Nikon KeyMission 360 Camera. Participants started the experiment at the static vantage point of the video recording (Nikon 360 camera, see Fig. 1), which is the same location for participants to perceive the virtual environment and locations of eight exits during the experiment. At the start of the experiment, all participants were facing the tables on the right, as indicated by the white arrow in Fig. 3. The white arrow points to the direction where participants looked at when they were first immersed in the virtual environment. Participants had a 360° view of the environment via rotating their head in real life. That is, participants could not move through the virtual environment. Instead, they could only move their field of view by rotating their head. The installation height of the camera (1.80 m) ensured that participants have a realistic vantage point of the entire workshop area. An alarm sound of the evacuation drill video (Nikon 360 camera) was added to all scenarios in the VR experiment in order to ensure participants received exactly the same information as in the field experiment. As at least two exits are clearly visible from the vantage point of the participants at the start of the VR experiment, we do not expect the notion that there were several exits to induce a bias in the participant's responses.

Besides the four scenarios, a general familiarisation scenario was developed to allow participants to become familiar with the way to observe the virtual environment and the sensation of VR. The familiarisation scenario entailed a 360° video of the workshop space, and it excluded any evacuation clues, evacuation alarm, or any pedestrians. In order to help participants to describe their exit choice, "Left" and "Right" signs were added on the ground of all scenarios (Fig. 4). The participants did not have a visible presence in the virtual environment (i.e., a participant cannot see their own body).

Fig. 4. Screenshots of the Validation scenario.

3.2.1.1. Validation scenario. In order to test the ecological validity, the Validation scenario presents participants with an identical evacuation scenario as the real-life evacuation drill. Thus, the students present during the evacuation drill were also present in the 360° videos, as shown in Fig. 4.

3.2.1.2. Experimental scenario. Next to the Validation scenario, three other scenarios were created to investigate the effect of different types of information on pedestrian exit choice behaviour. The three scenarios featured one without additional information, one with increased visibility of exit signs, and one with additional directional information. The video recording of the validation experiment was used as a benchmark to create these scenarios, which allows us to directly compare the participants' exit choice in three scenarios. All pedestrians appeared in the video recording were removed in the experimental scenarios. For a depiction of the visual changes to the scenario, see Fig. 5. The changes per scenario are:

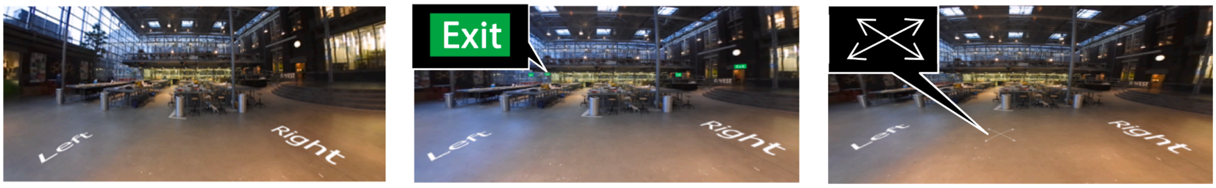
- ***No information scenario***: No additional information was added to this scenario (Fig. 5a).
- ***Exit sign scenario***: the concept of increasing visibility was incorporated by adding eight emergency exit signs with larger dimensions than the original signs to the environment. The signs were entirely text-based, containing a green background and white text (Fig. 5b). They were added on top of the original exit signs at the same location.
- ***Direction scenario***: four white arrows were added on the floor in front of the view of participants, which point to four directions directly connected exits (i.e., exit B, C, D, E, F and G) and outside of the building (Fig. 5c). The arrows were intended to inform the participants about the location of exits which were less easily observed (compare to exit A1 & A2).

3.2.2. Apparatus

This particular VR experiment does not require highly complex and expensive tools because the collected data was focused on pedestrian exit choice behaviour. Thus, a smartphone-based head-mounted display (HMD) device was deemed sufficient to capture the exit choice of participants. The smartphone-powered HMD device comprises an iPhone X and a VR Pro Virtual Reality Glasses. Participants were immersed in the virtual environment via the HMD, which has an approximate 90° horizontal and 110° vertical field of view. Fig. 6 shows the front view and the top view of the HMD device. The screen was 14 cm length and provided a resolution of 1125 × 2436 pixels for 3D effects. It has a refresh rate of 90 Hz.

3.2.3. Data collection

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



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

Fig. 5. Screenshots of three experimental scenarios.

(a) (b)

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

experiment and the actual exit choice of each participant.

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

The first section of the questionnaire recorded participants' exit choice behaviour, in particular, the number of identified exits, final exit choice, and the reason for choosing a certain exit choice. The identified exit is defined as the number of exits participants were able to observe during the experiment. The final exit choice is defined as the final exit participants chose to use at the end of the experiment. The participants were also asked to draw the identified exits immediately after finishing the task on a paper, which is a simplified version of Fig. 1. In addition, some personal details were collected, such as age, gender, familiarity with the building of the Architecture Faculty and previous experience with VR.

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

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

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

3.2.4. *Recruitment of participants*

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

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

3.2.5. *Experiment procedure*

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

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

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

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

Questionnaire: After the evacuation experiment was finished, participants were asked to remove the head-mounted display and fill in the questionnaire. After finishing the questionnaire, participants were thanked and some sweets were provided (Fig. 7).

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

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

4.1. Characteristic of the sampling population

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

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

(a) (b)

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

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

4.2. Exit choice behaviour in real-life and VR

Table 1 shows the exit choices obtained in the real-life evacuation drill and the VR experiment. During the real-life evacuation drill, most pedestrians either chose exit A1 or C. The other exits were not being chosen. The final exit choice of each individual was visualized in Fig. 8. It shows that students did not always choose the nearest exit, which implies that distance is not the only factor that influences their exit choice behaviour. To gain insights into the reasons, we analysed the video recordings in detail. In most cases, before starting their decisive evacuation movements to an exit, students decided to undertake a variety of activities, such as packing belongings, searching for others, investigating cues, and seeking confirmation from others. In total, 13 pedestrians showed waiting behaviour and moved to an exit with one or two other pedestrians together. That is, these particular individuals were stalling while waiting, facing and talking to other individuals in the space, before walking out together with the individual they were communicating with. Thus, the students performed so-called herding behaviour relatively frequent (Helbing et al., 2000), where students tend to follow friends or classmates to the exit.

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

4.3. Ecological validity analysis

To determine whether this VR simulator (i.e., the combination of smartphone-based HMD and 360° video) can be used to measure pedestrian behaviour, a justification for ecological validity is needed. In other words, in order to use the VR method for future experiments, it is important to determine whether participants behaved similarly in the virtual environment as they would in the real world (Deb et al., 2017). In this study, because exit choice is a categorical variable, the ecological validity of the results generated from the VR experiment was tested using the Pearson chi-square test. The null hypothesis is formulated as

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

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

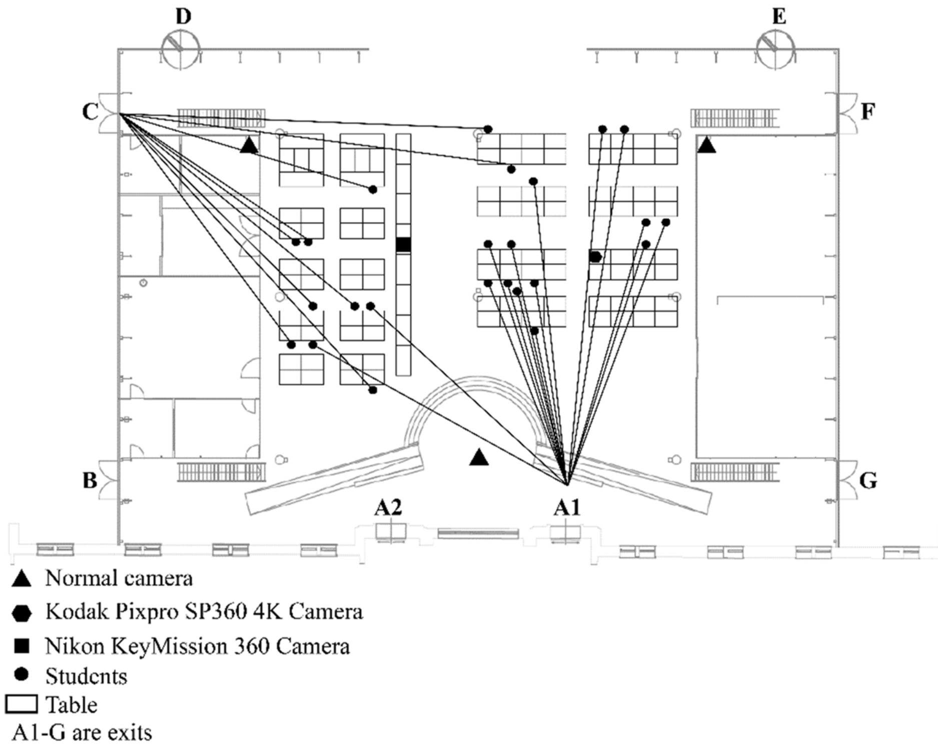


Fig. 8. The exit choice of each individual in the field experiment.

follows: the exit choice behaviour during evacuation does not depend on the experimental method. In order to meet the requirement of the chi-square test for its appropriate use (i.e., no more than 20% of the exits should be chosen less than 5 times), exit A1, B, G are combined into one category. That is because exit A1, B, G were all located at the right side of the workshop area, of which only exit A1 was chosen in both field experiment and Validation scenario. Thus, it results in 2 degrees of freedom for the chi-square distribution.

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

Another interesting finding is that in both experiments, the pedestrians' exit choice was asymmetrical. Although eight exits were available and all the students or participants could see all exits from their position, exit A1 and exit C were used more often than the other six exits. Moreover, the percentage of the participants that chose exit A1 was higher than the percentage that chose exit C in both experiments. Although we do not know the exact reason why pedestrians chose a particular exit in the real-life evacuation drill, the video recording shows that in total 13 pedestrians waited, talked with other students and moved towards exits A1 and C as two-person or three-person groups (Table 2). In the Validation scenario, 8 participants indicated that they saw other people move towards exit A1 and C. Thus, it could be argued that pedestrians in both the field experiment and the Validation scenario followed the choice behaviour of other pedestrians, which indicates that the VR method can be used to measure pedestrian exit choice behaviour in a qualitative way.

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

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

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

5. Results regarding the effect of information on exit choice behaviour

The previous section indicates that the VR experiment generated valid results pertaining to the exit choice in this particular VR setting. This section presents the results of using this VR experiment to investigate the impact of information on exit choice behaviour. First, an analysis of the participants' characteristics is presented in Section 5.1. Secondly, an analysis of questionnaire data is presented in Section 5.2. Afterwards, the exit choice behaviour over four scenarios is analysed in Section 5.3.

5.1. Characterisation of participant population

In total, 95 participants took part in the VR experiment, of which only 94 were accounted for the data analysis because one individual failed to make the exit choice before the experiment ended (as mentioned in Section 3.1). Table 3 presents the descriptive statistics of participants and their distribution over four scenarios. No significant differences were found according to the Fisher-Freeman-Halton exact test with regard to the distribution of participants' gender ($p = 0.845$), age ($p = 0.460$), familiarity with the building ($p = 0.697$) or previous VR experience ($p = 0.549$) over the four different scenarios.

5.2. Participant's perception of the virtual environment

Total scores were calculated for each questionnaire of each participant with respect to the Simulator Sickness Questionnaire (SSQ), System Usability Scale (SUS) and Presence Questionnaire (PQ), as shown in Table 4. In order to test significant differences of questionnaire results among four scenarios, the non-parametric Kruskal–Wallis was conducted for SSQ, and one-way ANOVA was used to compare the results of the SUS and the PQ between the participant groups. No significant difference was found in the SSQ among four scenarios, $H(3) = 3.044$, $p = 0.385$, as well as in the SUS, $F(3, 90) = 2.452$, $p = 0.068$ and in the PQ, $F(3, 90) = 1.519$, $p = 0.215$. This finding signals that the differences in perception between the four scenarios are very limited.

Furthermore, the mean scores and standard deviations of each questionnaire results were calculated (Table 5). The score of SSQ reflects the symptomatology of participants' experience in the virtual environment. The maximum total score of the SSQ is 236 (Kennedy et al., 2003). In general, the SSQ score of all participants was quite low in the present study. Table 6 shows the mean scores and standard deviations of each sub-scale in SSQ. It shows that the subscale of Nausea received the lowest score, increased by Oculomotor and Disorientation. Although the disorientation subscale is related to vestibular disturbances, such as dizziness and vertigo, it may also be an indicator of having experienced higher levels of virtual presence (Barfield and Weghorst, 1993). Meanwhile, none of the participants got sick during the experiment nor showed any symptoms, such as dizziness or nausea.

Besides that, the score of the Presence Questionnaire was obtained summing the responses of 22 items, scores can range from a minimum of 19 to a maximum of 133. The total scores of PQ with a mean of 71.40 and a standard deviation of 12.99 (Table 5) indicated that participants experienced a moderate amount of presence in the VR experiment. The mean scores and standard deviations of the five sub-factors in the PQ questionnaire (Witmer and Singer, 1998) were evaluated in more detail. As shown in Table 7, the interface quality receives the highest score, which indicates that the device had little distraction for participants performing their assignments. Meanwhile, the involvement factor also receives a relatively high score, which shows that participants experienced consistent concentration on the assignments they need to perform in the VR experiment. Last of all, the score of the System Usability Scale was calculated via multiplying the sum of the converted responses by 2.5. A SUS score above 68 identifies that the tool's usability is above average (Sauro, 2011). The mean score of SUS in the current experiment is 69.47, which indicates the participants were satisfied with the usability of the VR system.

Table 3
Demographic information of participants.

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

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

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

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

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

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

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

5.3. Exit choice behaviour in four scenarios

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

5.3.1. The number of identified exits

In the questionnaire, participants filled in the number of identified exits and drew these exits on a sheet of paper. If the location at which a participant drew an exit was reasonably close to the actual location of real-life exits, the exit was counted as one of the correctly identified exits. The results of the number of identified exits per scenario are depicted in Table 8, which shows that, on average, participants from the Exit sign scenario identified the most exits ($M = 5.81$, $SD = 2.11$). As expected, the average number of exits identified by participants in the

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

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

[a] Reversed items.

Table 8
The number of identified exits.

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

scenario with direction information was higher than the number of exits identified in the No information scenario. At the same time, in the No information scenario, participants identified the least exits (M = 2.62, SD = 1.12).

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

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

5.3.2. *Final exit choice*

On the same paper where the participants drew the location of exits, they also indicated which exit was their final exit choice, which is presented in Table 9. Even though eight exits were available, the exit choices were mainly distributed over exits A1, A2, C and D, which are the nearest exits compared to exit E, F and G. Besides that, the results show that participants had a variety of final exit choices amongst the four scenarios. As one can see, in these experimental scenarios (i.e., No information, Exit sign, Direction) a wider variation of final exit choices was considered than in the Validation scenario (i.e., exits A1 and C were most chosen). At the same time, when there was no additional information provided (i.e., the No information scenario) exits A1 and D were most often chosen. In the Direction scenario, the majority of participants chose exits C and D. Yet, in the increased visibility of exits in the Exit sign scenario, there is a fairly even division in terms of exit choices. Compared to the other three scenarios, the distribution of the participant's final exit choice in the Exit sign scenario was more symmetrical.

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

6. Discussions

6.1. *Discussion pertaining to the validation results*

The results and findings of the exit choice behaviour from the field experiment and the VR experiment were presented in section 4. These findings illustrate that the methodological differences between the two experiments do not result in significant differences regarding the pedestrians' exit choice behaviour.

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

Moreover, the findings highlight the influence of herding behaviour on pedestrian exit choice, where pedestrians choose to follow others during evacuations. In agreement with previous work (Helbing et al., 2000; Lovreglio et al., 2016; Moussaïd et al., 2016), herding behaviour was found in both the field experiment and VR experiment. While we found other factors influenced pedestrian exit choice (e.g., distance to

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

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

exits, visibility of exits), herding behaviour was a main influential factor consistent across in both experiments, in spite of the fact that the individuals from the field experiment were very familiar with the environment, while the participants in the VR experiment had a relatively low familiarity with the building.

6.2. Discussion pertaining to the effect of information

Section 5 presented the findings regarding the effect of different types of information on pedestrian exit choice behaviour amongst four different scenarios in the VR experiment, as well as the results regarding participants perception of the virtual environment. Now we turn to the implications of these findings for deepening our understanding of pedestrian exit choice behaviour during evacuations and application of VR experiments for pedestrian safety research.

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

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

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

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

7. Conclusion and future work

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

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

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

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

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

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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