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Comparison of pedestrian wayfinding behavior between a real and a virtual multi-story building – A validation study

Arco van Beek [*], Dorine C. Duives, Yan Feng, Serge P. Hoogendoorn

Department of Transport & Planning, Faculty of Civil Engineering and Geosciences, Delft University of Technology, Delft, The Netherlands

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ABSTRACT

Although numerous studies used Virtual Reality (VR) to study pedestrian behavior, there is an ongoing debate about the validity of using VR for studying pedestrian behavior. This study aims to contribute toward the validation of immersive VR systems for pedestrian wayfinding behavior studies by conducting a direct comparison of a field experiment and a matched virtual experiment. Both experiments feature three identical wayfinding assignments across multiple floors in a building. To evaluate the ecological validity of VR, three metrics of three different levels of wayfinding behavior are adopted, namely travel time (level: wayfinding performance), wayfinding strategy (level: decision-making), and angular speed of the head (level: observational behavior). Our findings show that VR can be used to study pedestrian wayfinding strategy in buildings with a single floor. However, there are significant differences in pedestrian wayfinding strategy between the field experiment and the VR experiment. Additionally, we found significant differences in the angular speed of the head between the two experiments. It suggests that researchers should take caution when using VR as a research tool to study the wayfinding strategy and the observational behavior of pedestrians in multi-story buildings.

1. Introduction

People spend quite some time each day walking through complex indoor environments, such as schools, university buildings, hospitals, and train stations. Under normal conditions, suboptimal designs can impact the well-being of pedestrians, as they may lead to confusion and frustration. In evacuations, the consequences can be more dire, resulting in lives lost. To enable people to find their way efficiently and allow them to evacuate safely, buildings are increasingly designed with a focus on accommodating the walking and choice behavior of occupants in mind.

In the last few decades, laboratory experiments, field experiments, and surveys have been performed to determine how pedestrians move and find their way through the built environment. Most studies feature experiments to derive the guiding principles of operational walking dynamics. For instance, the seminal works of Daamen and Hoogendoorn (2012), Kretz et al. (2006), Moussaid et al. (2012), Seyfried et al. (2009), and Zhang and Seyfried (2014) studied pedestrian operational walking dynamics. Another body of research features pedestrian exit choice behavior under emergency situations in a large variety of settings, such as single rooms (Duives and Mahmassani, 2012), campus buildings (Feng et al., 2021b; Zhu and Shi, 2016), transfer hubs (Galea et al., 2017; Shiwakoti et al., 2017), and museums (Lin et al., 2019). Moreover, a group of studies features pedestrian wayfinding performance and identifies which characteristics of the built environment, potential routes, and signage systems support efficient choice behavior of pedestrians in public spaces, such as malls (Zhang et al., 2021), parks (Mackay and Coulson, 1982), and hospitals (Kuliga et al.,

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[*] Corresponding author.
E-mail address: a.h.n.vanbeek@tudelft.nl (A. van Beek).

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2019; Pouyan et al., 2021). A final group, which is only a small partition of the pedestrian experimental literature, studies the observational behavior of pedestrians. In particular, to determine what information provided in the environment pedestrians use when making their wayfinding choices. For instance, Zhang et al. (2021) studied the impact of the turning angle on pedestrian rotation change, and Tian et al. (2019) investigated pedestrian gaze distribution and eye fixation for different types of emergency signs.

There are limitations in these experimental methodologies regarding their complexity, scale, and ability to study all levels of pedestrian choice and walking behavior simultaneously. For instance, the text and images in surveys inherently limit the realistic representation of complex environments and dynamic features of pedestrians' movement. Similarly, field and laboratory experiments are often limited in scale and complexity. In addition, there are constraints concerning the controllability of external factors in field experiments (Feng et al., 2021a). Likewise, laboratory experiments often feature stylized scenarios on one horizontal level and are relatively expensive to set up. Moreover, there are ethical constraints to study pedestrian behavior in mentally or physically unsafe scenarios like fires, earthquakes, and shooter scenarios.

Compared to traditional experimental methods, Virtual Reality (VR) has the advantage of higher experimental control and higher accuracy in collecting participants' movement data. Meanwhile, the physical risks for the participants are limited. Moreover, the scale and complexity of the observational area are more flexible. As a result, numerous studies have adopted VR to investigate pedestrian behavior, such as route and exit choice behavior (Feng et al., 2021b; Suzer et al., 2018; Vilar et al., 2014), and wayfinding behavior (Kalantari et al., 2022; Schrom-Feiertag et al., 2017; Zhang et al., 2021).

Even though many investigations into pedestrian behavior featuring VR technologies have been presented in the literature, there is a lack of studies validating the adoption of VR to study pedestrian choice behavior and walking dynamics. Some studies looked into the validation of certain metrics describing pedestrian wayfinding behavior in indoor environments, such as the travel distance (Kuliga et al., 2020), and pedestrian choice behavior (Ewart and Johnson, 2021). Another body of literature focused on the comparison of pedestrian exit choice behavior during (non-)emergency conditions (Arias et al., 2021; Kinateder and Warren, 2016; Kobes et al., 2010a; Li et al., 2019). The state-of-the-art literature displays two research gaps, namely lacking validation studies regarding pedestrian wayfinding behavior in complex environments, and establishing ecological validity of using VR to study pedestrian wayfinding behavior via direct real-life and VR comparison.

The objective of this research is to investigate to what extent VR is valid to study pedestrian wayfinding behavior in a complex indoor environment. In particular, this study establishes whether immersive VR can be adopted to study the three levels of pedestrian wayfinding behavior in multi-story buildings: pedestrian wayfinding performance (i.e., travel time), decision-making (i.e., wayfinding strategy), and observational behavior (i.e., angular speed of the head). This paper details a field experiment and accordingly compares the wayfinding results to a VR experiment that was performed by Feng et al. (2022a). Their study features pedestrian wayfinding behavior in a virtual replica of the campus building in the Netherlands where the current field experiment is performed. The virtual building has a similar layout and appearance as the real building. This allows for a direct comparison of various metrics gathered related to pedestrian wayfinding behavior in the physical as well as in the virtual environment.

This paper is organized as follows. The background corresponding to pedestrian wayfinding behavior and VR validation is given in Section 2. Section 3 details the research methodology of the field experiment, which is set up to validate the VR experiment. The experimental design, experimental procedure, apparatus, metrics of interest, and participant characteristics are described. This section also briefly describes the VR experiment performed by Feng et al. (2022b). Accordingly, Section 4 presents the results of the field experiment and the comparison with the VR experiment and existing literature. Section 5 closes this paper with a conclusion of the main findings and suggestions for future research.

2. Related work

Traditionally, pedestrian wayfinding behavior, including pedestrian choice behavior and pedestrian walking dynamics, are often studied by means of laboratory experiments, field experiments, and survey studies (e.g., Daamen and Hoogendoorn, 2012; Kobes et al., 2010b; Ronchi et al., 2018). More recently, there is also an increasing number of studies that used VR systems to investigate pedestrian wayfinding behavior due to its benefits compared to the above-mentioned traditional experimental methods (e.g., can investigate multiple metrics, high controllability, and easy data extraction) (Feng et al., 2021b; Kalantari et al., 2022; Vilar et al., 2014; Zhang et al., 2021). While the benefits of VR compared to traditional experimental methods are undeniable, it is essential to validate the usage of VR to study pedestrian behavior in order to ensure that results generated from VR align with those obtained in real-life scenarios.

There are a few studies in the literature that investigated whether pedestrians behave similarly in a VR environment as they would in a physical environment. Deb et al. (2017) established the face validity (i.e., the extent to which a VR environment appears realistic to the user) and construct validity (i.e., the extent to which VR adequately measures the metrics) of an immersive VR environment to study pedestrian crossing behavior and walking speed. Similarly, Feng et al. (2022a) established content validity (i.e., the extent to which VR is able to measure the metrics of interest) and construct validity of an immersive VR environment to study wayfinding strategies, route choice, and wayfinding performance in multi-story buildings.

The ecological validity, namely participants' perceptions and behavior in the virtual environment can be generalized to physical situations (Brewer and Crano, 2000), is rarely studied. The literature provides only a few studies focusing on the direct comparison of metrics related to pedestrian wayfinding, choice, and walking behavior between a real-life scenario and its identical virtual environment. Previous studies investigated the ecological validity of the pedestrian exit choice behavior in different scenarios (Arias

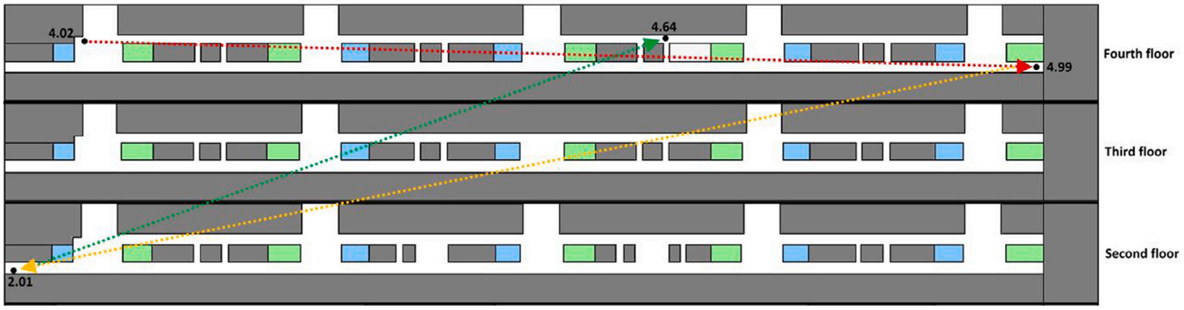


Fig. 1. The top-down view of the second, third, and fourth floor of the Civil Engineering and Geosciences building of Delft University of Technology are presented on top of each other. The assignments 1 (i.e., from office 4.02 to office 4.99), 2 (i.e., from office 4.99 to office 2.01), and 3 (i.e., from office 2.01 to office 4.64) of both experiments are indicated by the red, yellow and green arrow, respectively.

et al., 2021; Kinateder and Warren, 2016; Kobes et al., 2010a; Li et al., 2019). Amongst other findings, they found that the pedestrian exit choice is not significantly different between a physical hotel and its virtual replica (Kobes et al., 2010a; Arias et al., 2021).

More recently, a few studies compared pedestrian wayfinding behavior between a real and a virtual building, mostly focused on a single-story building (Dong et al., 2022), a few studies focused on a two-story building (Ewart and Johnson, 2021), or a multi-story building (Kuliga et al., 2020). Dong et al. (2022) found that the pedestrian wayfinding performance is similar in both the real and the virtual building, though the visual attention of pedestrians is different. Also, Kuliga et al. (2020) found similar travel distances for wayfinding tasks in a real and a virtual building. Lastly, Ewart and Johnson (2021) studied the validity of pedestrian route choice and pedestrian head movement when using VR. Their results showed that the pedestrian route choice is similar in both environments. However, the pedestrian head movement is lower in VR compared to the real-life scenario. Next to that, the participants using VR also had a higher tendency to show implausible behavior (e.g., jumping off a balcony).

The above-mentioned studies investigated the validity of VR systems to study certain types of pedestrian behavior. However, previous research only investigated the validity of VR via focusing on a limited number of metrics (e.g., wayfinding performance, and route choice) under specific conditions (e.g., emergency conditions, and fairly ‘simple’ indoor building layouts). These studies found both similarities and differences in pedestrian wayfinding behavior, choice behavior, and observational behavior. It is uncertain to what extent these findings hold true for each behavioral metrics of pedestrian wayfinding behavior in a complex multi-story building. Thus, it is different to gauge the valid usage of VR systems to study pedestrian wayfinding behavior based on these previous studies. As a result, more comparison studies are required to establish the validity of using VR to investigate pedestrian wayfinding behavior in multi-story buildings.

3. Research methodology

This section presents the research methodology of the field experiment that is used to determine the wayfinding behavior of pedestrians in a real-life multi-story building. Section 3.1 identifies the experimental design of the experiment, whereas the procedure is described in Section 3.2. The apparatus and the metrics of interest are discussed in Sections 3.3 and 3.4. In Section 3.5, the participants’ characteristics are briefly described. Finally, the reader is referred to Section 3.6 for a brief introduction to the VR experiment that was performed by Feng et al. (2022a).

3.1. Experimental design of the field experiment

This study aims to compare wayfinding behavior in terms of wayfinding performance, wayfinding strategy, and observational behavior of pedestrians in a multi-story building between a physical and a virtual environment. The VR experiment was performed in 2019. To allow for comparison, the experimental design of the field experiment is similar to the experimental design of the VR experiment. A brief introduction of the VR experiment is given in Section 3.6, for more detailed information, the readers are referred to Feng et al. (2022a,b).

The field experiment features three distinct wayfinding assignments in the Civil Engineering and Geosciences faculty building of the Delft University of Technology. The configuration of the observed floors of the faculty building is shown in Fig. 1. Here, the gray, green, and blue blocks are offices, stairways, and elevators, respectively, while the corridors of the building are indicated with the white areas. It should be mentioned that the field experiment only takes place on the second, third, and fourth floor of the building. For that reason, the figure only presents those three floors of the building. To give a rough estimation of the distance traveled by the participants, each floor is approximately 200 m long and 30 m wide.

During the first assignment, participants performed a wayfinding assignment on a single floor. They were asked to find their way from room 4.02 to room 4.99 – the red arrow in Fig. 1. The participants needed to transit between two main parallel corridors along the building’s length. Next, participants needed to find their way from room 4.99 to room 2.01 during assignment 2 (i.e., the yellow arrow in Fig. 1). In addition to walking the length of the building, they were also required to move between levels in the building. For assignment 3, participants were asked to switch between floors and between the main parallel corridors while walking from room 2.01 to room 4.64. This assignment is indicated with the green arrow in Fig. 1. After the third assignment, participants were asked to return to the starting point, i.e., room 4.02.

3.2. Experimental procedure of the field experiment

The field experiment was approved by the Human Research Ethics Committee of the Delft University of Technology (Reference ID 2271). The participants were recruited by means of flyers distributed at the campus and LinkedIn posts. All participants joined the experiment voluntarily. They received a 10 euro gift card once the experiment ended, irrespective of the outcome of the experiment. The experimental procedure consisted of four parts, namely (1) a general introduction to the experiment, (2) a calibration phase, (3) the wayfinding experiment, and (4) a post-experiment questionnaire. The four phases of the field experiment are described in more detail below.

1. *Introduction.* The procedure of the experiment was explained to the participants by means of a written statement and verbal communication. The verbal communication of the instructor was scripted to ensure that all participants were provided with exactly the same information. The participants were told that they needed to perform tasks that were communicated by signs at the destination of the previous task. During the experiment, they were required to wear a set of eye-tracking glasses and a shoulder bag at all times — see Fig. 2. Participants were not informed about the purpose of the glasses. However, it was evident that certain participants were aware that they were wearing an eye tracking device. It was emphasized that they should walk at their ‘normal’ walking pace, and not use the elevators. After these instructions, they were required to sign an informed consent form to participate in the experiment.
2. *Calibration.* The eye tracking device was (re-)calibrated for each participant. The participants were asked to gaze at a single word on a white piece of paper at eye level. This directive resulted in the alignment of the participant’s gaze and that specific word in the video data, leading to a more accurate video data featuring the participant’s gaze point. Afterward, to identify the bias in the glasses’ built-in measuring devices, the participants were asked to stand still and look straight forward at the word for 60 s. This allowed the researchers to identify the bias of the rotational data and subsequently eliminate this bias from the data during the analysis.
3. *Experiment.* Participants were instructed to begin with assignment 1 after the calibration was completed. The assignment was presented to the participants by means of written instructions on a piece of paper attached to the wall. It stated: ‘Stand still for 1-minute then walk toward office 4.99’. At the start of the experiment, participants did not know their current location unless they noticed the office numbers along their route toward the starting point, or had previous spatial knowledge regarding the layout of the building. All participants took exactly the same route from the entrance of the building to the starting location of the experiment. When they arrived at the destination of an assignment, the next assignment was communicated to them similarly as assignment 1, namely by means of a scripted message on white paper attached to the door of the prior destination (e.g., room 4.99). Eventually, after 3 assignments, the participants arrived back at the starting point and the field experiment was stopped. Please note that the instructor did not follow the participants through the building to not disturb their wayfinding behavior. At the endpoint, the researcher asked the participants whether they felt any type of discomfort during the experiment.
4. *Questionnaire.* A digital post-experiment questionnaire was provided to the participants directly after the experiment. The questionnaire contained questions about their personal characteristics (i.e., gender, age, and educational background), their wayfinding ability, and the wayfinding strategy they had applied. Before the participants left, they were rewarded with a gift card.

3.3. Apparatus

The participants were equipped with Pupil Labs’s eye tracking glasses, particularly the Pupil Invisible depicted in Fig. 3. They are able to register the eye movements of participants and record the environment from the participants’ perspective. The integration of the visual data with the comprehensive eye movement data leads to the gaze data of the participants. The eye-tracking glasses are also equipped with an accelerometer and a gyroscope to quantify the translational and rotational acceleration of the participants’ heads. The present study uses the data from the accelerometer and the gyroscope. The data featuring the gazing behavior of the participants has not been studied. Future research could look into the difference between the head gazing direction and the actual gazing behavior of participants.

3.4. Metrics of interest

The study aims to compare pedestrian wayfinding behavior inside a multi-story building between a field and a VR experiment. Pedestrian wayfinding behavior is defined as how pedestrians orientate themselves in the environment and navigate to their destination. Wayfinding behavior can be evaluated with three levels of metrics, namely wayfinding performance (e.g., time to complete the task), decision-making (e.g., route choice), and observational behavior (e.g., looking around) (Feng et al., 2022a; Ruddle and Lessels, 2006). In this study, the comparison between both experimental methods is made with a specific metric of all three levels. The definition of these terms is explained below, as well as a definition of the metrics of interest.

Fig. 2. An example of a participant equipped with the eye-tracking glasses connected to a mobile phone located in the red shoulder bag.

Fig. 3. The eye tracking glasses 'Pupil Invisible' of Pupil Labs.

Wayfinding performance indicates how well pedestrians find their way within an environment and navigate to their destination. Often, the wayfinding performance is evaluated using three metrics: travel time, travel distance, and travel speed (Feng et al., 2022a). In this study, the wayfinding performance is measured in terms of travel time and optimal walking speed, as the measured travel distance and travel speed were not representative due to the inaccuracy of the measuring device. Travel time is determined by manual annotation of the starting and the ending time of each wayfinding task for every participant. The optimal walking speed represents how quickly a participant finished the wayfinding task, however, it does not exactly represent the pedestrians' travel speed (i.e., the free-flow walking speed). The optimal walking speed is also influenced by the decision-making process (e.g., route length, hesitations, and stops). For instance, if the participant takes a longer route to its destination, the participant's optimal walking speed decreases, even though his free-flow walking speed might be constant throughout the entire route. The optimal walking speed is calculated by dividing the minimum distance of the assignment (i.e., the distance of the shortest path that a participant could take to complete the assignment) by the travel time of the participant in that specific assignment. The minimum distance is equal in both experiments and is the longest for assignment 2 (i.e., 224.24 m), followed by assignment 1 (i.e., 187.06 m), and assignment 3 (i.e., 153.12 m).

The pedestrian wayfinding strategy is considered as the metric regarding the decision-making of pedestrians. The pedestrian wayfinding strategy is considered as the metric regarding the decision-making of pedestrians. In this study, decision-making is defined as the route selection of the pedestrians, and the strategy is the systematic approach pedestrians take to reach their destination. Hölscher et al. (2006b) identified three different wayfinding strategies that pedestrians use to navigate themselves through multi-story buildings. Those strategies are called the *floor strategy* (i.e., pedestrians go up or down the stairs to the vertical position of their destination first), the *direction strategy* (i.e., pedestrians move toward the horizontal position of their destination first), and the *central point strategy* (i.e., pedestrians rely on well-known areas or objects to navigate). Those three strategies are used in this paper to investigate pedestrian wayfinding strategy. The wayfinding strategy and the global trajectory in general are extracted manually from the video data by the researcher, as the used tracking device was not accurate enough.

Table 1
Descriptive statistics featuring the participants' characteristics in both the field experiment (RL) and the VR experiment. Here, the Dutch education system is indicated in brackets.

Descriptive information	Category	Number RL (percentage)	Number VR (percentage)
Gender	Male	23 (67.6%)	17 (47.2%)
	Female	11 (32.4%)	19 (52.8%)
Highest education level	High school or equivalent	0 (0%)	5 (13.8%)
	Associate's degree or equivalent (MBO)	2 (5.9%)	–
	Bachelor's degree or equivalent (HBO or WO)	10 (29.4%)	6 (16.7%)
	Master's degree or equivalent (WO)	17 (50%)	19 (52.8%)
	Doctoral degree or equivalent (PhD)	5 (14.7%)	6 (16.7%)
High level of familiarity with the building	Strongly agree	10 (29.4%)	–
	Agree	8 (23.5%)	–
	Neutral	7 (20.6%)	–
	Disagree	3 (8.8%)	–
	Strongly disagree	6 (17.6%)	–

Pedestrians need to observe their surroundings to acquire information to navigate the environment (Hund and Gill, 2014; Spiers and Maguire, 2008). Various metrics can be used to study pedestrian behavior to acquire information, e.g., gaze points, head rotation, and hesitations (Feng et al., 2022a). These metrics are collectively defined as pedestrian observational behavior. This study limits the pedestrians' observational behavior to a singular metric diverted from the pedestrian head rotation. The angular speed of the head around the yaw axis (i.e., rotating their heads left to right) is studied; i.e., the absolute head rotation of pedestrians is not measured in this study. Other rotations (i.e., rotations around the pitch and roll axis) were excluded from the measurements to minimize the noise caused by pedestrians shaking their heads while moving (Zhang et al., 2021). Henceforth, when the study refers to the angular speed of the head, it specifically denotes the angular speed around the yaw axis. This angular speed refers to the rotation rate of the head around its axis, i.e., it measures how fast the head of the pedestrians is rotating.

3.5. Participant's characteristics

Over the course of three days, 34 participants took part in the field experiment. The number of participants is close to the 36 participants of the VR study in Feng et al. (2022a). None of the participants were involved previously in any way with this research. The participants were all adults, their ages ranged from 24 to 61 years (M = 31.3, SD = 9.8). The participant group featured 23 males and 11 females. Table 1 represents some general statistics related to the characteristics of the participants of both the field and the VR experiment. In total, 32 of the 34 participants in the field experiment have a Bachelor's degree and 22 of them also received a Master's degree. The level of education of the participants is similar to that in the VR experiment, but relatively high considering the Dutch average (i.e., only 30% of the population got a Bachelor's degree or higher (Centraal Bureau voor de Statistiek, 2018)). To the best of the authors' knowledge, there are almost no studies featuring the impact of educational background on pedestrian behavior. Therefore, it is difficult to state anything about the potential effect of our highly educated participant sample on the findings compared to the average Dutch population. Moreover, most participants were already 'somewhat' to 'very familiar' with the faculty building, in which the experiment took place. In this particular study, the potential effect of the participant's familiarity with the building on pedestrian behavior has not been studied; however, it is in an interesting topic for further research. It is worth noting that the participant's familiarity with the building is unknown, as it was not asked in the post-experiment questionnaire.

3.6. Virtual reality experiment

The VR experiment was already performed in 2019, and the study was published in 2022 (Feng et al., 2022a). Its research set up is reported extensively by Feng et al. (2022a). In summary, this experiment adopted an HTC Vive HMD VR system featuring 360-degree head tracking and a 110-degree view. Unreal Engine 4 and SteamVR were used to run the virtual environment. A hand controller was used by participants to control their movement in the VR environment, and a physical limit was set on their walking speed to ensure realistic walking speeds in the VR environment. Participants were able to move with a maximum speed of 1.4 m/s by pressing the home pad of the controller with their thumb, either continuously or multiple times per second. The direction of the motion was based on the participants' head orientation.

Similarities between both experiments

The virtual environment used in the VR experiment is a representation of the same building that was used in the field experiment. The layout of the virtual building has the exact same dimensions as the real building. Fig. 4 shows one example of the real-life view and the same view in the virtual building. To the extent possible, the procedure, and the assignments in the virtual and field experiments were the same. In particular, the wayfinding assignments were identical to each other, the tasks were set in the same order, and there were no other people in the building during the real-life as well as the VR experiment.

(a) Real-life view. (b) Virtual reality view.

Fig. 4. A picture from the building of (a) the field experiment and (b) the VR experiment.

(a) Signage in field experiment. (b) Signage in VR experiment.

Fig. 5. A picture of the signage with the office number 4.24 directly next to the office door in (a) the field experiment and (b) the VR experiment.

Differences in the visual appearance

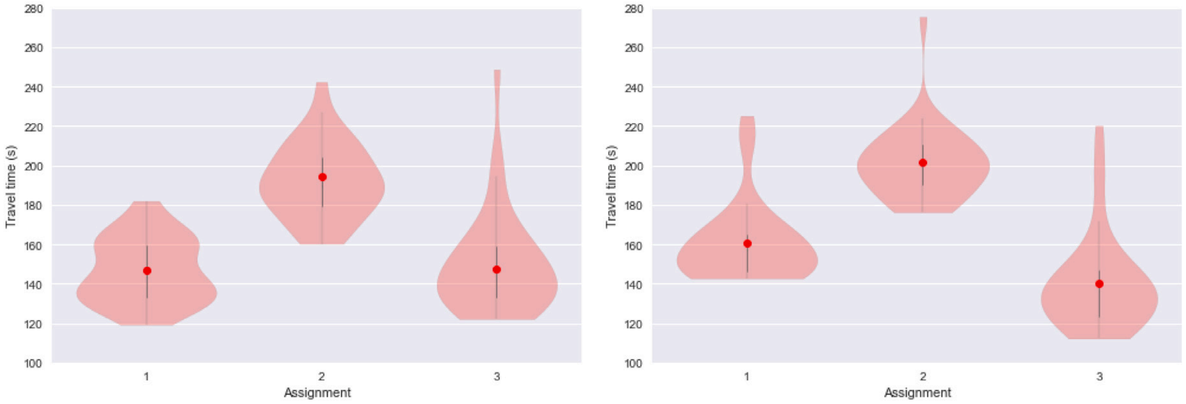
The virtual building has a similar layout and appearance as the real building. However, the appearance of the signage in the VR environment differs from that of the real-life signage. The signage in the VR environment differs from the real-life signage in terms of font size. This difference in font size between the virtual and the real building is depicted in Fig. 5. Though the discrepancy between both signs seems significant, the font size of the signage was a conscious design choice by the responsible researchers of the VR application of the building (Feng et al., 2022a). In trials, it was evident that people perceive the font size in the VR environment differently than in real-life. In particular, the font size in the VR environment is perceived as smaller than the same font size in real-life. Therefore, the researchers decided to enlarge the font size in the VR environment based on trial and error. They found that the font size in the VR environment (see Fig. 5(b)) was perceived as similar to the font size in the real building (see Fig. 5(a)).

This study builds upon the assumption of similar perceptions regarding the signage. Based on the consistency in perception, our expectation is that pedestrian behavior is not affected by the difference in visual appearances seen in Fig. 5. This does not mean that the three metrics of interest should be similar in both the VR and the field experiment. It only indicates that it is hypothesized that font size of the signage does not cause the differences between both experiments.

Yet, next to the experiences piloting this VR environment, there is no scientific proof for the statement of similar perception regarding the font size of the signage between both experiments. Though our observations suggested a similar perception, it is essential to note that certain findings might rely on an assumption lacking scientific validation. The validation of this assumption is an interesting angle for future research and would also strengthen the presented results of this study.

Differences in architectural layout and experimental procedure

Moreover, there were four minor deviations between the virtual and field experiments in the architectural layout and the experimental procedure. Firstly, a notable difference in the architectural layout was the absence of an additional stairway located



(a) Field experiment.

(b) VR experiment.

Fig. 6. The distribution of the travel time among the three assignments for the (a) field experiment and (b) VR experiment.

near rooms 2.01, 3.01, and 4.01 in the virtual environment. The participants of the field experiment were permitted to use this stairway. Secondly, there is a distinction between the number of floors in both experiments. In the virtual environment, the fourth floor is the highest level. In contrast, the building of the real-life experiment features six floors. Firstly, the VR experiment consisted of four assignments instead of three assignments as in the field experiment. For the last assignment, the participants of the VR experiment were instructed to evacuate the building on the first floor in response to an evacuation alarm and accompanying voice message, while participants in the field experiment were asked to return to the starting point after the third assignment. Consequently, the walking behavior of the fourth assignment in the VR experiment is not taken into account in the comparison. Secondly, the assignments were communicated slightly different to the participants in both experiments. The assignments in the VR experiment were communicated by a text at the bottom of their sight, while the assignments in the field experiment were communicated using scripted texts on white sheets of paper on the corresponding office doors.

We expect that the procedural and architectural modifications between the virtual and field experiment are minor and do not impact the direct comparison in this study.

4. Results & discussion

This research aims to study the impact of the experimental method on the wayfinding behavior of pedestrians. This section presents the findings featuring three metrics regarding wayfinding behavior and compares these metrics between the field and the VR experiment. Firstly, the pedestrian wayfinding performance in terms of travel time is discussed in Section 4.1. Next, the pedestrian decision-making in terms of the wayfinding strategy is compared in Section 4.2. Section 4.3 presents and discusses the differences in the participants' observational behavior in terms of the angular speed of the head.

However, the wayfinding behavior of both experimental settings must be established before doing so. Therefore, the three sections featuring the findings of the wayfinding performance (i.e., Section 4.1), decision-making (i.e., Section 4.2), and the observational behavior (i.e., Section 4.3) are separated into three parts. Firstly, the findings of the field experiment related to the specific metric are discussed, as well as the potential differences between the three assignments within the field experiment (see Sections 4.1.1, 4.2.1, and 4.3.1). Secondly, the findings of the VR experiment are presented (see Sections 4.1.2, 4.2.2, and 4.3.2). Finally, the knowledge of the relative differences in behavior per experimental method will allow us to identify the differences between the experiments more specifically. The comparison between both experiments is presented in Sections 4.1.3, 4.2.3, and 4.3.3. The reader is referred to these sections for the main findings of this study.

4.1. Wayfinding performance: Travel time

4.1.1. Findings of the field experiment

The average travel time of the participants was 489.42 s (SD = 50.52 s) for the field experiment. More specifically, the participants had the longest travel average travel during assignment 2 ($M_{2,RL}$ = 192.53 s, SD = 18.74 s), followed by assignment 3 ($M_{3,RL}$ = 150.16 s, SD = 25.65 s), and assignment 1 ($M_{1,RL}$ = 146.73 s, SD = 16.15 s). In Fig. 6(a), the distribution of the pedestrians' travel time during the three assignments are shown. A statistical test is performed to study the normality of these distributions. The Shapiro–Wilk test showed that the travel time is not normally distributed for assignment 3 ($p < 0.01$), whereas the travel time of assignment 1 ($p = 0.12$) and 2 ($p = 0.75$) do not reject the normal-distribution hypothesis. Therefore, the assumption of normality can be used for the travel time distributions of assignment 1 and 2.

As mentioned in Section 3.4, an optimal walking speed of the participants is determined for each assignment. The optimal walking speed does not represent the free-flow walking speed of the pedestrians, please refer to Section 3.4 for further details. The

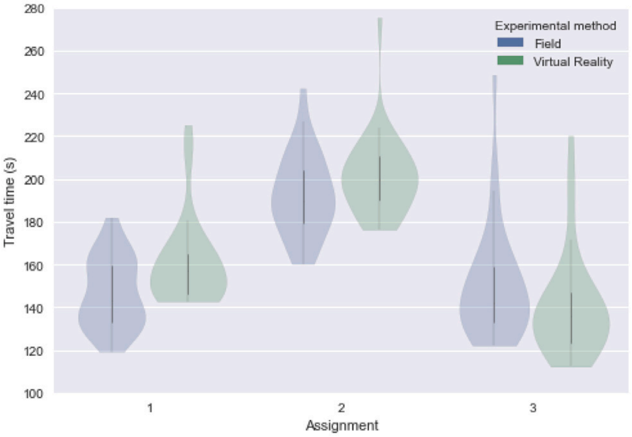


Fig. 7. The distribution of the travel time for all three assignments in both the field (i.e., the left plot of a pair) and VR experiment (i.e., the right plot of a pair).

optimal walking speed is the highest during assignment 1 ($v_{1,RL}$ = 1.29 m/s, SD = 0.14 m/s), followed by assignment 2 ($v_{2,RL}$ = 1.18 m/s, SD = 0.11 m/s) and assignment 3 ($v_{3,RL}$ = 1.04 m/s, SD = 0.14 m/s). Results of the Friedman test showed statistically significant differences in the optimal walking speed among the three assignments: p < 0.001. The Wilcoxon signed-rank test found statistically significant differences for all tests between two assignments (p < 0.001). That is, the assignments are different in terms of the optimal walking speed, which suggests that participants change their optimal walking speed over the assignments.

4.1.2. Findings of the VR experiment

Feng et al. (2022a) found an average travel time of 502.23 s (SD = 55.75 s) for the three assignments combined. In particular, the participants spent the most amount of time on assignment 2 ($M_{2,VR}$ = 201.30 s, SD = 18.30 s), followed by assignment 1 ($M_{1,VR}$ = 160.79 s, SD = 20.19 s), and assignment 3 ($M_{3,VR}$ = 140.14 s, SD = 24.02 s). The distributions of the pedestrians' travel time for all three assignments are shown in Fig. 6(b). All three distributions do not significantly deviate from a normal distribution, i.e., the Shapiro–Wilk test is performed (p < 0.01).

Regarding the optimal walking speed, for the participants in the VR experiment, the optimal walking speed is the highest during assignment 1 ($v_{1,VR}$ = 1.18 m/s, SD = 0.12 m/s), followed by assignment 2 ($v_{2,VR}$ = 1.12 m/s, SD = 0.09 m/s) and assignment 3 ($v_{3,VR}$ = 1.12 m/s, SD = 0.16 m/s). The Friedman test showed that there are statistically significant differences in the optimal walking speed among the virtual assignments: p = 0.001. Results of the Wilcoxon signed-rank test showed that there is a statistically significant difference in the optimal walking speed for all tests between two assignments (p ≤ 0.01), except for the test between assignments 2 and 3 (p = 0.52). That is, the virtual wayfinding assignments involving level changes are similar to each other in terms of optimal walking speed, but significantly lower than the single-level wayfinding assignment.

4.1.3. Comparison between both experiments

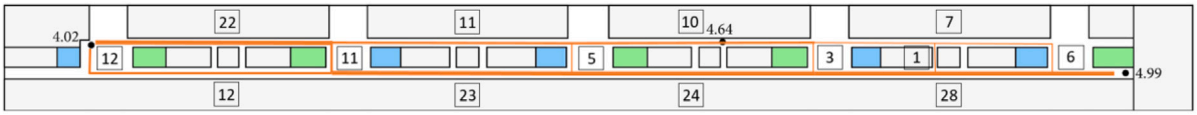
The Wilcoxon signed-rank test showed that the average travel time is not significantly different between the two experiments ($p > 0.05$). That is, the average travel time of pedestrians is similar in both experiments if we combine all three assignments together. The average travel time is also discussed for each assignment individually. In both experiments, the travel time is highest for assignment 2, but there is a discrepancy between the travel time of the two experiments regarding assignments 1 and 3.

Statistical tests are performed to compare the average travel time between the two experimental methods per assignment. Results of the Mann–Whitney U test showed that the difference in travel time is significant between the two experiments for assignment 1 (p = 0.003, U statistic = 357), and assignment 3 (p = 0.03, U statistic = 796). However, the test also indicated that the difference in travel time is not significant for assignment 2 (p = 0.06, U statistic = 451). While this difference did not reach statistical significance ($p < 0.05$), it is worth noticing that the findings approach significance. Potentially, the significance difference in the average travel time of assignment 2 between both experiments can be proved with a larger sample size in future research.

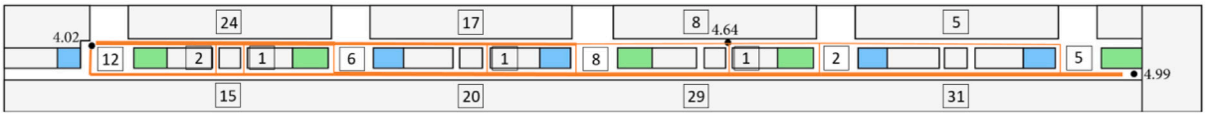
These statistical tests are based on the distribution of the pedestrians' travel time for both experiments. Fig. 7 presents these distributions just like Fig. 6. Here, for each assignment, the distributions of both experiments are aggregated to simplify the comparison between both experimental methods.

Regarding the optimal walking speed, the statistical tests featuring a comparison of both experimental methods do not differ from those comparing the travel time for each assignment. There is a significant difference in optimal walking speed between both experimental methods for assignments 1 and 3. However, the difference for assignment 2 is not significant.

Overall, the results regarding the travel time and the optimal walking speed indicate significant differences in two of the three assignments. This statement does not indicate that a VR system cannot be used to study pedestrian wayfinding performance. In the VR experiment, the movement speed of participants was calibrated to accommodate maximum pedestrian walking speeds. This



(a) Field experiment.



(b) VR experiment.

Fig. 8. The pedestrian route choice during assignment 1 (i.e., from room 4.02 to room 4.99) in (a) the field experiment and (b) the VR experiment.

calibration limits the movement freedom of the participants; for example., some participants might want to move faster than the capped maximum speed. Therefore, the average travel time of the participants in the VR experiment might be affected by the accommodation of a maximum walking speed. Further study is required to conclude anything regarding the validity of using a VR system to study pedestrian wayfinding performance.

4.2. Decision-making: Wayfinding strategy

4.2.1. Findings of the field experiment

The wayfinding strategy of the participants can be extracted from participants' movement trajectories. The global pedestrian trajectories are shown with the orange lines in Fig. 8(a) for assignment 1 in the field experiment. Here, the thickness of the orange line is a rough estimation of the number of participants that used that pathway. The exact number using a pathway is given in the rectangular box. The thickness of the orange line is a rough visualization of that number In this assignment, participants were required to walk from office 4.02 (i.e., the top left corner of the figure) to office 4.99 (i.e., the bottom right corner of the figure). Fig. 8(a) shows that most participants of the field experiment decided to walk straight into the corridor with the even-numbered, and that they switched to the corridor with the odd-numbered offices further along the route. That is, the central-point strategy is used by the majority of pedestrians for finding their way on a single floor in the field experiment.

Table 2 shows the number of participants using a certain wayfinding strategy for all three assignments in both experiments. For assignment 1 in the field experiment, a smaller group of participants (i.e., 12 participants - 35%) used the direction strategy, i.e., they immediately switched to the corridor where the destination was located. The other 22 participants (65%) used the central-point strategy as mentioned above.

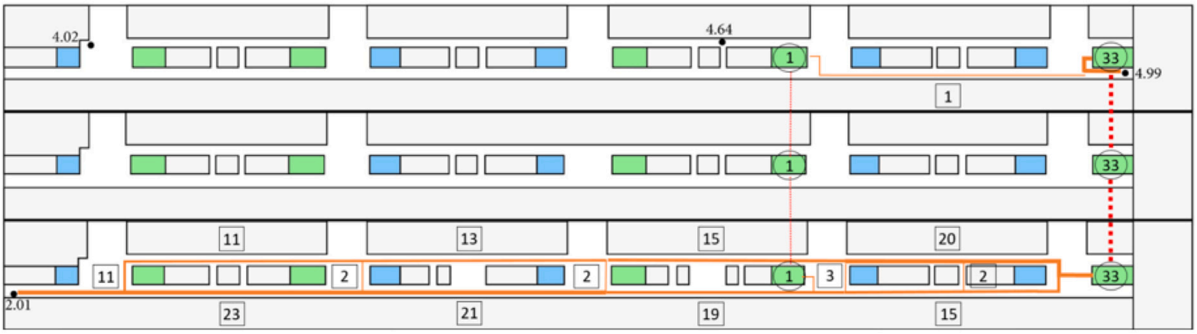
For assignment 2 of the field experiment, in which participant walk from office 4.99 to office 2.01, the pedestrian global trajectories are shown in Fig. 9(a). These trajectories indicate the route choice of the pedestrians, therefore, the wayfinding strategy as well. Fig. 9(a) shows that pedestrians preferred the floor strategy over the direction strategy, i.e., pedestrians used the stairs closest to office 4.99 to navigate to the second floor before finding the horizontal position of their destination. Table 2 shows that 33 participants (97%) used the floor strategy, and only 1 participant (3%) used the direction strategy.

The same pattern holds true for the wayfinding strategy in assignment 3, in which pedestrians walk from office 2.01 to office 4.64. The pedestrian route choice for assignment 3 of the field experiment are shown in Fig. 10(a). Again, the majority of pedestrians decided to use closest to their starting point. Please note, in assignment 3 of the field experiment, the usage of the first stairway on either side of room 4.02 is considered to be the floor strategy. The quantitative data presented in Fig. 10(a) shows that 32 participants (94%) used the floor strategy, while only 2 participants (6%) used the direction strategy.

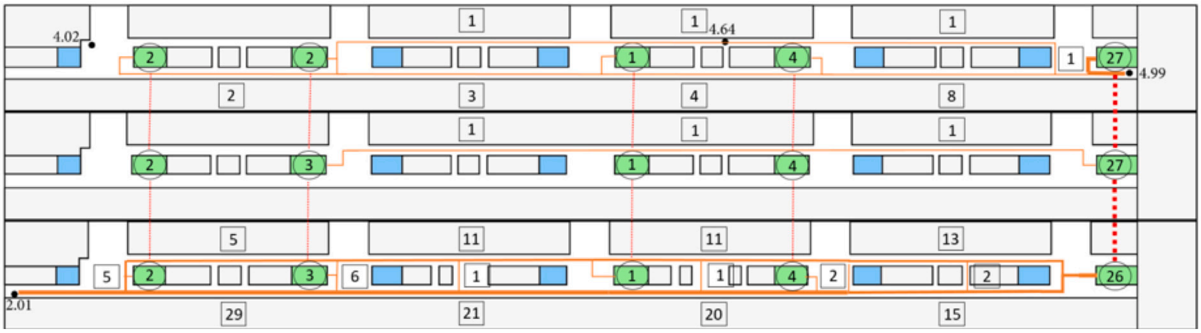
4.2.2. Findings of the VR experiment

Fig. 8(b) shows the global pedestrian trajectory of the participants in the VR experiment during assignment 1, in which they moved from office 4.02 to office 4.99. This global trajectory indicates that most participants of the VR experiment moved into the corridor right in front of them, i.e., they used the central point strategy. Specifically, 24 participants (67%) employed the central point strategy, whereas 12 participants (33%) used the direction strategy (see Table 2).

The route choice behavior of the participants in the VR experiment are visualized for assignment 2 in Fig. 9(b), and for assignment 3 in Fig. 10(b). Based on both figures, it is evident that for both assignment 2 (i.e., walking from office 4.99 to office 2.01) and assignment 3 (i.e., walking from office 2.01 to office 4.64) in the VR experiment, the majority of the participants used the stairs closest to their starting point. That is, they preferred the floor strategy while navigating through the virtual environment. Table 2 quantitatively shows that the floor strategy is preferred in assignment 2 (i.e., 27 participants - 75%) and assignment 3 (i.e., 26 participants - 72%). The direction strategy was used by 9 participants (25%) in assignment 2, and by 10 participants (28%) in assignment 3.



(a) Field experiment.



(b) VR experiment.

Fig. 9. The pedestrian route choice in assignment 2 (i.e., from room 4.99 to room 2.01) in both (a) the field experiment and (b) the virtual reality experiment. Here, the red dotted lines indicate the vertical movement of the pedestrians (i.e., the stairway they used to switch floors), whereas the number of pedestrian using a certain stairway is given within the circle.

Table 2
The applied wayfinding strategies of participants for the three assignments in the two different experiments.

Assignment	Experiment	The floor strategy	The direction strategy	The central point strategy
1	Field	0	12	22
	VR	0	12	24
2	Field	33	1	0
	VR	27	9	0
3	Field	32	2	0
	VR	26	10	0

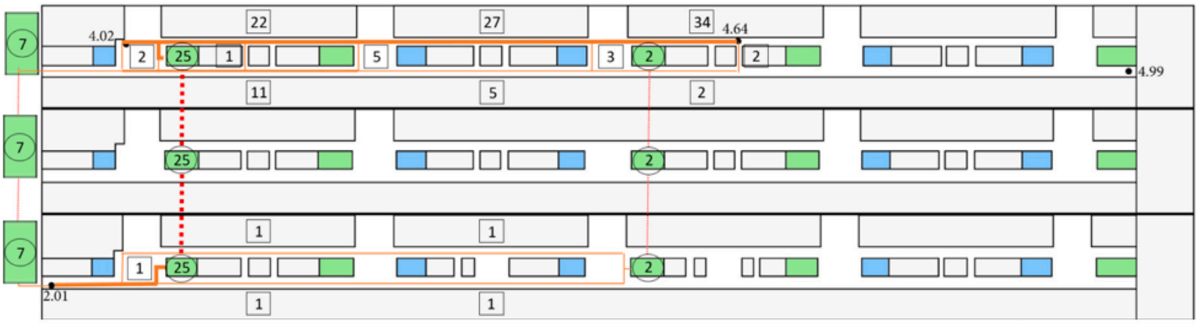
4.2.3. Comparison between both experiments

The employed wayfinding strategy in assignment 1 seems similar in both experimental methods. The majority of participants in both experiments used the central point strategy in assignment 1 (i.e., 65% of participants in the field experiment and 67% of participants in the VR experiment).

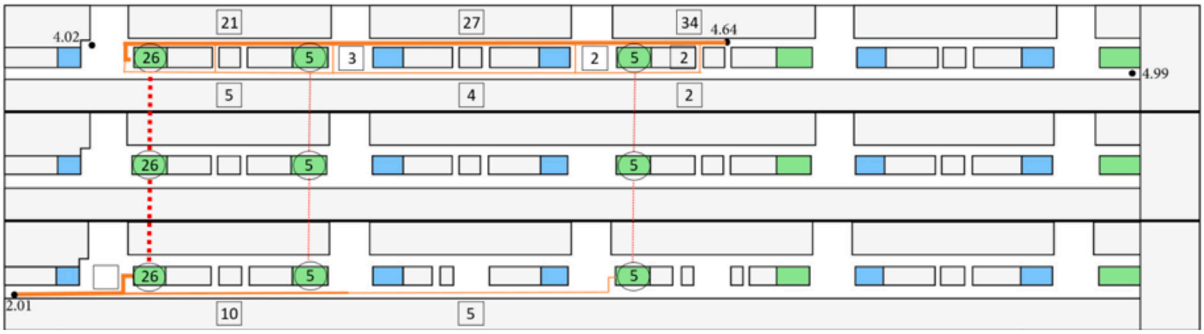
The Fisher exact test is performed to analyze the used strategies statistically for assignment 1. That is, the test compared the probability of adopting a certain wayfinding strategy (i.e., the direction strategy or the central point strategy) between the two groups (i.e., the participants of the field experiment and of the VR experiment), under the assumptions that the characteristics of both populations are equal. The result showed that there is no association between the experimental method and the wayfinding strategy. In other words, we cannot prove that there are significant differences in wayfinding strategy as a result of the experimental method ($p = 1.0$).

Another finding is that the participants of both experiments preferred to switch corridors using the larger connecting areas instead of the smaller ones (see Fig. 8). This result is in line with the findings of Vilar et al. (2013), who showed that pedestrians prefer to use wider paths over narrower ones in emergency conditions.

Altogether, these results seem to indicate that the pedestrian behavior in terms of wayfinding strategy is similar for participants in the field and the VR experiment during the single-story wayfinding assignment. More research is needed to see whether this effect holds true for other building configurations, but the finding seems to validate the usage of a VR system to study pedestrian route



(a) Field experiment.



(b) VR experiment.

Fig. 10. The pedestrian route choice in assignment 3 (i.e., from room 2.01 to room 4.64) in both (a) the field experiment and (b) the virtual reality experiment. Here, the red dotted lines indicated the vertical movement of the pedestrians (i.e., the stairway they used to switch floors), whereas the number of pedestrian using certain stairway is given within the circle.

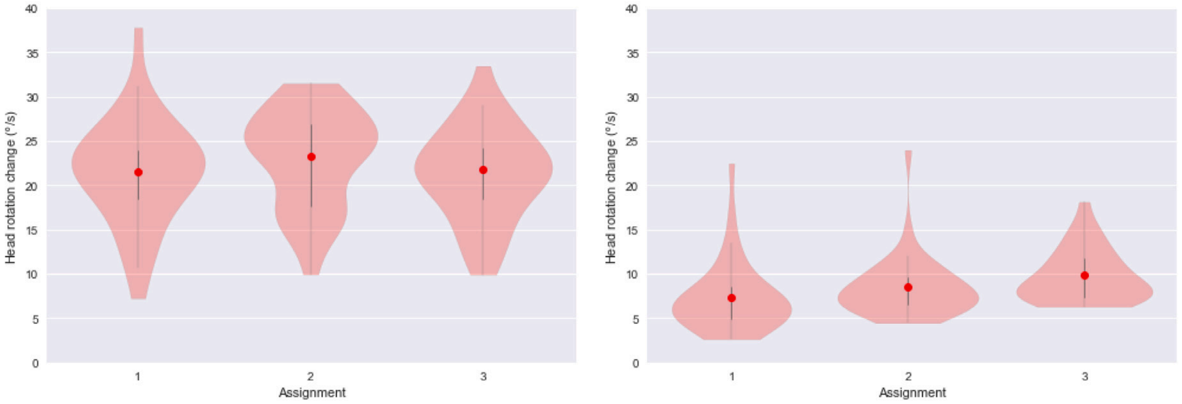
choice in a single-story building. Though it is worth noting that the findings do not prove that the results are similar, they only proved that there was no significant difference.

For the multi-story assignments, as discussed in Sections 4.2.1 and 4.2.2, the findings show that the floor strategy was preferred in assignment 2 and 3 for both experimental methods. That is, the results established that the trend toward the floor strategy is similar for multi-story assignments in both the field and the VR experiment. Our findings align with Hölscher et al. (2006a), who also found a tendency for the floor strategy in a multi-story wayfinding assignment. However, a few studies, such as Büchner et al. (2007), and Hölscher et al. (2009) showed the preference for the direction strategy in multi-story buildings. The observed difference in the preferred wayfinding strategy between literature does not mean that the findings of this study are inaccurate. It only indicates that external factors influence the wayfinding strategy (e.g., configuration of the building). That is, the wayfinding strategy does not seem universal for all buildings.

Despite the similarity in the preference for the floor strategy, there is a quantitative difference between both experiments in this study. The floor strategy is employed more often by the participants in the field experiment (i.e., 97% and 94% for assignment 2 and 3) than by those in the VR experiment (i.e., 75% and 72% for assignment 2 and 3), see Table 2. The Fisher exact test is performed for both assignment 2 and 3. The test showed that the null hypothesis is rejected for both assignment 2 ($p = 0.014$) and assignment 3 ($p = 0.024$). This means that the adopted wayfinding strategy is significant different between the field experiment and the VR experiment during assignment 2 and 3.

The authors hypothesize that the movement restrictions of the VR participants potentially cause the quantitative. The VR experiment used an HMD VR system with 360-degree head tracking and one controller to facilitate the participants' movement in the VR environment. This device limited the participants' freedom of movement, as they could only move in the direction they were facing (e.g., taking corners is more challenging in VR compared to real-life). This restriction potentially led to different route choices to prevent difficulties while walking around corners. Future studies need to indicate whether this hypothesis is valid. At this moment, researcher need to be cautious when studying pedestrian wayfinding strategy in a multi-story building solely based on a VR experiment. In particular, when a quantitative analysis of the wayfinding strategy is required. It is worth noticing that the general preference of the floor strategy is observed in both the field experiment as the VR experiment.

In conclusion, the findings indicate that the pedestrian wayfinding strategy for a single-floor building can be studied using VR. The results suggest that the wayfinding strategy of pedestrians in our VR environment is equal to that of pedestrians in the field experiment for the single-floor assignment, as there is no significant difference between both experimental methods. For multi-story buildings, the results indicated that the participants have a strong preference for the floor strategy in both experiments. However,



(a) Field experiment.

(b) VR experiment.

Fig. 11. The distribution of the participants' angular speed of the head for each assignment in both the (a) field experiment and (b) VR experiment.

the quantitative difference in the wayfinding strategy between the two experiments is statistically significant. For now, researchers should take this into account with respect to the usage of a VR system as the sole research tool to study pedestrian wayfinding strategies in multi-story buildings.

4.3. Observational behavior: Angular speed of the head

4.3.1. Findings of the field experiment

The distribution of the participants' angular speed of the head is shown in Fig. 11(a). Results showed that the angular speed of the head is the highest for assignment 2 ($M_{2,RL}$ = 23.12 deg/s, SD = 5.43 deg/s), followed by assignment 1 ($M_{1,RL}$ = 21.57 deg/s, SD = 5.90 deg/s), and assignment 3 ($M_{3,RL}$ = 21.34 deg/s, SD = 5.24 deg/s). These values were determined solely from the measurements taken in the corridors of the building, excluding any data from the stairways. Statistical tests were performed to compare the angular speed of the head in the three assignments of the field experiment. The Friedman test showed statistically significant differences in the angular speed of the head among the assignments: $p < 0.001$. The Wilcoxon signed-rank test found statistically significant differences in the angular speed of the head for all tests between two assignments ($p < 0.01$), except for the test between assignments 1 and 3. That is, the findings indicate that the angular speed of the head might be similar during assignments 1 and 3, which suggests that the observational behavior of pedestrians does not necessarily vary over the assignments in the field experiment.

4.3.2. Findings of the VR experiment

The average angular speed of the head was the highest for assignment 3 ($M_{3,VR}$ = 9.82 deg/s, SD = 2.97 deg/s) followed by assignment 2 ($M_{2,VR}$ = 8.51 deg/s, SD = 2.44 deg/s), and assignment 1 ($M_{1,VR}$ = 7.38 deg/s, SD = 4.00 deg/s). These averages are based on the distributions of the angular speed of the head that are shown in Fig. 11(b), which excludes the movement on the stairways. Statistical analysis shows that there are significant differences in the angular speed of the head between the assignments of the VR experiment. The Friedman test shows statistically significant differences among the assignments in terms of the angular speed of the head: $p < 0.001$. In particular, results of the Wilcoxon signed-rank tests found significant differences for all tests between two assignments ($p < 0.01$), except the test of assignments 1 and 2.

4.3.3. Comparison between both experiments

The distributions of the angular speed of the head are individually shown for both experimental methods in Fig. 11. In order to compare the parameter between both experimental methods for each assignment, the distributions of both experiments are aggregated to simplify the comparison between both experimental methods. These distributions are presented in Fig. 12, in which the field experiment is the left plot for each assignment and the VR experiment is the right plot. The aggregated distributions clearly show a disparity in the angular speed of the head for all three assignments between the field experiment and the VR experiments. Observations indicate that the participant's average angular speed of the head in the field experiment is two to three times higher than that of the participants in the VR experiment.

A statistical test is performed to determine the significance of the difference between the two experimental methods. The Mann–Whitney U test show that there is a significant difference in the angular speed of the head between the field and the VR experiment

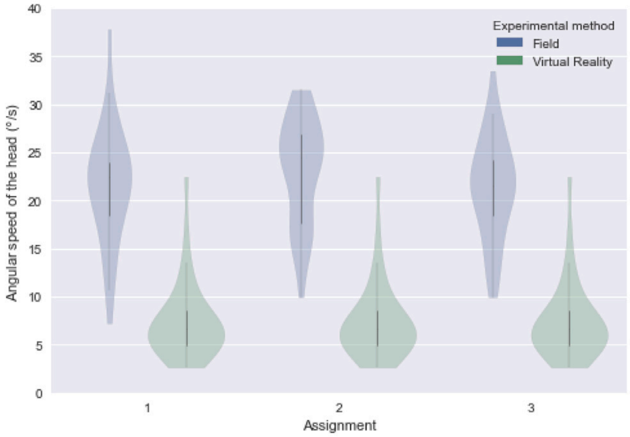


Fig. 12. The distribution of the participants' angular speed of the head for all three assignments in both the field (i.e., the left plot of a pair) and VR experiment (i.e., the right plot of a pair).

for assignment 1 ($p < 0.01$, U statistic = 1184), assignment 2 ($p < 0.01$, U statistic = 1201), and assignment 3 ($p < 0.01$, U statistic = 1183). The findings show that participants in the field experiment move their head faster than the ones in the VR experiment.

The difference in the angular speed of the head might indicate that participants in the field experiment look around more than the participants in the VR experiment. To examine this statement, the authors compared the video data of various participants in both experiments. The video data shows that participants in the VR experiment look straight ahead for most of the time, whereas the participants in the field experiment often look around in the environment. However, this observation lacks empirical proof, as it is not supported by scientific evidence like the absolute head rotation data of the participants. Therefore, the authors can only hypothesize that there is a difference in the participant's absolute head rotation between both experiments. Further study featuring absolute head rotation data is necessary to either validate or reject the hypothesis that participants in the field experiment look around more than those in the VR experiment. Earlier findings of Suma et al. (2009) found that pedestrians turn their heads less in a virtual maze than in a real maze, though it is worth noticing that their experiment was performed with a heavier HMD (i.e., 805 grams in their study in comparison with 468 grams in the present study).

The authors propose three rationales that might have caused the difference in the angular speed of the head between the field and the VR experiment. However, due to limitations in the available data, one cannot validate whether one of the two explanations is the underlying cause of this difference in angular speed of the head.

Firstly, the difference in the angular speed may be attributed to the movement method of the participants in the VR experiment. In the VR experiment of this particular study, participants 'walk' by pressing the home pad of the controller with their thumb, moving in the direction of their head orientation. For instance, if a participant gazes toward an object on their left while pressing the home pad, they take one step toward that object. Similarly, to walk straight forward, the participant should face straight ahead when using the controller. Thus, participants in the VR experiment are encouraged to limit any head movements (i.e., both absolute rotation and angular speed) to have an optimal path. Secondly, the difference in the font size of the signage between both experiments (see Fig. 5) could result in a difference in the angular speed of the head. Without empirical data regarding the signage perception of the participants in both experiments, the authors can only hypothesize that the signage is perceived similar in both experiments. That is, the participants in the VR experiment potentially perceive the signage differently than those in the field experiment. When participants in the VR experiment perceive signage as having larger font sizes than those in the field experiment, they may require less head rotation to read the signage. As a result, the participants had less reason to rotate their head in the VR experiment (i.e., lower absolute head rotation in the VR experiment), potentially leading to a lower angular speed of the head. Thirdly, the virtual environment contains fewer objects, such as posters and art sculptures, that might captivate the pedestrians' attention. With fewer distractions, one could argue that participants in the VR experiment see the signage faster. Therefore, the participants probably need to rotate their head less often in the virtual experiment than in the field experiment, which also might affect the angular speed of their head.

Another interesting finding is the difference in angular speed of the head between the two experiments during the between-floor assignments (i.e., assignment 2 and 3). In the VR experiment, the results show a significantly higher angular speed of the head during the more complex between-floor assignment (i.e., assignment 3) compared to the simple between-floor assignment (i.e., assignment 2). However, the participants in the field experiment show the opposite trend, with a lower angular speed of the head during the complex between-floor assignment. The observed discrepancy cannot be explained based on current knowledge and requires further study to understand the impact of using a VR system on pedestrian head rotation.

In conclusion, the findings show that there is a significant difference in the participants' angular speed of the heads between both experiments. Participants in the field experiment moved their heads much faster than those in the VR experiment. However, the authors emphasize that there is a need for further study regarding pedestrian head rotation (i.e., not limited to the angular speed of the head). The rationale behind the difference in the angular speed of the heads between both experimental methods cannot be determined based on the available data. Therefore, more research is required to substantiate our hypotheses. Moreover, there is no empirical data regarding the absolute head rotation (i.e., to what extent pedestrians look around in the environment). Therefore, without further research, the authors can only hypothesize that participants in the field experiment look around more in the environment than in the VR experiment.

5. Conclusion

VR systems are more frequently used to study pedestrian wayfinding behavior. However, the validation of using VR as a research tool to study this behavior is barely studied to the authors' knowledge. The present study adds to the existing body of literature by performing a validation study of an immersive VR system to study pedestrian wayfinding behavior in multi-story buildings. In particular, this paper directly compared the pedestrian wayfinding performance, wayfinding strategy, and the angular speed of the head in a physical and virtual multi-story building.

Our conclusions are threefold. Firstly, the results regarding the travel time and the optimal walking speed indicate significant difference between the two experimental methods in two out of three assignments, however, this result cannot conclude anything regarding the validation of the usage of VR. Secondly, with respect to the pedestrian decision-making in terms of wayfinding strategy, we found that similarity exist between immersive VR system and field experiments in the case of wayfinding within a single floor. However, this study also showed that relative similarity and absolute difference in wayfinding strategy arise when pedestrians need to find their way between floors in a multi-story building. That is, participants of both experiments show similar preference for the floor strategy, but this preference is stronger in the case of the field experiment compared to the VR experiment. A plausible explanation is that the limited field of view and freedom of motion in VR causes the difference between the two. Thirdly, pedestrian angular speed of the head is significantly different in the field and the VR experiment. The findings indicate that pedestrians move their head faster in the real environment than in the virtual one. That is, the head's angular speed of pedestrians in immersive VR systems is underestimated in comparison to real-life.

There are several limitations in the current study and should be addressed in future studies. Firstly, the observed differences in the travel time, and subsequently in the optimal walking speed, does not necessarily reject the validity of using VR systems to study pedestrian wayfinding performance. The VR environment was calibrated to accommodate for maximum walking speed, which can affect findings featuring walking speed and travel time. Additionally, the travel time measurements alone are not sufficient to conclude whether there are behavioral differences between the pedestrians' movement dynamics in real-life and in VR. More research is required to study the use of VR to study pedestrian wayfinding performance. Secondly, regarding the observed differences in both the metrics for the pedestrian decision-making (i.e., the wayfinding strategy) and the pedestrian observational behavior (i.e., the angular speed of the head) between the two experiments, the underlying causes of these differences are unclear. For both metrics, the study presented two possible explanations for the observed difference, however, the exact cause remains undetermined based on our results. As a result, more direct comparison studies regarding pedestrian decision-making and observational behavior between real-life and VR environments are required to determine the factors contributing to the observed difference.

Our findings do not invalidate the use of VR systems, but urge researchers to be careful when interpreting the results of VR studies featuring pedestrians in more complex scenarios. We are looking forward to more validation studies to identify the extent to which VR systems can support the research regarding wayfinding behavior and walking dynamics.

CRediT authorship contribution statement

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

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.

Data availability

Data will be made available on request.

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