Data collection methods for studying pedestrian behaviour

A systematic review

Feng, Y.; Duives, Dorine; Daamen, Winnie; Hoogendoorn, Serge

DOI
10.1016/j.buildenv.2020.107329

Publication date
2021

Document Version
Final published version

Published in
Building and Environment

Building and Environment 187 (2021) 107329

Contents lists available at ScienceDirect

Building and Environment

journal homepage: http://www.elsevier.com/locate/buildenv

Data collection methods for studying pedestrian behaviour: A systematic review

Yan Feng *, Dorine Duives, Winnie Daamen, Serge Hoogendoorn

Department of Transport & Planning, Delft University of Technology, Stevinweg 1, 2628 CN, Delft, the Netherlands

A R T I C L E   I N F O

Keywords:
Pedestrian behaviour
Data collection method
Literature review
Virtual reality
Crowd
IoT

A B S T R A C T

Collecting pedestrian behaviour data is vital to understand pedestrian behaviour. This systematic review of 145 studies aims to determine the capability of contemporary data collection methods in collecting different pedestrian behavioural data, identify research gaps and discuss the possibilities of using new technologies to study pedestrian behaviour. The review finds that there is an imbalance in the number of studies that feature various aspects of pedestrian behaviour, most importantly (1) pedestrian behaviour in large complex scenarios, and (2) pedestrian behaviour during new types of high-risk situations. Additionally, three issues are identified regarding current pedestrian behaviour studies, namely (3) little comprehensive data sets featuring multi-dimensional behaviour data simultaneously, (4) generalizability of most collected data sets is limited, and (5) costs of pedestrian behaviour experiments are relatively high. A set of new technologies offers opportunities to overcome some of these limitations. This review identifies three types of technologies that can become a valuable addition to pedestrian behaviour research methods, namely (1) applying VR experiments to study pedestrian behaviour in the environments that are difficult or cannot be mimicked in real-life, repeat experiments to determine the impact of factors on pedestrian behaviour and collect more accurate behavioural data to understand the decision-making process of pedestrian behaviour deeply, (2) applying large-scale crowd monitoring to study pedestrian movements in large complex environments and incident situations, and (3) utilising the Internet of Things to track pedestrian movements at various locations that are difficult to investigate at the moment.

1. Introduction

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

In order to understand the decision-making process and movement dynamics of pedestrians, pedestrian behaviour has been extensively studied over the last decades. Essential to understanding pedestrian behaviour are data collection efforts featuring pedestrian behaviour under different circumstances, from daily trips, mass gatherings and even disasters. This had led to abundant studies which used a variety of data collection methods to investigate pedestrian behaviour, including field observations (e.g., [1–4]), controlled experiments (e.g., [5–8]), and survey methods (e.g., [9–12]).

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

* Corresponding author.
E-mail address: y.feng@tudelft.nl (Y. Feng).

https://doi.org/10.1016/j.buildenv.2020.107329
Received 6 July 2020; Received in revised form 31 August 2020; Accepted 21 September 2020
Available online 25 September 2020

literature.

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

In order to address this, a comprehensive review of the use of contemporary data collection methods to study pedestrian behaviour is needed. Several reviews provided a partial overview of the use of various new technologies to study several stereotypical pedestrian behaviours. For instance, Feng et al. [13], Kinateder et al. [14], Lovreglio and Kinateder [15] and Moussaïd et al. [16] focused on reviewing studies used VR or AR to study pedestrian evacuation and crowd behaviour. Some reviews discussed a broad range of empirical studies featuring pedestrian behaviour, for instance, Haghani and Sarvi [17], Haghani [18,19], Shi et al. [20], Schweiker et al. [21], and Zhu et al. [22]. However, to our knowledge, there are no reviews that classify pedestrian behaviour systematically, cover a wide range of data collection methods and techniques for featuring pedestrian behaviour, and determine new opportunities to enhance the research toolbox with new technologies. Thus, this review is a complement to the current body of review studies, which helps clarify the contemporary technical and methodological challenges, and indicates the potential contribution of new technologies.

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

This paper is organised as follows. Section 2 describes the review methodology and introduces the behavioural taxonomy that is used to assess the literature. Section 3 applies this taxonomy to review the literature using data collection methods for pedestrian behaviour research. Based on a review of 145 studies, section 4 discusses the research gaps and opportunities for new technologies to study pedestrian behaviour. The last section summarises the main conclusions of this review.

2. Review methodology

This section details the review methodology. First, the scope of the study is introduced in section 2.1. Secondly, a taxonomy to classify the range of pedestrian behaviour is presented in section 2.2.

2.1. Scope of the literature review

A systematic literature search was conducted using the PRISMA Statement (Preferred Reporting Items for Systematic Reviews and Meta-Analysis) [23]. In the following, we describe the process of scoping the literature in detail. The literature was firstly identified using "Scopus" and "Web of Science" databases in January 2020. A limited set of keywords was used to search through the databases and, in particular, applied to article title, abstract and keywords. No limitation pertaining to the publication date of the articles was applied. Only articles published in English were included in the list of potential articles. The list of keywords included the combination of terms of 'pedestrian behaviour' and terms of 'data collection method'. Therefore, the following keywords were used for searching: "pedestrian behaviour", "pedestrian dynamics"; and "experiment", "controlled experiment", "laboratory experiment", "field experiment", "survey", "virtual reality", "augmented reality", "Wi-Fi", "Bluetooth", "GPS", "GMS", "social media", "IoT". This set of references was enhanced by means of forward and backward snowballing [24].

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

The scoping procedure and results are presented in Fig. 1. The first search yielded a total of 720 records (including duplicates). After removing duplicates, the abstracts were reviewed by authors to confirm the inclusion of studies meeting the search criteria. 203 articles were screened for full-text review to check their eligibility. After we evaluated the eligibility of identified articles by reviewing the full text, 145 papers remained on the list. In total, 145 articles were identified that use data collection methods to study pedestrian behaviour between 1971 and 2020.

2.2. Taxonomy of pedestrian behaviours

In order to establish the potential of a data collection method, one needs to determine the different types of pedestrian behaviour and whether a data collection method is able to study certain types of behaviour. This section introduces a taxonomy to structure pedestrian behaviours. The taxonomy explicitly represents the decision-making process of pedestrian behaviour (Fig. 2). It includes a hierarchical structure of pedestrian behaviour and the including pedestrian behaviours, which together represent a broad range of pedestrian behaviours. This taxonomy will be used to assess literature in section 3.

2.2.1. The global layout of the taxonomy

From a traffic engineering point of view, pedestrian behaviour can be classified using a hierarchical structure consisting of three levels, being strategic, tactical and operational level [25]. These levels feature three distinct temporal scales pertaining to choices that pedestrians make, and have served as an umbrella concept in the pedestrian research community to categorise pedestrian behaviours for at least two decades. This categorisation shapes the first layer of our taxonomy of pedestrian behaviours. The second to fourth layer detail specific pedestrian behaviours we identified in the first layer. Here, the second layer distinguishes between the choice dimensions. The third and fourth layer further disentangle the various interactions that jointly determine the overarching choice behaviour. Underneath, the taxonomy is further elaborated upon in sections 2.2.2-2.2.4.

2.2.2. Strategic level behaviour

Strategic level behaviour considers pedestrian behaviours which take place prior to their trip. At the highest level, pedestrians make decisions featuring their activity, corresponding destination and activity schedule. These choice behaviours are generic, have a very long-term impact on a pedestrian's movement and choice behaviour (i.e., up to 24 h) and reflect the purpose of the trip [25]. From the set of activities, pedestrians choose (a subset of) *activities* to achieve the purpose of travelling. Accordingly, pedestrians choose a *destination* at which they

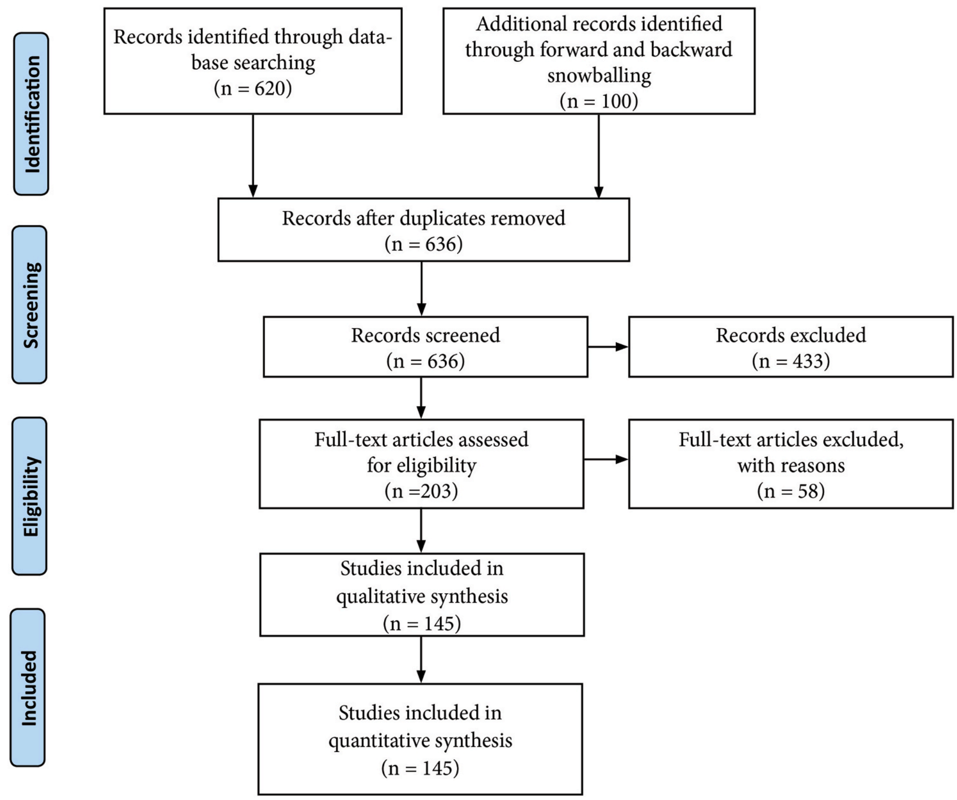

Fig. 1. The scoping procedure and results of literature.

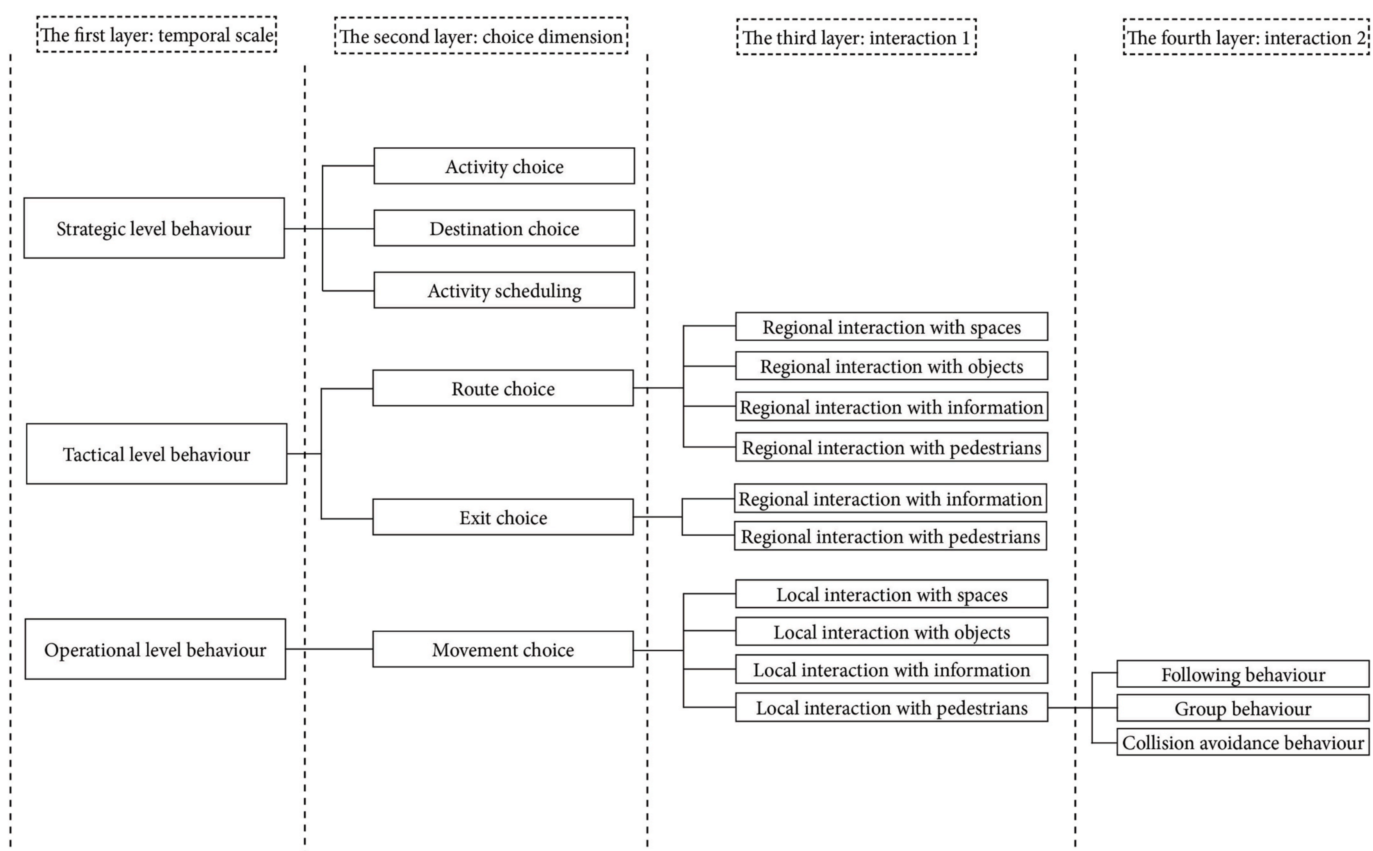

Fig. 2. A conceptual taxonomy of pedestrian behaviour.

would like to perform the activity [4]. Last of all, pedestrians decide on the *scheduling of their intended activities*, which is called activities scheduling [25]. Once the activity set, destination and activity schedule are decided, the basis for movement is formed.

2.2.3. Tactical level behaviour

The tactical level describes the decision of choosing a specific route in order to move from one location to the next [26]. The tactical level includes a range of pedestrian behaviours on a medium time scale, featuring *route and exit choice behaviour*. Here, *route choice* defines the process during which pedestrians choose between a number of routes to reach the destination [27]. *Exit choice* behaviour features the choice of one exit within a set of alternative exits to enter or leave a room and/or a building [28].

Pedestrian route choice behaviours are determined by four types of interactions. First, pedestrian route choice behaviour can be the result of *interactions with the types of space*. Daamen and Hoogendoorn [29] distinguished between functional, physical and specialised spaces (e.g., stairs and waiting areas). Moreover, *objects in the environment can attract, distract, hinder, or repulse* pedestrians during walking. For example, pedestrians might change their route in order to watch a storefront or avoid a dirty pathway. Additionally, pedestrians tend to *interact with information* (e.g., signs, lights, sounds and mobile phones) [30,31]. Lastly, pedestrian route choice behaviour can be impacted by the *movements and choices of other pedestrians in a pedestrian's vicinity* (e.g., [32]). Here, *exit choice* behaviour can be seen as a special type of route choice behaviour. The literature illustrates that pedestrians *interact with information and other pedestrians* in order to establish their exit choice (e.g., [4,33,34]).

2.2.4. Operational level behaviour

At the operational level, pedestrians continuously make short-term movement decisions on their route to respond to their immediate environment [35]. It entails the *operational walking dynamics* of individual pedestrians within a demarcated space and a demarcated period of time [36]. Literature featuring pedestrian behaviour identifies at least four distinct types of behaviour, namely the *movement through certain types of space*, *the local interaction with objects*, *interaction with information*, and the *interaction with other pedestrians* (e.g., [7,37–39]).

The first two types of interactions at this level feature the pedestrian *interaction with a certain type of space,* and the *interaction with information*, the demarcation of both types is similar to the tactical level. The third type of interaction is the *interaction with objects*, where four types of objects can be distinguished, namely objects that attract, repulse, obstruct and distract. For example, in a classroom, students try to avoid colliding with tables to the exits. The fourth type of interaction is *the interaction between pedestrians* [40]. Here, three typical types of interaction are described. Firstly, *following behaviour*, which entails the tendency of an individual to follow another individual, in order to benefit from the space they create. Secondly, *group behaviour*, which describes group members that share some collective behaviour, share a salient social identity and act according to the social norms of that group [41]. Thirdly, *collision avoidance behaviour*, where pedestrians adjust their movements to avoid potential future collisions of two or more pedestrians occupying the same area at the same time [42].

3. The capabilities of contemporary data collection methods concerning pedestrian behaviour research

This section presents a comprehensive review of studies that feature data collection methods that are frequently used to study pedestrian behaviour. There are three frequently adopted data collection methods, namely: field observations, controlled experiments, and survey methods. The literature concerning all three categories is detailed in subsections 3.1–3.3.

In each subsection, one of the three data collection methods is briefly defined, after which a summary is provided of the studies that have used this method to study pedestrian behaviour. For each study, the data collection set up is detailed and summarised in a table based on the taxonomy defined in section 2.2. The outcomes of the first three sections are used in section 4 to identify the research gaps in the current data collection toolbox.

3.1. Field observations

The first data collection method, namely field observations, involves the study of humans who move and make choices in realistic, natural environments, which include normal and emergency conditions. Here, the goal is to study pedestrian behaviour as unobtrusively as possible. This data collection method usually requires researchers to record pedestrian behaviour in specific situations and/or particular locations, either using manual labour (e.g., manual counting), digital recording equipment (e.g., camera), or sophisticated sensor system (e.g., GPS, Wi-Fi, Bluetooth). In general, one can distinguish between the traditional techniques (section 3.1.1) and newer digital technologies (section 3.1.2). The reader is referred to Appendix A, Table A1 for an assessment of the studies discussed underneath.

3.1.1. Field observations using traditional techniques

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

The first major research theme was the study of *pedestrian behaviour during evacuations* in real venues and unannounced emergencies. One of the early studies was performed by Shields and Boyce [2], who used in-house closed-circuit television cameras to study pedestrian route and exit choice behaviour during unannounced evacuations at retail stores. Several other studies followed, which predominantly researched unannounced evacuation drills. For instance, Kobes et al. [34] investigated the influence of smoke and exit signs on pedestrian exit behaviour, and Yang [43] used video recordings of staircases to investigate pedestrian speed difference under emergency conditions. Galea et al. [44] and Nilsson and Johansson [3] determined the effect of the social relationship on pedestrian evacuation behaviour in a theatre.

The second theme focused predominantly on *pedestrian flow characteristics* at different spaces and, in particular, the relationships between speed, flow and density. One early study was conducted by Fruin [45], who collected pedestrian flow data on the walkway and analysed the relationships of density-speed and density-flow volumes. A large number of studies followed his example and used time-lapse photography and video recordings to investigate pedestrian walking dynamics at walkways (e.g., Corbetta et al. [46]; Lam et al. [47]; Virkler and Elayadath [48]), sidewalks (e.g., Al-Azzawi and Raeside [49]; Tanaboriboon et al. [50]), and stairways (e.g., Shah et al. [51]; Tanaboriboon and Guyano [52]).

The third theme featured the *movement dynamics of pedestrian groups*. Moussaïd et al. [1] and Duives et al. [53], for instance, collected video recordings to study the impact of group behaviour on crowd dynamics. Gorrini et al. [54] and Do et al. [12] focused on the spatial movement behaviour of social groups. Lastly, Feng and Li [55,56] observed the movement of groups consisting of family members or friends. Most of the studies featuring this theme analysed the walking velocity, interpersonal distance, step frequency, and walking patterns of pedestrians in relation to group size.

The last group of field observations studied *pedestrian movements at mass events using video recordings*. Duives [4] and Zhang et al. [57] were the first to record crowd movement dynamics using an unmanned aerial vehicle (UAV), infrared counters and video recordings. In contrast to the relatively safe crowd movements, studies of Helbing and Johansson [58], Johansson et al. [59], Ma et al. [60] and Larsson et al. [61] investigated crowd dynamics under high densities at religious events, festivals and public events. More recently, Wang et al. [62] used recorded videos to analyse crowd movement in a terrorist-attack event. All five studies only used material captured by unrelated third parties and had no control over the location or vantage point of the videos.

3.1.2. Field observations using monitoring techniques

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

The first group of studies featured the use of camera-based monitoring systems to study *pedestrian crowd movements on multiple occasions*, which generally feature a combination of a camera, a stand-alone mini-computer and a set of AI or computer vision algorithms. Earlier versions of these systems predominantly counted people or moving objects within the field of view (e.g., [63]). More recent studies automatically derived crowd speed and density information from video images (e.g., Favaretto et al. [64]; Wang et al. [65]). Duives [36] combined video systems and computer vision algorithms to study pedestrian walking dynamics at five mass events, and Li et al. [66] determined the pedestrian Level of Service using multiple overlapping cameras.

The second group of studies featured Wi-Fi and Bluetooth sensors (e.g., Centorrino et al. [67]; Danalet et al. [68]; Ton et al. [69]; Versichele et al. [70]; Yoshimura et al. [71,72]). These researchers adopted this type of sensor to study *pedestrian activity location and route choice behaviour* in, respectively, a museum, a university campus, a train station, a festival, and a museum. Other studies researched the *operational walking behaviour of crowds* (e.g., Bonne et al. [73]; Duives et al. [74]; Gioia et al. [75]). Besides that, some studies combined Wi-Fi sensors with other digital sensor types to *monitor pedestrian crowd conditions*. For instance, Wirz et al. [76] collected pedestrians' location traces and information through GPS and Wi-Fi to infer real-time crowd conditions. Farooq et al. [77] applied Wi-Fi sensors and infrared to monitor a large-scale crowd at a festival; and Daamen et al. [78] monitored crowd movements using a combination of Wi-Fi, counting cameras and GPS trackers.

The third group of studies featured the use of GPS traces to study *pedestrian movements at public space or large-scale events*. For example, Van der Spek [79] and Galama [80] used GPS trackers to monitor pedestrian movements in city centres and a public event. Daamen et al. [81] used the same technique to study the activity choice and route choice behaviour of visitors at a music event. Blanke et al. [82] studied the dynamics of crowd and activity location choice by means of GPS traces from smartphones. Similarly, Duives et al. [83] adopted GPS-traces from smartphones to analyse tactical and operational crowd movements at mass events in real-time.

The fourth type of analysis made use of GSM data obtained from mobile-cellular networks to *capture pedestrian crowd information*. This type of mobile phone data was used by Gao [84] and Keij [85] to explore human mobility patterns. Calabrese et al. [86] and Zhang et al. [87] used GSM data to identify the locations of large pedestrian flow and crowd density.

The last group of studies featured the use of social media to *determine the crowd's characteristics at large events*. Botta et al. [88] and Yang et al. [89], for instance, used Twitter to determine the global movement patterns of pedestrians through an urban context. Gong et al. [90,91] used similar social media platforms to derive information on the crowd itself, for instance, crowd distribution, age and country of origin. More recently, Yang et al. [92] used social media to determine pedestrian activity patterns, and Alkhatib et al. [93] determined incidents at pedestrian gathering events using social media messages.

3.1.3. Pros and cons of field observations to study pedestrian behaviour

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

Controllability. The factors influencing pedestrian behaviour cannot be controlled during field observations, and the conditions under which data are collected cannot be influenced by the researcher directly [94]. Besides that, acquiring permissions for collecting such data in public and some restricted areas can be difficult because of safety, security, and privacy issues. In particular, in relation to (new) digital monitoring techniques, this often hampers their adoption in the public domain. Moreover, in some contexts, such as evacuation and panic situations, video recordings are rarely accessible to researchers. Furthermore, individual characteristics of the pedestrians are hard to capture during field observations.

Data richness and quality. One advantage of field observations is that one can track the movements of many pedestrians over a long-term period. Consequently, the collected pedestrian behavioural data contains rich information considering the fundamental quantities of pedestrian behaviour [95]. However, the accuracy of behavioural data is highly influenced by the sensor setup and techniques, for instance, camera position and angel, satellite signal strength, granularity of the data and distribution density of the beacons. As a result, collected pedestrian behaviour data is often not accurate and reliable enough for a detailed analysis (e.g., Love Parade 2010).

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

Representativeness. Data collection during field observation usually occurs coincidentally during the time and at the location of the study [94]. It means that only the behaviour of a sample of the pedestrian population during a certain period or at a specific location is collected. Therefore, the sample of observed pedestrians in a field observation may not be representative of the population, or the observed behaviours may not be representative of the individual [96].

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

3.2. Controlled experiments

Contrary to field observations, controlled experiments entail the participants' movements in a controlled condition and a temporary experimental setup designed by the researchers [17]. The literature considering controlled experiments can be split into three parts, namely studies featuring normal conditions (section 3.2.1), studies featuring evacuation conditions (section 3.2.2), and Virtual Reality experiments (section 3.2.3). Table A2 and Table A3 in Appendix A provide a summary of the studies that feature controlled experiment (both in normal and evacuation conditions), and VR experiments.

3.2.1. Traditional controlled experiments featuring normal condition in real life

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

A large number of studies have used laboratory experiments to study *pedestrian's operational walking dynamics in various settings*. Many studies conducted experiments to investigate the impact of bottleneck width on pedestrian movement dynamics (e.g., Bukáček et al. [97]; Daamen and Hoogendoorn [29]; Helbing et al. [98]; Hoogendoorn and Daamen [99]; Kretz et al. [100]; Liao et al. [101]; Seyfried et al. [102,103]; Zhang and Seyfried [6]). Numerous studies investigated other pedestrian movement base cases (e.g., corridors, intersections). Seyfried et al. [104], Chattaraj et al. [105] and Liu et al. [106], for instance, conducted experiments to investigate the movement dynamics of single-file pedestrians at corridors. Zhang et al. [107] and Zhang and Seyfried [108] conducted experiments to study uni- and bidirectional flow experiments in straight and T-junctions corridors. Wong et al. [109] and Zhang and Seyfried [110] studied pedestrian movement behaviour at intersections with different angles. Shiwakoti et al. [111] and Lian et al. [112] studied pedestrian merging movements under various angles and flow rates. While Gorrini et al. [113], Dias et al. [114] and Rahman et al. [115] examined the effect of turning angled corridors on pedestrian movement dynamics. Recently, more experiments have been performed in diverse experimental settings. For instance, Ziemer et al. [116] experimented in a high-density ring corridor to study pedestrian dynamics in crowded situations. Huang et al. [117] investigated individual and single-file pedestrian walking behaviour in a narrow seat aisle. Cao et al. [118] investigated pedestrian movement by single-file experiments under different visibilities in a ring-shaped corridor. Hu et al. [119] and Xiao et al. [120] conducted multidirectional flows experiments in a circle setup to study pedestrian movement choice.

Another set of studies thoroughly researched *collision avoidance behaviour*. In the experiment conducted by Paris [38], pedestrian collision avoidance behaviour was observed via a motion capture system. Also, Moussaïd et al. [7] and Versluis [121] conducted experiments with pedestrians performing avoidance tasks in a corridor with various interaction distances and angles. In another study by Moussaïd et al. [122] studied collision avoidance behaviour in a ring-shaped corridor. Huber et al. [123] investigated path and speed adjustments when participants avoid another person at different angles and walking speeds. In the study of Parisi et al. [124], collision avoidance behaviour was investigated individually and collectively in crossing and head-on encounters. In contrast, Liu et al. [125] investigated another type of collision avoidance, namely the effect of inactive pedestrians on the pedestrian walking dynamics on other pedestrians, and Li et al. [126] investigated the influence of obstacles in the travel path on pedestrian route choice behaviour.

3.2.2. Traditional controlled experiments featuring evacuation conditions in real life

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

The first type of pedestrian behaviour, namely *pedestrians' operational movement dynamics* during evacuations, has first been studied by Daamen and Hoogendoorn [127], who captured pedestrian movements through emergency doorways under stressful conditions. Tian et al. [128] studied pedestrian movements when participants entered a bottleneck during an evacuation. Another study by Jo et al. [129] researched the change of crowd speed around doors as a result of the change of corridor density. Huo et al. [130] conducted evacuation experiments in a high-rise building and investigated pedestrian movements on stairs. Shahhoseini et al. [8] investigated the movement of merging crowds under emergency egress, and Cao et al. [131] studied pedestrian movement characteristics under low visibility conditions. Various studies, amongst which Zhao et al. [132] and Ding et al. [133], studied the impact of various types of obstacles on pedestrian evacuation efficiency.

The second type of studies researched *pedestrian route and exit choice behaviour* in evacuation situations. Most of these studies focused on exit and route choice behaviour for a specific type of infrastructure. For example, Fang et al. [134] carried out an evacuation experiment in a teaching building and investigated the exit choice of pedestrians. Jeon et al. [39] investigated the effect of different visibility condition at a transfer hub. Guo et al. [135] and Zhu and Shi [136] performed classroom evacuation experiments to contrast route choice behaviour under varying visibility conditions, occupant distributions and alarm information.

Other researchers studied how the *information provided by evacuation installations (e.g., signs, sounds, lights) influences pedestrian evacuation decisions*. Fridolf et al. [137] and Galea et al. [138] studied the impact of evacuation installations on pedestrian exit choice and movement speed. D'Orazio et al. [139] compared pedestrian movement speed and evacuation time between continuous wayfinding system and punctual signs in a theatre. Ronchi et al. [140] and Porzycki et al. [141] conducted a series of experiments to study pedestrian evacuation behaviour during a road tunnel with artificial smoke. Cao et al. [142] conducted evacuation experiments to compare pedestrian evacuation behaviour under varying visibility.

The fourth group of studies featured the *impact of social behaviours*. Heliövaara et al. [143], for example, conducted an evacuation experiment to study the effect of selfish and cooperative behaviour on evacuation performance. The study of Von Krüchten and Schadschneider [144] investigated the impact of social groups and intergroup interactions on pedestrian movement during evacuations. Haghani and Sarvi [145] and Xie et al. [146] investigated the effect of social interaction on pedestrian route and exit choice in a room during an evacuation.

3.2.3. Controlled experiments using virtual reality (VR)

In VR experiments, participants experience an immersive virtual world through a continuous stream of highly realistic images and soundscapes. Individuals experience a feeling of immersion via VR equipment and are provided with the ability to interact with the virtual environment through a human-machine interface (e.g., joystick, gloves) [147]. Overall, the VR studies pertaining to pedestrian behaviour mainly featured the effect of various factors on pedestrian choice behaviour under normal and evacuation conditions. Here, the latter category can be split into the impact of other pedestrians' behaviours and the impact of information on pedestrian evacuation behaviour.

VR has been used to analyse the *influence of various factors on pedestrian behaviour* under normal conditions in immersive and controllable environments. Tan et al. [148], for example, collected pedestrian responses to hypothetical changes in virtual urban environments, namely activity choices and scheduling. Natapov and Fisher-Gewirtzman [149] captured pedestrian movement trajectories walking through a virtual environment to investigate the impact of the distributions of urban attractors and the urban street network on pedestrian route choices. Feng et al. [150] investigated pedestrian route and exit choice behaviour in a multi-level building.

Another set of studies featured *pedestrian obstacle avoidance behaviour* *and collision avoidance behaviour*. Fink et al. [151] and Sanz et al. [152] investigated pedestrian movement and walking trajectory when they need to avoid obstacles in a virtual environment. Li et al. [126] studied pedestrian route choice behaviour in a top-down view virtual environment with obstacles. Bruneau et al. [153] used a VR simulator for a different application, namely to investigate how pedestrians avoid collision with a group of pedestrians.

Also, the *impact of other pedestrian's activities on pedestrian choice behaviours* during evacuation situations was widely investigated using VR. For instance, Kinateder et al. [154,155] and Kinateder and Warren [156] studied the effect of social influence on pedestrian exit choice. Bode et al. [157], moreover, investigated the impact of queues in front of the exits on pedestrian evacuation exit and route choice behaviour. Van den Berg [32] used a 3D multi-user virtual game to study herding behaviour during an evacuation, and Moussaïd et al. [158] adopted a VR platform to investigate high-stress evacuation scenarios. More recently, Kinateder et al. [159] investigated the influence of exit familiarity and neighbour behaviour on pedestrian exit choice in a virtual museum. Lin et al. [160] examined the influence of crowd movements on pedestrian evacuation route choice.

The last group of studies investigated the *impact of information on pedestrian behaviour* in evacuations. Tang et al. [161] created a VR game to determine the effect of emergency signs containing different information on pedestrian way-finding behaviour. Kobes et al. [162] investigated the influence of smoke and location of exit signs on pedestrian exit and route choice in a virtual hotel. Ahn and Han [163,164] investigated building evacuations using AR-assisted guidance on smartphones. Silva et al. [165] used a serious game to investigate pedestrian evacuation time and exit choice in a hospital while the game system provided continuous information about the evacuation's progress. More recently, Duarte et al. [166] examined how dynamic features in exit signs affect pedestrian exit behaviour. Cosma et al. [167] studied pedestrian behaviour in a virtual tunnel evacuation with different lighting situations. Furthermore, Kinateder et al. [168], Cao et al. [169] and Zhu et al. [170] studied the impact of coloured signs, virtual fire and visual access on pedestrian exit and route choice behaviour.

Several above-mentioned studies also *compared pedestrian behaviour in VR and real life*. For example, one of the earliest validation studies was conducted by Kobes et al. [162], which compared pedestrian evacuation behaviour in a real-life hotel and a virtual hotel. Kinateder and Warren [156] compared the impact of social influence on pedestrian exit choice behaviour in a real and virtual environment. More recently, Feng et al. [171] compared pedestrian exit choice behaviour in a real-life evacuation drill and a virtual environment using mobile-based HMD. Besides pedestrian evacuation behaviour, several studies also compared obstacle avoidance behaviour. In the study of Fink et al. [151] and Sanz et al. [152] compared participants' collision avoidance behaviour surrounding static obstacles in matching physical and virtual environments. In a recent study, Li et al. [126] compared pedestrian route choice behaviour in a virtual environment with obstacles to similar real-life conditions.

3.2.4. Pros and cons of controlled experiments to study pedestrian behaviour

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

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

Controllability. The review illustrates that a major advantage of laboratory experiments is that experimental conditions can be controlled well. That is, researchers can take tight control of the scenarios that participants experience and the moments in time at which participants make decisions [172]. However, controlled experiments are also restricted by ethical considerations and need to ensure a reasonable balance between the realism and level of invasiveness of their design at all times [17].

Data richness and quality. Due to high controllability, controlled experiments provide the opportunity to easily observe and analyse the effect of very specific factors [173]. Meanwhile, the control of the data collection devices also assures a higher level of data accuracy, considering the detection and extraction of pedestrian behavioural data.

Validity and representativeness. In controlled experiments, pedestrian behavioural data is usually collected in a specific context. Therefore, it is questioned if collected data can either represent pedestrian behaviour in real life or it can be generalised to different situations. Meanwhile, students are over-represented in many controlled experiments, which limits the overall validity and representativeness of most controlled experiments [173].

Costs. In order to conduct controlled experiments to collect data, it is essential to create an artificial experiment environment, install data collection devices and gather a large number of participants, which often proves costly and labour intensive. Meanwhile, the built environment is mostly in a simple setup and missing architectural features (e.g., colour, texture). Furthermore, once the environment is built, it can hardly be changed during experiments [29].

3.2.4.2. Pros and cons of using VR in controlled experiments to study pedestrian behaviour. In summary, VR experiments mainly have been focused on investigating the impact of various factors on pedestrian behaviour under normal and evacuation conditions (i.e., the impact of other pedestrians and the impact of information on evacuation behaviour of pedestrians).

Controllability. The studies presented in section 3.2.3. identify that one of the main advantages of VR is high experimental control. It means that the virtual scenes can be quickly built, modified, and a number of possible factors that potentially influence pedestrian behaviour can be controlled in the virtual environment. Compared with traditional controlled experiments, VR allows participants to be immersed in virtual environments that they are either not likely to encounter in real-life or which are too dangerous to expose. Thus, participants can be fully immersed in a VR environment without exposing them to risk of injury [174].

Data richness and quality. Compared to other data collection methods, using VR is more likely to collect pedestrian behavioural data more accurately and automatically. It means that VR may provide easier and quicker access to the collected behavioural data [17]. Besides, researchers can design and develop virtual environments which are complicated, stressful and even dangerous, in which they can still collect sufficient behavioural data [154,175].

Validity. One often recorded concern is whether participants' behaviour in VR environments is consistent with their behaviour during real-life situations. In particular, because participants know they move and act within the virtual environment, and they face no real danger [176].

Representativeness. VR experiments using some VR devices (i.e., HMDs, desktop displays) can be conducted at different locations and different times [167], which increase the heterogeneity of sampling. However, the potential pre-selection effects might influence the representativeness the results, for instance, elder or people who have issues with dizziness might not be included in the sample, participants are more familiar with new technologies might perform more smoothly (e.g., [177]).

Cost. Another significant advantage of VR simulators is its cost-effectiveness [178]. That is, both the operational and logistics costs of VR experiments are lower than those of comparable lab experiments [172]. Furthermore, once the VR simulator system is set up, it can be used repeatedly.

3.3. Survey methods

Research featuring survey methods collects and analyses data using a list of predetermined questions. There are two main types of surveys, namely stated preference surveys (SP) and revealed preference surveys (RP). The first type is based on the participants' response or answers to hypothetical scenarios, while the latter is based on experienced scenarios with a given set of questions. Table A4 in Appendix A provides a summary of the studies discussed in this section.

3.3.1. Pedestrian behaviour study using surveys

Several studies used surveys to understand *pedestrian route and exit choice behaviour*. Duives and Mahmassani [9] used a web SP-questionnaire to investigate pedestrian evacuation decisions, including pre-evacuation behaviour, route and exit choice. Lovreglio et al. [11] also used SP survey to study the effect of nearness to the exit, the density of near exits, herding behaviour and cooperative or selfish behaviour on pedestrian exit choice. Haghani and Sarvi [179] used an SP questionnaire to investigate pedestrian exit choice behaviour during evacuations. Olander et al. [180] performed a questionnaire study to evaluate the design of dissuasive emergency signage, and Chen et al. [181] used a questionnaire-based experiment to study children route choice behaviour in an evacuation scene in a classroom. Aleksandrov et al. [182] used an online questionnaire and designed multiple scenarios to investigate pedestrian route choice during evacuations.

Next to the use of standalone surveys, survey data is also often combined with field observations or controlled experiments, during which people, who have been involved in an experiment and have personal experiences in the (real-life) scenarios are questioned. Do et al. [12], for instance, combined RP survey data with field observations to understand groups and single pedestrian behaviour at a train station and Haghani and Sarvi [10] collected RP data regarding pedestrian exit decision in a train station. D'Orazio et al. [139] used the survey another way, namely to collect qualitative data regarding pedestrian pre-movement time activities and evacuation route choice after an evacuation experiment. Daamen et al. [81], similarly, combined GPS trajectory data with a survey regarding pedestrian experiences and personal characteristics to identify the factors influencing route choice.

3.3.2. Pros and cons of survey methods

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

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

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

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

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

Cost. One of the main benefits of surveys is that the time to develop and perform a survey study is, in general, limited. That is, questionnaires can be quickly and repeatedly distributed. As such, it allows researchers to collect large data samples at low costs [96]. However, a full orthogonal survey requires a vast number of respondents which have proven costly to achieve.

4. Research gaps and opportunities

The review of contemporary data collection methods used to study pedestrian behaviour illustrates that there are certain imbalances using contemporary research toolbox. Table 1 shows an overview of reviewed studies featuring different types of pedestrian behaviour. Table 2 shows an overview of the pros and cons of different data collection methods for collecting pedestrian behaviour data. Moreover, the review also identifies there are new technologies that can potentially enhance our research capabilities. This section first identifies five research gaps pertaining to the contemporary research method toolbox for pedestrian behaviour research. These gaps are identified by using the reviewed empirical studies featuring pedestrian behaviour (Section 3) in combination with the taxonomy framework (Section 2). Section 4.2 accordingly determines three potential opportunities pertaining to new technologies to potentially bridge the research gaps identified in section 4.1. The process of identifying research gaps and opportunities for new technologies is conceptualised in Fig. 3.

4.1. Research gaps

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

Gap 1: studying pedestrian behaviour under vast complex scenarios

Although there have been many studies that use controlled experiments to investigate pedestrian behaviour in varying scenarios, more than half of the studies focused on pedestrian behaviour in simple experimental conditions (e.g., corridor, bottleneck, simple room). Apart from these, studies featuring strategic level behaviour were limited. The lack of studies of pedestrian behaviour under vast complex scenarios seems to be the result of three things. First, longitudinal data collection of pedestrian behaviour is difficult to arrange. Second, data collection methods (i.e., controlled experiments, surveys) have a limited scope, which makes it difficult to provide participants with a wide range of options. Third, the variability and complexity of pedestrian behaviour, the variety of contexts, and the variety of geometric and architecture features [8] are challenging to achieve from the contemporary research toolbox. Consequently, more complex scenarios cannot be represented entirely realistically, experiments featuring these complex situations are hardly controllable and repeatable [153]. Thus, there is a need for data collection methods that can create and mimic realistic complex scenarios while retaining the capability of collecting pedestrian behaviour data.

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

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

Note: colour scale.

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

Data collection methods		Controllability	Data richness and quality	Validity	Representativeness	Cost
Field observations		• External factors cannot be controlled • Acquiring permissions for collecting such data in public and some restricted areas can be difficult	• Track the movements of many pedestrians over a long-term period • Accuracy of behavioural data is highly influenced by the experimental setup • Often not accurate and reliable enough for a detailed analysis	• A relatively high degree of validity	• May not be representative of the population, or the observed behaviours may not be representative of the individual	• Time-consuming and challenging to obtain approval to perform a field observation • Require a large investment in labour to extract the collected data
Controlled experiments	Traditional controlled experiments	• Experimental conditions can be controlled well	• Easily observe and analyse the effect of very specific factors • A higher level of data accuracy	• Questioned whether collected data can represent pedestrian behaviour in real life	• Questioned if collected data can be generalised to different situations • Overrepresented students limit the overall representativeness	• Install data collection devices and gather a large number of participants, which often proves costly and labour intensive • Once the environment is built, it can hardly be changed during experiments
	VR controlled experiments	• High experimental control	• More accurately and automatically collect data	• Questioned whether participants' behaviour in VR environments is consistent with their behaviour during real-life situations	• Can be conducted at different locations and different times which increase the heterogeneity of sampling • Potential pre-selection effects might influence the representativeness	• Lower than those of comparable lab experiments • Can be used repeatedly
Surveys		• High experimental control	• Acquire complementary (qualitative) information • Not all pedestrian behaviours can be collected, for example, pedestrian walking dynamics	• Answers from respondents may differ from their actions in a real situation	• Allow researchers to collect relatively comprehensive data samples to represent the pedestrian population well	• Questionnaires can be quickly and repeatedly distributed • A full orthogonal survey requires a vast number of respondents can be costly to achieve

Gap 2: capturing comprehensive behavioural data sets

Pedestrians perceive the environment while walking, and their behaviour is the result of decision-processes that range from the long-term strategic level to the short-term operational level [36,183]. However, the internal relationship between different choice dimensions and the details considering each of the choice dimensions is, to a large extent, currently not yet understood.

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

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

Furthermore, this review shows that while pedestrian behaviour has been extensively investigated in traditional emergency scenarios such as fire, new types of high-risk scenarios (e.g., earthquakes, terrorist attacks, stampedes) have received far less attention. Examples of these newer types of high-risk scenarios include the crowd disaster during Hajj [58], the Love Parade disaster [184] and the Kunming terrorist attack event in China [62]. These studies show that pedestrian behaviour during those scenarios differs from pedestrian behaviour in traditional evacuation scenarios. There is a lack of research approaches that can study pedestrian behaviour during these newer risky situations while being in a relatively safe environment. For example, although studies of pedestrian behaviour during fire situations have been done on a number of field observations and lab controlled experiments, it generally suffers from a lack of controllability, precision, reality and replicability [8]. Meanwhile, the limited information provided to participants restricts their behavioural responses to the situation because of the physical dangers involved when they are walking [185]. Consequently, a data collection method is required that allows participants to experience and move through dangerous environments with comprehensive information, while they remain physically safe.

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

It is known that pedestrian behaviour is highly dependent on the external environment and surrounding pedestrians, however, for controlled experiments and survey methods, pedestrian behaviour data are usually collected in a specific context (i.e., temporary experimental setup, participants need to follow certain instructions) with a single type of participants (e.g., university students). Therefore, it is questioned if collected data through these methods can either represent pedestrian behaviour in real life or it can be generalised to different situations. The review shows that there are only a few studies that have attempted to address this issue (e.g., [126,151,162,171]). Thus, more studies are needed to be conducted repeatedly in various data collection methods or with various heterogeneity of participants.

Gap 5: alternative choices with low experimental costs

To study pedestrian behaviour at the operational level, predominantly field observations and controlled experiments are used due to the stringent data requirements. Finding the optimal place and obtain the access to perform a field observation takes time. Besides that, it is challenging and costly to install all necessary sensors. At the same time, it is also very costly to design, develop and conduct controlled experiments. And it is challenging, and often expensive to acquire participants. Consequently, researchers need to choose between two costly alternatives to study operational behaviour, which limits the amount of

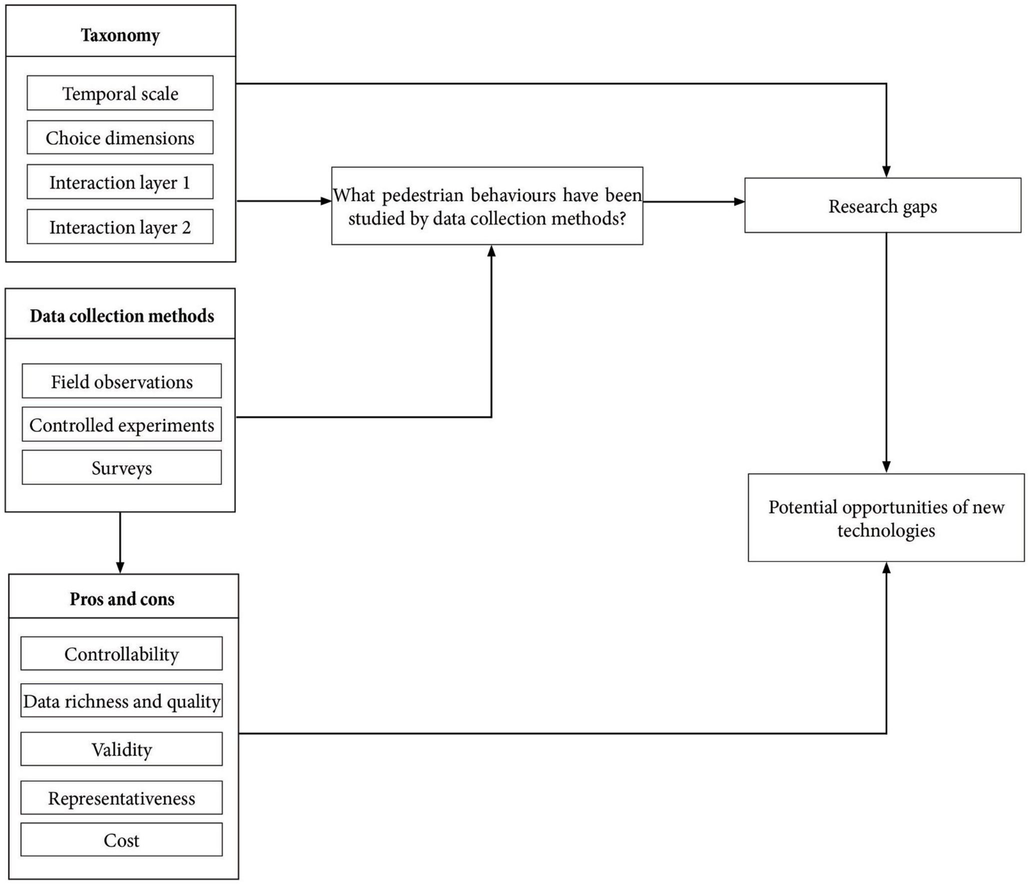

Fig. 3. A conceptual framework for identifying research gaps and opportunities.

research being performed featuring pedestrian operational movement behaviour. Thus, there is a need for a data collection method that allows researchers to set up, alter or change between different experimental setup quickly at no or very limited costs.

4.2. Opportunities pertaining to the use of new technologies

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

Opportunity 1: conducting VR experiments

The last few years VR technologies have improved with incredible speed. This allows researchers to generate large complex, realistic scenarios while still ensuring that researchers can collect behavioural data with great experimental control. Meanwhile, VR provides the opportunity to study pedestrian behaviour with a variety of dangerous situations, such as building fires, earthquakes, or crowd motion during massive events [172]. At the same time, with the ability to simulate a variety of contexts, VR allows researchers to investigate pedestrian behaviour in hypothetic scenarios (e.g., new building designs and new transportation systems). It helps researchers understand the interaction between pedestrians and scenarios that do not exist today and also helps planners through dilemmas when designing future infrastructure [186].

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

Thirdly, precise tracking technology (e.g., full-body tracking, eye tracking), which is incorporated in most VR technologies, allows researchers to collect and accurately analyse various aspects of pedestrian behaviour in great detail. Brief actions can also be captured, such as small steps, hesitations, or glances, that would be difficult to observe in the real world [187]. In combination with questionnaire data, VR also provides opportunities to acquire complementary information to further our understanding of the decision-making processes.

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

Opportunity 2: leveraging large-scale crowd monitoring

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

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

At the same time, limited information is available regarding the validity of, in particular, these newer sensor types. Some studies, such as Duives et al. [74], illustrate that derivation of crowd dynamics information from sensor networks is less trivial than one might think. Thus, in order to add these new sensors to the pedestrian research method toolbox, studies into the valid usage of crowd monitoring system data are essential.

Opportunity 3: utilising the Internet of Things (IoT)

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

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

5. Conclusion

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

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

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

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.

Acknowledgements

We thank the China Scholarship Council for their financial contribution. Meanwhile, this research is also supported by the ALLEGRO project, which is financed by the European Research Council (Grant Agreement No. 669792).

Appendix A

Table A1
Studies based on field observations using traditional techniques and monitoring techniques.

Article	Experimental Set-Up				Pedestrian behaviour															
	Sample size	Sample type	Condition	Equipment	Strategic			Tactical						Operational						
					Activity choice	Destination choice	Activity scheduling	Route choice				Exit choice		Movement through spaces	Interaction with objects	Interaction with information	Interaction with pedestrians		
								Interaction with spaces	Interaction with information	Interaction with objects	Interaction with pedestrians	Interaction with information	Interaction with pedestrians				Following behaviour	Group behaviour	Collision avoidance behaviour
Shields and Boyce [2]	2072	customer, staff	store	video	·	·	✓	·	✓	·	·	✓	·	·	·	·	·	·	·
Kobes et al. [34]	103	guest	hotel	video	·	·	·	·	·	·	·	✓	·	·	·	·	·	·	·
Yang [43]	?	student	teaching building	video	·	·	·	·	·	·	·	·	·	✓	·	·	·	✓	·
Galea et al. [44]	1200	audience	theatre	video	·	·	✓	·	·	·	·	·	·	·	·	·	·	·	·
Nilsson and Johansson [3]	135	audience	cinema	video	·	·	✓	·	·	·	·	·	·	·	·	·	·	·	·
Fruin [45]	?	commuter	walkway in a bus terminal	photography	·	·	·	·	·	·	·	·	·	✓	·	·	·	·	·
Corbetta et al. [46]	80,000	passenger	main walkway of the train station	Microsoft Kinect TM sensors	·	·	·	·	·	·	·	·	·	✓	·	·	·	·	·
Lam et al. [47]	?	pedestrian	stairway, walkway, etc.	video and manual count	·	·	·	·	·	·	·	·	·	✓	·	·	·	·	·
Virkler and Elayadath [48]	?	pedestrian	walkway	video, stopwatch	·	·	·	·	·	·	·	·	·	✓	·	·	·	·	·
Al-Azzawi and Raeside [49]	7535	pedestrian	sidewalk	video	·	·	·	·	·	·	·	·	·	✓	·	·	·	·	·
Tanaboriboon et al. [50]	519	pedestrian	sidewalk, walkway	video recorder	·	·	·	·	·	·	·	·	·	✓	·	·	·	·	·
Shah et al. [51]	?	passenger	stairway	video	·	·	·	·	·	·	·	·	·	✓	·	·	·	·	·
Tanaboriboon and Guyano [52]	?	pedestrian	stairway	video	·	·	·	·	·	·	·	·	·	✓	·	·	·	·	·
Moussaïd et al. [1]	1500	group	public place; commercial walkway	video	·	·	·	·	·	·	·	·	·	·	·	·	·	✓	·
Duives et al. [53]	712	group	corridor	video	·	·	·	·	·	·	·	·	·	✓	·	·	·	✓	·
Gorrini et al. [54]	1645	group	commercial walkway	video	·	·	·	·	·	·	·	·	·	·	·	·	·	✓	·
Do et al. [12]	50	group	train station	video	·	·	·	·	·	·	·	·	·	✓	·	·	·	✓	·
Feng and Li [55,56]	300; 830	group	campus; metro station	video	·	·	·	·	·	·	·	·	·	·	·	·	·	✓	·
Duives [4]	?	visitor	festival	drone	·	·	·	·	·	·	·	·	·	✓	·	·	·	·	·
Zhang et al. [57]	30,000	visitor	festival		·	·	·	·	·	·	·	·	·	✓	·	·	·	·	·

(*continued on next page*)

Table A1 (*continued*)

Article	Experimental Set-Up				Pedestrian behaviour															
	Sample size	Sample type	Condition	Equipment	Strategic			Tactical						Operational					
					Activity choice	Destination choice	Activity scheduling	Route choice				Exit choice		Movement through spaces	Interaction with objects	Interaction with information	Interaction with pedestrians		
								Interaction with spaces	Interaction with information	Interaction with objects	Interaction with pedestrians	Interaction with information	Interaction with pedestrians				Following behaviour	Group behaviour	Collision avoidance behaviour
				video, infrared counter															
Helbing and Johansson [58]	?	visitor	festival	video	·	·	·	·	·	·	·	·	·	✓	·	·	·	·	·
Johansson et al. [59]	?	visitor	festival	video	·	·	·	·	·	·	·	·	·	✓	·	·	·	·	·
Ma et al. [60]	?	visitor	festival	video	·	·	·	·	·	·	·	·	·	✓	·	·	·	·	·
Larsson et al. [61]	?	visitor	public events	video footage	·	·	·	·	·	·	·	·	·	✓	·	·	·	·	·
Wang et al. [62]	?	pedestrian	terrorist attack	recorded video	·	·	·	·	·	·	·	·	·	✓	·	·	·	✓	·
Favaretto et al. [64]	?	crowd	multi-crowded scenes	video	·	·	·	·	·	·	·	·	·	✓	·	·	·	·	·
Wang et al. [65]	?	pedestrian	normal, abnormal scene	video	·	·	·	·	·	·	·	·	·	✓	·	·	·	·	·
Duives [36]	?	visitor	festival	video	·	·	·	·	·	·	·	·	·	✓	·	·	·	·	·
Li et al. [66]	?	crowd	road intersection area; festival	video	·	·	·	·	·	·	·	·	·	✓	·	·	·	·	·
Centorrino et al. [67]	900	visitor	museum	Bluetooth	·	·	✓	·	·	·	·	·	·	·	·	·	·	·	·
Danalet et al. [68]	5902	employee, student	campus	Wi-Fi	·	✓	✓	·	·	·	·	·	·	·	·	·	·	·	·
Ton et al. [69]	240,949	passenger	train station	Wi-Fi, Bluetooth	·	✓	✓	✓	·	·	·	·	·	·	·	·	·	·	·
Versichele et al. [70]	80,828	visitor	festival	Bluetooth	·	·	·	·	·	·	·	·	·	✓	·	·	·	·	·
Yoshimura et al. [71]	24, 452	visitor	museum	Bluetooth	✓	✓	✓	·	·	·	·	·	·	·	·	·	·	·	·
Yoshimura et al. [72]	105,597	visitor	museum	Bluetooth	✓	✓	✓	·	·	·	·	·	·	·	·	·	·	·	·
Bonne et al. [73]	29,296; 16,486	visitor	festival; university campus	Wi-Fi	·	✓	·	·	·	·	·	·	·	·	·	·	·	·	·
Duives et al. [74]	659	visitor	festival	Wi-Fi, camera	·	✓	·	·	·	·	·	·	·	·	·	·	·	·	·
Gioia et al. [75]	7623	visitor	public event	Wi-Fi	·	·	·	·	·	·	·	·	·	✓	·	·	·	·	·
Wirz et al. [76]	800	visitor	festival	GPS, Wi-Fi	·	·	·	·	·	·	·	·	·	✓	·	·	·	·	·
Farooq et al. [77]	156,789	pedestrian	festival	Wi-Fi, infrared sensors	·	✓	✓	✓	·	·	·	·	·	·	·	·	·	·	·
Daamen et al. [78]	?	visitor	festival	camera, Wi-Fi, GPS	·	·	·	·	·	·	·	·	·	✓	·	·	·	·	·
Van der Spek [79]	80; 150; 130	pedestrian	city centre	GPS	✓	✓	·	·	·	·	·	·	·	·	·	·	·	·	·

(*continued on next page*)

Table A1 (*continued*)

Article	Experimental Set-Up				Pedestrian behaviour															
	Sample size	Sample type	Condition	Equipment	Strategic			Tactical						Operational						
					Activity choice	Destination choice	Activity scheduling	Route choice				Exit choice		Movement through spaces	Interaction with objects	Interaction with information	Interaction with pedestrians			
								Interaction with spaces	Interaction with information	Interaction with objects	Interaction with pedestrians	Interaction with information	Interaction with pedestrians				Following behaviour	Group behaviour	Collision avoidance behaviour	
Galama [80]	155	visitor	festival	GPS	·	·	·	✓	✓	✓	✓	·	·	·	·	·	·	·	·	
Daamen et al. [81]	109	visitor	festival	GPS	·	✓	·	·	✓	✓	✓	·	·	·	·	·	·	·	·	
Blanke et al. [82]	29,000	visitor	festival	GPS	✓	✓	·	·	·	·	·	·	·	✓	·	·	·	·	·	
Duives et al. [83]	9748	visitor	festival	GPS	·	✓	·	✓	·	·	·	·	·	·	·	·	·	·	·	
Gao [84]	74,000,000	mobile phone caller/ receiver	city	mobile phone	✓	✓	·	·	·	·	·	·	·	·	·	·	·	·	·	
Keij [85]	?	SMS sender/ caller	city corridor	mobile phone	·	·	✓	·	·	·	·	·	·	·	·	·	·	·	·	
Calabrese et al. [86]	30, 000	mobile phone caller	public transport	mobile phone	✓	✓	·	✓	·	·	·	·	·	·	·	·	·	·	·	
Zhang et al. [87]	?	mobile phone caller	CBD	mobile phone	·	✓	·	·	·	·	·	·	·	·	·	·	·	·	·	
Botta et al. [88]	?	social media user	city	social media	·	✓	·	·	·	·	·	·	·	·	·	·	·	·	·	
Yang et al. [89]	70,000	social media user	city	social media	✓	✓	✓	·	·	·	·	·	·	·	·	·	·	·	·	
Gong et al. [90,91]	? 378	social media user	festival	social media	·	✓	·	·	·	·	·	·	·	·	·	·	·	·	·	
Yang et al. [92]	3757	social media user	university	social media	✓	✓	·	·	·	·	·	·	·	·	·	·	·	·	·	
Alkhatib et al. [93]	?	social media user	incident	social media	·	✓	·	·	·	·	·	·	·	·	·	·	·	·	·	

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

Table A2
Studies based on controlled experiments under normal and emergency conditions.

Article	Experiment Set-Up				Pedestrian behaviour															
	Sample size	Sample type	Condition	Equipment	Strategic			Tactical						Operational						
					Activity choice	Destination choice	Activity scheduling	Route choice				Exit choice		Movement through spaces	Interaction with objects	Interaction with information	Interaction with pedestrians			
								Interaction with spaces	Interaction with information	Interaction with objects	Interaction with pedestrians	Interaction with information	Interaction with pedestrians				Following behaviour	Group behaviour	Collision avoidance behaviour	
Bukáček et al. [97]	76	student	bottleneck	Camera	·	·	·	·	·	·	·	·	·	✓	·	·	·	·	·	
Daamen and Hoogendoorn [29]	80	?	bottleneck	Camera	·	·	·	·	·	·	·	·	·	✓	·	·	·	·	·	
Helbing et al. [98]	100	student	bottleneck	Camera	·	·	·	·	·	·	·	·	·	✓	·	·	·	·	·	
Hoogendoorn and Daamen [99]	60–90	?	bottleneck	Camera	·	·	·	·	·	·	·	·	·	✓	·	·	·	·	·	
Kretz et al. [100]	94	student	bottleneck	Camera	·	·	·	·	·	·	·	·	·	✓	·	·	·	·	·	
Liao et al. [101]	350	student	bottleneck	Camera	·	·	·	·	·	·	·	·	·	✓	·	·	·	·	·	
Seyfried et al. [102]	20,40,60	student, staff	bottleneck	Camera	·	·	·	·	·	·	·	·	·	✓	·	·	·	·	·	
Seyfried et al. [103]	250	soldier	bottleneck	Camera	·	·	·	·	·	·	·	·	·	✓	·	·	·	·	·	
Zhang and Seyfried [6]	400	?	bottleneck	Camera	·	·	·	·	·	·	·	·	·	✓	·	·	·	·	·	
Seyfried et al. [104]	1; 15; 20; 25; 30; 34	student, staff	corridor	Camera	·	·	·	·	·	·	·	·	·	✓	·	·	·	·	·	
Chattaraj et al. [105]	1; 15; 20; 25; 30; 34	student	corridor	Camera	·	·	·	·	·	·	·	·	·	✓	·	·	·	·	·	
Liu et al. [106]	1; 15; 20; 25; 30; 34	student, staff, local resident	corridor	Camera	·	·	·	·	·	·	·	·	·	✓	·	·	·	·	·	
Zhang et al. [107]	350	student	corridor, T-junction	Camera	·	·	·	·	·	·	·	·	·	✓	·	·	·	·	·	
Zhang and Seyfried [108]	400	mostly student	straight corridor	stereo camera	·	·	·	·	·	·	·	·	·	✓	·	·	·	·	·	
Wong et al. [109]	24–90	student	walkway with angles	Camera	·	·	·	·	·	·	·	·	·	✓	·	·	·	·	·	
Zhang and Seyfried [110]	350; 46	student	corridor; intersection with pillar and staircase	Camera	·	·	·	·	·	·	·	·	·	✓	·	·	·	·	·	
Shiwakoti et al. [111]	22	student	merging corridor	Camera	·	·	·	·	·	·	·	·	·	✓	·	·	·	·	·	
Lian et al. [112]	295	student	angled channel	Video	·	·	·	·	·	·	·	·	·	✓	·	·	·	·	·	
Gorrini et al. [113]	68	?	room with corridor	Camera	·	·	·	·	·	·	·	·	·	✓	·	·	·	✓	·	
Dias et al. [114]	16	?	corridors with turning angles	Camera	·	·	·	·	·	·	·	·	·	✓	·	·	·	·	·	
	60				·	·	·	·	·	·	·	·	·	✓	·	·	·	·	·	

(*continued on next page*)

Table A2 (*continued*)

Article	Experiment Set-Up				Pedestrian behaviour														
	Sample size	Sample type	Condition	Equipment	Strategic			Tactical						Operational					
					Activity choice	Destination choice	Activity scheduling	Route choice				Exit choice		Movement through spaces	Interaction with objects	Interaction with information	Interaction with pedestrians		
								Interaction with spaces	Interaction with information	Interaction with objects	Interaction with pedestrians	Interaction with information	Interaction with pedestrians				Following behaviour	Group behaviour	Collision avoidance behaviour
Rahman et al. [115]		undergraduate student	angled corridor	GoPro 5 camera															
Ziemer et al. [116]	1000	student	ring corridor	Camera	·	·	·	·	·	·	·	·	·	✓	·	·	·	·	·
Huang et al. [117]	25	student	seat with aisle	Camera	·	·	·	·	·	·	·	·	·	·	✓	·	·	·	✓
Cao et al. [118]	30	?	ring corridor	camera	·	·	·	·	·	·	·	·	·	✓	·	·	·	·	·
Hu et al. [119]	72	student	circle	camera	·	·	·	·	·	·	·	·	·	·	·	·	·	·	✓
Xiao et al. [120]	64	university student	circle	camera	·	·	·	·	·	·	·	✓	·	✓	·	·	·	·	·
Paris [38]	6; 24	?	a square area visible	motion capture system	·	·	·	·	·	·	·	·	·	·	·	·	·	·	✓
Moussaïd et al. [7]	40	?	hospital	camera, tracking system	·	·	·	·	·	·	·	·	·	·	·	·	·	·	✓
Versluis [121]	12	?	educational building	camera, tracking system	·	·	·	·	·	·	·	·	·	·	·	·	·	·	✓
Moussaïd et al. [122]	119	?	a ring-shaped corridor	motion capture system	·	·	·	·	·	·	·	·	·	·	·	·	·	·	✓
Huber et al. [123]	10	?	middle of a room	video, tracking system	·	·	·	·	·	·	·	·	·	·	·	·	·	·	✓
Parisi et al. [124]	20	?	parking lot	GoPro 3 camera	·	·	·	·	·	·	·	·	·	·	·	·	·	·	✓
Liu et al. [125]	40	student	rectangular room	camera	·	·	·	·	·	·	·	·	·	·	·	·	·	·	✓
Li et al. [126]	233	visitor	hall with obstacles	camera	·	·	·	·	·	✓	·	·	·	·	·	·	·	·	·
Daamen and Hoogendoorn [127]	90–150	children, adult, elder	emergency door	video	·	·	·	·	·	·	·	·	·	✓	·	·	·	·	·
Tian et al. [128]	62	student	bottleneck	video	·	·	·	·	·	·	·	·	·	✓	·	·	·	·	·
Jo et al. [129]	56	?	room connect to corridor	video	·	·	·	·	·	·	·	·	·	✓	·	·	·	·	·
Huo et al. [130]	73	college student	high-rise building.	video	·	·	·	·	·	·	✓	·	✓	✓	·	·	·	·	·
Shahhoseini et al. [8]	150	?	merging corridor	video	·	·	·	·	·	·	·	·	·	✓	·	·	·	·	·
Cao et al. [131]	65	?	supermarket	video	·	·	·	·	·	·	✓	·	✓	·	·	·	·	·	·
Zhao et al. [132]	80	college student	room with obstacles	video	·	·	·	·	·	·	·	·	·	·	✓	·	·	·	·
Ding et al. [133]	52	college student		video	·	·	·	·	·	·	·	·	·	·	✓	·	·	·	·

(*continued on next page*)

Table A2 (*continued*)

Article	Experiment Set-Up				Pedestrian behaviour														
	Sample size	Sample type	Condition	Equipment	Strategic			Tactical							Operational				
					Activity choice	Destination choice	Activity scheduling	Route choice				Exit choice		Movement through spaces	Interaction with objects	Interaction with information	Interaction with pedestrians		
								Interaction with spaces	Interaction with information	Interaction with objects	Interaction with pedestrians	Interaction with information	Interaction with pedestrians				Following behaviour	Group behaviour	Collision avoidance behaviour
Fang et al. [134]	294	?	room with obstacles educational hall with two exits and stairs	video	·	·	·	·	·	·	✓	·	·	✓	·	·	·	·	·
Jeon et al. [39]	125	citizen	transportation building	recorder	·	·	·	·	✓	·	·	·	·	·	·	✓	·	·	·
Guo et al. [135]	78	?	classroom with obstacles and desks	video	·	·	·	·	✓	✓	✓	·	✓	·	·	·	·	·	·
Zhu and Shi [136]	102	?	teaching building	video	·	·	·	✓	✓	·	✓	✓	✓	·	·	·	·	·	·
Fridolf et al. [137]	100	?	tunnel with artificial cold smoke and acetic acid	video	·	·	·	·	·	·	·	✓	·	✓	·	·	·	·	·
Galea et al. [138]	700	?	rail station platform	video	·	·	·	·	·	·	·	✓	·	·	·	·	·	·	·
D'Orazio et al. [139]	113	?	theatre	video	·	·	·	·	·	·	·	·	·	·	·	✓	·	·	·
Ronchi et al. [140]	66	?	road tunnel	thermal imaging camera	·	·	·	·	·	·	·	✓	·	✓	·	✓	·	·	·
Porzycki et al. [141]	28; 50	tunnel professional; student	road tunnel	video, infrared cameras	·	·	·	·	·	·	·	·	·	·	·	✓	·	·	·
Cao et al. [142]	30	graduate student	rectangle room	video	·	·	·	·	·	·	·	·	·	✓	·	·	·	·	·
Heliövaara et al. [143]	54	student	a corridor with two exits	video	·	·	·	·	·	·	✓	·	✓	·	·	·	·	·	·
Von Krüchten and Schadschneider [144]	32–46	student	built room	video	·	·	·	·	·	·	·	·	·	·	·	·	·	✓	·
Haghani and Sarvi [145]	150	?	room with multiple exits	video	·	·	·	·	·	·	·	·	·	·	·	·	✓	·	·
Xie et al. [146]	36	college student	rectangle steel structure room	video	·	·	·	·	·	·	·	·	·	✓	·	·	✓	·	·

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

Table A3
VR studies related to pedestrian behaviour.

Article	Experiment Set-up				Pedestrian behaviour														
					Strategitcal			Tactical						Operational					
								Route choice				Exit choice					Interaction with pedestrians		
	Sample size	Sample type	Scenario	VR/AR equipment	Activity choice	Destination choice	Activity scheduling	Interaction with spaces	Interaction with information	Interaction with objects	Interaction with pedestrians	Interaction with information	Interaction with pedestrians	Movement through spaces	Interaction with objects	Interaction with information	Following behaviour	Group behaviour	Collision avoidance behaviour
Tan et al. [148]	?	?	city scene	video-based	✓	✓	✓	·	·	·	·	·	·	·	·	·	·	·	·
Natapov and Fisher-Gewirtzman [149]	40	students, researcher, staff	city district	HMD, joystick	✓	✓	·	·	·	·	·	·	·	·	·	·	·	·	·
Feng et al. [150]	16	?	mulitlevel building	HMD	·	·	·	✓	·	·	·	·	·	·	·	·	·	·	·
Fink et al. [151]	10	?	room with obstacle	HMD; bicycle helmet	·	·	·	·	·	·	·	·	·	·	✓	·	·	·	·
Sanz et al. [152]	17	student or professional	room with obstacle	shutter glasses, CAVE-like environment	·	·	·	·	·	·	·	·	·	·	✓	·	·	·	·
Li et al. [126]	146	mostly student	hall with obstacles	computer-based	·	·	·	·	✓	·	·	·	·	·	·	·	·	·	·
Bruneau et al. [153]	13	?	street-like	CAVE	·	·	·	·	·	·	·	·	·	·	·	·	·	·	✓
Kinateder et al. [154]	40	mainly student	road tunnel	two video projectors, powerwall, polarized glasses	·	✓	✓	·	·	·	·	·	·	·	·	·	·	·	·
Kinateder et al. [155]	42	mainly student	road tunnel	CAVE	·	✓	✓	·	·	·	✓	·	·	·	·	·	·	·	·
Kinateder and Warren [156]	150	?	room with exits	HMD	·	·	·	·	·	·	·	✓	·	·	·	·	·	·	·
Bode et al. [157]	464	?	a central room and two corridors	computer-based	·	·	·	·	·	·	✓	·	✓	·	·	·	·	·	·
Van den Berg [32]	378	student, mixed population	island	computer-based	✓	✓	✓	·	✓	·	✓	·	·	·	·	·	·	·	·
Moussaïd et al. [158]	36	?	corridor; bottleneck	computer-based	·	·	·	·	·	·	✓	·	·	·	·	·	·	·	·

(continued on next page)

Table A3 (*continued*)

Article	Experiment Set-up				Pedestrian behaviour														
	Sample size	Sample type	Scenario	VR/AR equipment	Strategitcal			Tactical							Operational				
					Activity choice	Destination choice	Activity scheduling	Route choice				Exit choice			Movement through spaces	Interaction with objects	Interaction with information	Interaction with pedestrians		
								Interaction with spaces	Interaction with information	Interaction with objects	Interaction with pedestrians	Interaction with information	Interaction with pedestrians					Following behaviour	Group behaviour	Collision avoidance behaviour
Kinateder et al. [159]	40	mostly student	a museum room with two exits	HMD	·	·	·	·	·	·	·	·	✓	·	·	·	·	·	·
Lin et al. [160]	169	?	metro station	HMD	·	·	·	·	·	·	✓	·	·	·	·	·	·	·	·
Tang et al. [161]	107	student, employee, firefighter, etc.	single floor with rooms and corridors	video-based	·	·	·	·	✓	·	·	✓	·	·	·	·	·	·	·
Kobes et al. [162]	153	?	one floor of a hotel	video-based	·	·	✓	·	✓	·	·	✓	·	·	·	·	·	·	·
Ahn and Han [163,164]	179; 162	?	an indoor building	AR evacuation system, phone	·	·	·	·	✓	·	·	✓	·	·	·	·	·	·	·
Silva et al. [165]	20	mainly student	hospital	serious game	·	·	·	·	·	·	·	✓	·	·	·	·	·	·	·
Duarte et al. [166]	90	student	company headquarters with rooms and corridors	HMD	·	·	✓	·	·	·	·	✓	·	·	·	·	·	·	·
Cosma et al. [167]	60	student	tunnel	HMD	·	·	·	·	✓	·	·	·	·	·	·	·	·	·	·
Kinateder et al. [168]	24	?	room with two exits	HMD	·	·	·	·	·	·	·	✓	·	·	·	·	·	·	·
Cao et al. [169]	64	undergraduate or graduate student	museum	HMD	·	·	·	·	✓	·	·	✓	·	·	·	·	·	·	·
Zhu et al. [170]	226	?	metro station	HMD	·	·	·	·	✓	·	·	·	·	·	·	·	✓	·	✓
Feng et al. [171]	24; 95	?	room with mutilple exits	HMD	·	·	·	·	·	·	·	✓	·	·	·	·	·	·	·

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

Table A4
Studies based on survey methods.

Article	Experiment Set-up				Pedestrian behaviour														
	Sample size	Sample type	Condition	Questionnaire	Strategic			Tactical						Operational					
					Activity choice	Destination choice	Activity scheduling	Route choice				Exit choice		Movement through spaces	Interaction with objects	Interaction with information	Interaction with pedestrians		
								Interaction with spaces	Interaction with information	Interaction with objects	Interaction with pedestrians	Interaction with information	Interaction with pedestrians				Following behaviour	Group behaviour	Collision avoidance behaviour
Duives and Mahmassani [9]	117	?	evacuation at a shopping mall	online questionnaire (SP)	·	·	·	·	·	·	✓	✓	✓	·	·	·	✓	·	·
Lovreglio et al. [11]	191	?	two emergency exits in a closed environment	online questionnaire (SP)	·	·	·	·	·	·	✓	·	✓	·	·	·	·	·	·
Haghani and Sarvi [179]	167	pedestrian, student	a floor of an educational building	interview (SP)	·	·	·	·	·	·	·	✓	✓	·	·	·	·	·	·
Olander et al. [180]	46	student, worker	emergency signage	questionnaire (RP)	·	·	·	·	✓	·	·	✓	·	·	·	·	·	·	·
Chen et al. [181]	173	children	a classroom with desks, chairs and two exits	questionnaire (RP)	·	·	·	·	✓	·	✓	·	·	·	·	·	·	✓	·
Aleksandrov et al. [185]	566	student, resident	75-story building	online questionnaire (SP)	·	·	·	✓	✓	·	✓	·	·	·	·	·	·	·	·
Do et al. [12]	50	passenger	train station	interview (SP)	·	·	·	·	·	·	·	·	·	·	·	·	·	✓	·
Haghani and Sarvi [10]	110	passenger	train station with six exits	interview (RP)	·	·	·	·	·	·	·	·	✓	·	·	·	·	·	·
D'Orazio et al. [139]	113	?	theatre	questionnaire (RP)	·	·	·	·	·	·	·	·	✓	·	·	·	·	·	·
Daamen et al. [81]	88	?	festival	questionnaire (RP)	·	·	·	·	✓	✓	✓	·	·	·	·	·	·	·	·

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

References

[1] M. Moussaïd, N. Perozo, S. Garnier, D. Helbing, G. Theraulaz, The walking behaviour of pedestrian social groups and its impact on crowd dynamics, PLoS One 5 (2010) 1–7, https://doi.org/10.1371/journal.pone.0010047.

[2] T.J. Shields, K.E. Boyce, A study of evacuation from large retail stores, Fire Saf. J. 35 (2000) 25–49, https://doi.org/10.1016/S0379-7112(00)00013-8.

[3] D. Nilsson, A. Johansson, Social influence during the initial phase of a fire evacuation-Analysis of evacuation experiments in a cinema theatre, Fire Saf. J. 44 (2009) 71–79, https://doi.org/10.1016/j.firesaf.2008.03.008.

[4] D. Duives, Analysis of Pedestrian Crowd Movements at Lowland, 2012.

[5] S. Hoogendoorn, W. Daamen, Self-organization in Walker Experiments, Civ. Eng., 2004, pp. 121–132.

[6] J. Zhang, A. Seyfried, Quantification of bottleneck effects for different types of facilities, Transp. Res. Procedia. 2 (2014) 51–59, https://doi.org/10.1016/j.trpro.2014.09.008.

[7] M. Moussaïd, D. Helbing, S. Garnier, A. Johansson, M. Combe, G. Theraulaz, Experimental study of the behavioural mechanisms underlying self-organization in human crowds, Proc. R. Soc. B Biol. Sci. 276 (2009) 2755–2762, https://doi.org/10.1098/rspb.2009.0405.

[8] Z. Shahhoseini, M. Sarvi, M. Saberi, M. Haghani, Pedestrian crowd dynamics observed at merging sections: impact of designs on movement efficiency, Transp. Res. Rec. J. Transp. Res. Board. 2622 (2017) 48–57, https://doi.org/10.3141/2622-05.

[9] D. Duives, H. Mahmassani, Exit choice decisions during pedestrian evacuations of buildings, Transp. Res. Rec. J. Transp. Res. Board. 2316 (2012) 84–94, https://doi.org/10.3141/2316-10.

[10] M. Haghani, M. Sarvi, Human exit choice in crowded built environments: investigating underlying behavioural differences between normal egress and emergency evacuations, Fire Saf. J. 85 (2016) 1–9, https://doi.org/10.1016/j.firesaf.2016.07.003.

[11] R. Lovreglio, D. Borri, L. Dell'Olio, A. Ibeas, A discrete choice model based on random utilities for exit choice in emergency evacuations, Saf. Sci. 62 (2014) 418–426, https://doi.org/10.1016/j.ssci.2013.10.004.

[12] T. Do, M. Haghani, M. Sarvi, Group and single pedestrian behavior in crowd dynamics, Transp. Res. Rec. J. Transp. Res. Board. 2540 (2016) 13–19, https://doi.org/10.3141/2540-02.

[13] Z. Feng, V. Gonzalez, R. Amor, R. Lovreglio, G. Cabrera-Guerrero, Immersive virtual reality serious games for evacuation training and Research : a systematic literature review, Comput. Educ. 127 (2018) 252–266, https://doi.org/10.1016/j.compedu.2018.09.002.

[14] M. Kinateder, T.D. Wirth, W.H. Warren, Crowd dynamics in virtual reality, Model. Simul. Sci. Eng. Technol. 1 (2018) 15–36, https://doi.org/10.1007/978-3-030-05129-7_2.

[15] R. Lovreglio, M. Kinateder, Augmented reality for pedestrian evacuation research: promises and limitations, Saf. Sci. 128 (2020), https://doi.org/10.1016/j.ssci.2020.104750, 104750.

[16] M. Moussaïd, V.R. Schinazi, M. Kapadia, T. Thrash, Virtual sensing and virtual reality: how new technologies can boost research on crowd dynamics, Front. Robot. AI. 5 (2018) 14, https://doi.org/10.3389/frobt.2018.00082.

[17] M. Haghani, M. Sarvi, Crowd behaviour and motion: empirical methods, Transp. Res. Part B Methodol. 107 (2018) 253–294, https://doi.org/10.1016/j.trb.2017.06.017.

[18] M. Haghani, Empirical methods in pedestrian, crowd and evacuation dynamics: Part I. Experimental methods and emerging topics, Saf. Sci. 129 (2020), https://doi.org/10.1016/j.ssci.2020.104760, 104743.

[19] M. Haghani, Empirical methods in pedestrian, crowd and evacuation dynamics: Part II. Field methods and controversial topics, Saf. Sci. 129 (2020), https://doi.org/10.1016/j.ssci.2020.104760, 104760.

[20] X. Shi, Z. Ye, N. Shiwakoti, O. Grembek, A state-of-the-art review on empirical data collection for external governed pedestrians complex movement, J. Adv. Transport. 2018 (2018), https://doi.org/10.1155/2018/1063043.

[21] M. Schweiker, E. Ampatzi, M.S. Andargie, R.K. Andersen, E. Azar, V. M. Barthelmes, C. Berger, L. Bourikas, S. Carlucci, G. Chinazzo, L.P. Edappilly, M. Favero, S. Gauthier, A. Jamrozik, M. Kane, A. Mahdavi, C. Piselli, A.L. Pisello, A. Roetzel, A. Rysanek, K. Sharma, S. Zhang, Review of multi-domain approaches to indoor environmental perception and behaviour, Build. Environ. 176 (2020), https://doi.org/10.1016/j.buildenv.2020.106804, 106804.

[22] R. Zhu, J. Lin, B. Becerik-gerber, N. Li, Human-building-emergency interactions and their impact on emergency response performance : a review of the state of the art, Saf. Sci. 127 (2020), https://doi.org/10.1016/j.ssci.2020.104691, 104691.

[23] D. Moher, A. Liberati, J. Tetzlaff, D.G. Altman, T.P. Group, Preferred reporting Items for systematic reviews and meta-analyses : the PRISMA statement, PLoS Med. 6 (2009), https://doi.org/10.1371/journal.pmed.1000097 e1000097.

[24] B. Van Wee, D. Banister, How to write a literature review paper? Transp. Rev. 36 (2016) 278–288, https://doi.org/10.1080/01441647.2015.1065456.

[25] S.P. Hoogendoorn, P.H.L. Bovy, Pedestrian route-choice and activity scheduling theory and models, Transp. Res. Part B Methodol. 38 (2004) 169–190, https://doi.org/10.1016/S0191-2615(03)00007-9.

[26] H. Li, T. Thrash, C. Hölscher, V.R. Schinazi, The effect of crowdedness on human wayfinding and locomotion in a multi- level virtual shopping mall, J. Environ. Psychol. 65 (2019), https://doi.org/10.1016/j.jenvp.2019.101320, 101320.

[27] A. Schadschneider, W. Klingsch, H. Klüpfel, T. Kretz, C. Rogsch, A. Seyfried, Evacuation dynamics: empirical results, modeling and applications, Encycl. Complex. Syst. Sci. (2009) 3142–3176, https://doi.org/10.1007/978-0-387-30440-3_187.

[28] C.G. Prato, Route choice modeling: past, present and future research directions, J. Choice Model. 2 (2009) 65–100, https://doi.org/10.1016/S1755-5345(13)70005-8.

[29] W. Daamen, S. Hoogendoorn, Experimental research of pedestrian walking behavior, Transport. Res. Rec. 1828 (2003) 20–30, https://doi.org/10.3141/1828-03.

[30] J.D. Sime, Crowd psychology and engineering 21 (1995) 1–14.

[31] J. Mwakalonge, S. Siuhi, J. White, Distracted walking: examining the extent to pedestrian safety problems, J. Traffic Transp. Eng. (English Ed. 2 (2015) 327–337, https://doi.org/10.1016/j.jtte.2015.08.004.

[32] M. van den Berg, The influence of herding on departure choice in case of an evacuation design and analysis of a serious gaming experimental set-up. https://doi.org/10.4233/uuid, 2016.

[33] Y. Feng, D.C. Duives, S.P. Hoogendoorn, The impact of guidance information on exit choice behavior during an evacuation – a VR study, in: Traffic Granul. Flow, 2019 (Accepted/In press).

[34] M. Kobes, I. Helsloot, B. de Vries, J.G. Post, N. Oberijé, K. Groenewegen, Way finding during fire evacuation; an analysis of unannounced fire drills in a hotel at night, Build. Environ. 45 (2010) 537–548, https://doi.org/10.1016/j.buildenv.2009.07.004.

[35] W. Daamen, Modelling passenger flows in public transport facilities, 2004.

[36] D. Duives, Analysis and modelling of pedestrian movement dynamics at large-scale events. https://doi.org/10.4233/uuid, 2016.

[37] W. Daamen, S. Hoogendoorn, Controlled experiments to derive walking behaviour, Eur. J. Transport Infrastruct. Res. 3 (2003) 39–59.

[38] S. Paris, J. Pettré, S. Donikian, Pedestrian reactive navigation for crowd Simulation : a predictive approach, Comput. Graph. Forum 26 (2007) 665–674, https://doi.org/10.1111/j.1467.8659.2007.01090.x.

[39] G. Jeon, J. Kim, W. Hong, G. Augenbroe, Evacuation performance of individuals in different visibility conditions, Build. Environ. 46 (2011) 1094–1103, https://doi.org/10.1016/j.buildenv.2010.11.010.

[40] Wolff, Notes on the Behaviour of Pedestrians, in: A. Birenbaum, E. Sagarin (Eds.), People Places Sociol. Fam., Nelson, London, 1973.

[41] K. Ando, H. Ota, T. Oki, Forecasting the flow of people, Railw. Res. Rev. 45 (1988) 8–14.

[42] E. Goffman, Relations in Public: Microstudies in the Public Order, Basic Books, New York, 1971.

[43] L. Yang, P. Rao, K. Zhu, S. Liu, X. Zhan, Observation study of pedestrian flow on staircases with different dimensions under normal and emergency conditions, Saf. Sci. 50 (2012) 1173–1179, https://doi.org/10.1016/j.ssci.2011.12.026.

[44] E.R. Galea, S.J. Deere, C.G. Hopkin, H. Xie, Evacuation response behaviour of occupants in a large theatre during a live performance, Fire Mater. 41 (2017) 467–492, https://doi.org/10.1002/fam.2424.

[45] J.J. Fruin, Designing for pedestrians: a level-of-service concept, Highw. Res. Rec. 355 (1971) 1–15, https://doi.org/10.1016/j.ascom.2016.03.003.

[46] A. Corbetta, J. Meeusen, C.M. Lee, F. Toschi, Continuous measurements of real-life bidirectional pedestrian flows on a wide walkway, 2016. 1607.02897.

[47] W.H.K. Lam, J.F. Morall, H. Ho, Pedestrian flow characteristics in Hong Kong, Transport. Res. Rec. (1995) 56–62. http://onlinepubs.trb.org/Onlinepubs/trr/1995/1487/1487-009.pdf.

[48] R. Virkler, S. Elayadath, Pedestrian speed-flow-density relationships, Transport. Res. Rec. 1438 (1992).

[49] M. Al-azzawi, R. Raeside, Modeling pedestrian walking speeds on sidewalks, J. Urban Plann. Dev. 133 (2007) 211–219, https://doi.org/10.1061/(asce)0733-9488 (2007)133:3(211).

[50] Y. Tanaboriboon, S.S. Hwa, C.H. Chor, Pedestrian characteristics study in Singapore, J. Transport. Eng. 112 (1986) 229–235. https://doi.org/10.1061/(ASCE)0733-947X(1986)112:3(229).

[51] J. Shah, G.J. Joshi, P. Parida, Behavioral characteristics of pedestrian flow on stairway at railway station, Procedia - Soc. Behav. Sci. 104 (2013) 688–697, https://doi.org/10.1016/j.sbspro.2013.11.163.

[52] Y. Tanaboriboon, J.A. Guyano, Analysis of pedestrian movements in bangkok, Transport. Res. Rec. 1294 (1991) 52–56.

[53] D. Duives, W. Daamen, S. Hoogendoorn, Influence of group size and group composition on the adhered distance headway, Transp. Res. Procedia. 2 (2014) 183–188, https://doi.org/10.1016/j.trpro.2014.09.026.

[54] A. Gorrini, S. Bandini, G. Vizzari, Empirical Investigation on Pedestrian Crowd Dynamics and Grouping Empirical Investigation on Pedestrian Crowd Dynamics and Grouping, in: Traffic Granul. Flow'13, 2015, pp. 83–91, https://doi.org/10.1007/978-3-319-10629-8.

[55] Y. Feng, D. Li, An empirical study and a conceptual model on heterogeneity of pedestrian social groups for friend-group and family-group, in: Proc. Pedestr. Evacuation Dyn. 2016, 2016, pp. 402–407.

[56] Y. Feng, D. Li, Improved social force models considering heterogenous characteristics among social groups, CICTP (2017), https://doi.org/10.1061/9780784480915.385, 2017.

[57] X.L. Zhang, W.G. Weng, H.Y. Yuan, J.G. Chen, Empirical study of a unidirectional dense crowd during a real mass event, Physica A 392 (2013) 2781–2791, https://doi.org/10.1016/j.physa.2013.02.019.

[58] D. Helbing, A. Johansson, H.Z. Al-Abideen, Dynamics of crowd disasters: An empirical study, Phys. Rev. E. 75 (2007), https://doi.org/10.1103/PhysRevE.75.046109, 046109.

[59] A. Johansson, D. Helbing, H.Z. Al-Abideen, S. Al-Bosta, From Crowd Dynamics to Crowd Safety: A Video-Based Analysis, Adv. Complex Syst. 11 (2008) 497–527, https://doi.org/10.1142/S0219525908001854.

[60] L. Dong, D. Lan, X. Li, J. Ma, W.G. Song, S.M. Lo, Z.M. Fang, New insights into turbulent pedestrian movement pattern in crowd-quakes, J. Stat. Mech. Theor. Exp. 2013 (2013), https://doi.org/10.1088/1742-5468/2013/02/P02028.
[61] A. Larsson, E. Ranudd, E. Ronchi, A. Hunt, S. Gwynne, The impact of crowd composition on egress performance, Fire Saf. J. (2020), https://doi.org/10.1016/j.firesaf.2020.103040, 103040.
[62] J. Wang, S. Ni, S. Shen, S. Li, Empirical study of crowd dynamic in public gathering places during a terrorist attack event, Phys. A Stat. Mech. Its Appl. 523 (2019) 1–9, https://doi.org/10.1016/j.physa.2019.01.120.
[63] H.-D. Yang, B.-K. Sin, S.-W. Lee, Automatic Pedestrian Detection and Tracking for Real-Time Video Surveillance, in: J. Kittler, M.S. Nixon (Eds.), Audio- Video-Based Biometric Pers. Authentication, Springer Berlin Heidelberg, Berlin, Heidelberg, 2003, pp. 242–250.
[64] R.M. Favaretto, L.L. Dihl, S.R. Musse, Detecting crowd features in video sequences, Proc. - 2016 29th SIBGRAPI Conf. Graph. Patterns Images, SIBGRAPI (2016) 201–208, https://doi.org/10.1109/SIBGRAPI.2016.036, 2017.
[65] B. Wang, M. Ye, X. Li, F. Zhao, J. Ding, Abnormal crowd behavior detection using high-frequency and spatio-temporal features, Mach. Vis. Appl. 23 (2012) 501–511, https://doi.org/10.1007/s00138-011-0341-0.
[66] Y. Li, M. Sarvi, K. Khoshelham, M. Haghani, Multi-view crowd congestion monitoring system based on an ensemble of convolutional neural network classifiers, J. Intell. Transport. Syst. Technol. Plann. Oper. 2450 (2020), https://doi.org/10.1080/15472450.2020.1746909.
[67] P. Centorrino, A. Corbetta, E. Cristiani, E. Onofri, Measurement and Analysis of Visitors' Trajectories in Crowded Museums, in: IMEKO TC4 Int. Conf. Metrol. Archaeol. Cult. Heritage, MetroArchaeo, 2019, pp. 423–428, 2019, 2019.
[68] A. Danalet, L. Tinguely, M. De Lapparent, M. Bierlaire, Location choice with longitudinal WiFi data, J. Choice Model. 18 (2016) 1–17, https://doi.org/10.1016/j.jocm.2016.04.003.
[69] D. Ton, J. van den Heuvel, W. Daamen, S. Hoogendoorn, Route and activity location choice behaviour of departing passengers in train stations, in: Hear. (European Assoc. Res. Transp., 2015, pp. 9–11.
[70] M. Versichele, T. Neutens, M. Delafontaine, N. Van de Weghe, The use of Bluetooth for analysing spatiotemporal dynamics of human movement at mass events: a case study of the Ghent Festivities, Appl. Geogr. 32 (2012) 208–220, https://doi.org/10.1016/j.apgeog.2011.05.011.
[71] Y. Yoshimura, S. Sobolevsky, C. Ratti, F. Girardin, J.P. Carrascal, J. Blat, R. Sinatra, An analysis of visitors' behavior in the louvre museum: a study using bluetooth data, Environ. Plann. Plann. Des. 41 (2014) 1113–1131, https://doi.org/10.1068/b130047p.
[72] Y. Yoshimura, A. Amini, S. Sobolevsky, J. Blat, C. Ratti, Analysis of pedestrian behaviors through non-invasive Bluetooth monitoring, Appl. Geogr. 81 (2017) 43–51, https://doi.org/10.1016/j.apgeog.2017.02.002.
[73] B. Bonne, A. Barzan, P. Quax, W. Lamotte, WiFiPi: involuntary tracking of visitors at mass events, IEEE 14th Int. Symp. a World Wireless, Mob. Multimed. Networks, WoWMoM 2013 (2013) 1–6, https://doi.org/10.1109/WoWMoM.2013.6583443, 2013.
[74] D.C. Duives, W. Daamen, S.P. Hoogendoorn, HOW TO MEASURE STATIC CROWDS?Monitoring the number of pedestrians at large open areas by means of Wi-Fi sensors, in: Transp. Res. Board 97th Annu. Meet., 2018, https://doi.org/10.1109/robot.1994.350900.
[75] C. Gioia, F. Sermi, D. Tarchi, M. Vespe, On cleaning strategies for WiFi positioning to monitor dynamic crowds, Appl. Geomatics. 11 (2019) 381–399, https://doi.org/10.1007/s12518-019-00260-z.
[76] M. Wirz, T. Franke, D. Roggen, E. Mitleton-Kelly, P. Lukowicz, G. Tröster, Inferring crowd conditions from pedestrians' location traces for real-time crowd monitoring during city-scale mass gatherings, Proc. Work. Enabling Technol. Infrastruct. Collab. Enterp. WETICE. (2012) 367–372, https://doi.org/10.1109/WETICE.2012.26.
[77] B. Farooq, A. Beaulieu, M. Ragab, V. Dang Ba, Ubiquitous monitoring of pedestrian dynamics: exploring wireless ad hoc network of multi-sensor technologies, IEEE SENSORS - Proc (2015) 1–4, https://doi.org/10.1109/ICSENS.2015.7370450, 2015.
[78] W. Daamen, Y. Yufei, D.C. Duives, S. Hoogendoorn, Comparing three types of real-time data collection techniques: counting cameras, Wi-Fi sensors and GPS trackers, Proc. Pedestr. Evacuation Dyn. (2016) 568–574, 2016.
[79] S. Van der Spek, Spatial Metro: tracking pedestrians in historic city centres, Urban, Track Appl. Track. Technol. Urban. 1 (2008) 77–97, https://doi.org/10.7480/rius.1.198.
[80] I.M. Galama, Route choice behaviour at mass events, 2015.
[81] W. Daamen, E. Kinkel, D.C. Duives, S.P. Hoogendoorn, Monitoring Visitor Flow and Behavior during a Festival: the Mysteryland Case Study, 2017.
[82] U. Blanke, G. Tröster, T. Franke, P. Lukowicz, Capturing crowd dynamics at large scale events using participatory GPS-localization, IEEE ISSNIP, 2014, in: IEEE 9th Int. Conf. Intell. Sensors, Sens. Networks Inf. Process. Conf. Proc, 2014, https://doi.org/10.1109/ISSNIP.2014.6827652, 2014.
[83] D.C. Duives, G. Wang, J. Kim, Forecasting pedestrian movements using recurrent neural networks: an application of crowd monitoring data, Sensors 19 (2019), https://doi.org/10.3390/s19020382.
[84] S. Gao, Spatio-temporal analytics for exploring human mobility patterns and urban dynamics in the mobile age, Spatial Cognit. Comput. 15 (2015) 86–114, https://doi.org/10.1080/13875868.2014.984300.
[85] J. Keij, Smart Phone Counting Location-Based Applications Using Mobile Phone Location Data, 2014.
[86] F. Calabrese, M. Colonna, P. Lovisolo, D. Parata, C. Ratti, Real-time urban monitoring using cell phones: a case study in Rome, IEEE Trans. Intell. Transport. Syst. 12 (2011) 141–151, https://doi.org/10.1109/TITS.2010.2074196.
[87] K. Zhang, M. Wang, B. Wei, D. Sun, Identification and prediction of large pedestrian flow in urban areas based on a hybrid detection approach, Sustain 9 (2017), https://doi.org/10.3390/su9010036.
[88] F. Botta, H.S. Moat, T. Preis, Quantifying crowd size with mobile phone and Twitter data, R. Soc. Open Sci. 2 (2015) 1–6, https://doi.org/10.1098/rsos.150162.
[89] Y. Yang, A. Heppenstall, A. Turner, A. Comber, Who, where, why and when? Using smart card and social media data to understand urban mobility, ISPRS Int. J. Geo-Inf. 8 (2019), https://doi.org/10.3390/ijgi8060271.
[90] V.X. Gong, J. Yang, W. Daamen, A. Bozzon, S. Hoogendoorn, G.J. Houben, Using social media for attendees density estimation in city-scale events, IEEE Access 6 (2018) 36325–36340, https://doi.org/10.1109/ACCESS.2018.2845339.
[91] V.X. Gong, W. Daamen, A. Bozzon, S.P. Hoogendoorn, Crowd characterization for crowd management using social media data in city events, Travel Behav. Soc. 20 (2020) 192–212, https://doi.org/10.1016/j.tbs.2020.03.011.
[92] C. Yang, M. Xiao, X. Ding, W. Tian, Y. Zhai, J. Chen, L. Liu, X. Ye, Exploring human mobility patterns using geo-tagged social media data at the group level, J. Spat. Sci. 64 (2019) 221–238, https://doi.org/10.1080/14498596.2017.1421487.
[93] M. Alkhatib, M. El Barachi, K. Shaalan, An Arabic social media based framework for incidents and events monitoring in smart cities, J. Clean. Prod. 220 (2019) 771–785, https://doi.org/10.1016/j.jclepro.2019.02.063.
[94] S. Hoogendoorn, Walking behavior in bottlenecks and its implications for capacity, in: Transp. Res. Board Annu. Meet., 2004.
[95] L.D. Vanumu, K. Ramachandra Rao, G. Tiwari, K.R. Rao, G. Tiwari, Fundamental diagrams of pedestrian flow characteristics: a review, Eur. Transp. Res. Rev. 9 (2017), https://doi.org/10.1007/s12544-017-0264-6.
[96] A. Millonig, N. Brändle, M. Ray, D. Bauer, S. Van der Spek, Pedestrian Behaviour Monitoring: Methods and Experiences, in: Behav. Monit. Interpret. - BMI, 2009, p. 11, https://doi.org/10.3233/978-1-60750-048-3-11.
[97] M. Bukáček, P. Hrabák, M. Krbálek, Microscopic travel-time analysis of bottleneck experiments, Transp. A Transp. Sci. 14 (2018) 375–391, https://doi.org/10.1080/23249935.2017.1419423.
[98] D. Helbing, L. Buzna, A. Johansson, T. Werner, Self-Organized pedestrian crowd dynamics: experiments, simulations, and design solutions, Transp. Sci. 39 (2005) 1–24, https://doi.org/10.1287/trsc.1040.0108.
[99] S.P. Hoogendoorn, W. Daamen, Pedestrian behavior at bottlenecks, Transp. Sci. 39 (2005) 147–159, https://doi.org/10.1287/trsc.1040.0102.
[100] T. Kretz, A. Grünebohm, M. Schreckenberg, Experimental study of pedestrian flow through a bottleneck, J. Stat. Mech. Theor. Exp. 2006 (2006), https://doi.org/10.1088/1742-5468/2006/10/P10014. P10014–P10014.
[101] W. Liao, A. Seyfried, J. Zhang, M. Boltes, X. Zheng, Y. Zhao, Experimental study on pedestrian flow through wide bottleneck, Transp. Res. Procedia. 2 (2014) 26–33, https://doi.org/10.1016/j.trpro.2014.09.005.
[102] A. Seyfried, B. Steffen, A. Winkens, T. Rupprecht, M. Boltes, W. Klingsch, Empirical Data for Pedestrian Flow through Bottlenecks, in: Traffic and Granular Flow '07, Springer Berlin Heidelberg, Berlin, Heidelberg, 2009, pp. 189–199.
[103] A. Seyfried, M. Boltes, J. Kähler, W. Klingsch, A. Portz, T. Rupprecht, A. Schadschneider, B. Steffen, A. Winkens, Enhanced empirical data for the fundamental diagram and the flow through bottlenecks, Pedestr. Evacuation Dyn. (2008) 145–156, https://doi.org/10.1007/978-3-642-04504-2_11, 2010.
[104] A. Seyfried, B. Steffen, W. Klingsch, M. Boltes, The fundamental diagram of pedestrian movement revisited, J. Stat. Mech. Theor. Exp. 10002 (2005) 41–53, https://doi.org/10.1088/1742-5468/2005/10/P10002.
[105] U. Chattaraj, A. Seyfried, P. Chakroborty, Comparison of Pedestrian Fundamental Diagram across Cultures, 2009, pp. 1–12.
[106] X. Liu, W. Song, J. Zhang, Extraction and quantitative analysis of microscopic evacuation characteristics based on digital image processing, Phys. A Stat. Mech. Its Appl. 388 (2009) 2717–2726, https://doi.org/10.1016/j.physa.2009.03.017.
[107] M. Boltes, J. Zhang, A. Seyfried, B. Steffen, T-junction, Experiments, trajectory collection, and analysis, Proc. IEEE Int. Conf. Comput. Vis. (2011) 158–165, https://doi.org/10.1109/ICCVW.2011.6130238.
[108] J. Zhang, A. Seyfried, Empirical characteristics of different types of pedestrian streams, Procedia Eng 62 (2013) 655–662, https://doi.org/10.1016/j.proeng.2013.08.111.
[109] S.C. Wong, W.L. Leung, S.H. Chan, W.H.K. Lam, N.H.C. Yung, C.Y. Liu, P. Zhang, Bidirectional Pedestrian Stream Model with Oblique Intersecting Angle 136, 2010, pp. 234–243.
[110] J. Zhang, A. Seyfried, Comparison of intersecting pedestrian flows based on experiments, Phys. A Stat. Mech. Its Appl. 405 (2014) 316–325, https://doi.org/10.1016/j.physa.2014.03.004.
[111] N. Shiwakoti, Y. Gong, X. Shi, Z. Ye, Examining influence of merging architectural features on pedestrian crowd movement, Saf. Sci. 75 (2015) 15–22, https://doi.org/10.1016/j.ssci.2015.01.009.
[112] L. Lian, X. Mai, W. Song, Y.K.K. Richard, Y. Rui, S. Jin, Pedestrian merging behavior analysis: an experimental study, Fire Saf. J. 91 (2017) 918–925, https://doi.org/10.1016/j.firesaf.2017.04.015.
[113] A. Gorrini, S. Bandini, C. Dias, N. Shiwakoti, An empirical study of crowd and pedestrian dynamics : the impact of different angle paths and grouping, Transport. Res. Rec. 41 (2013) 19.
[114] C. Dias, O. Ejtemai, M. Sarvi, N. Shiwakoti, Pedestrian walking characteristics through angled corridors, Transp. Res. Rec. J. Transp. Res. Board. 2421 (2014) 41–50, https://doi.org/10.3141/2421-05.

[115] N.A. Rahman, N.A. Alias, N.S.A. Sukor, H. Halim, H. Gotoh, F.H. Hassan, Trajectories and walking velocity of pedestrian walking through angled-corridors: a unidirectional scenario, IOP Conf. Ser. Mater. Sci. Eng. 572 (2019), https://doi.org/10.1088/1757-899X/572/1/012114.
[116] V. Ziemer, A. Seyfried, A. Schadschneider, Congestion Dynamics in Pedestrian Single-File Motion, 2016, pp. 1–9, https://doi.org/10.1007/978-3-319-33482-0_12.
[117] S. Huang, T. Zhang, S. Lo, S. Lu, C. Li, Experimental study of individual and single-file pedestrian movement in narrow seat aisle, Phys. A Stat. Mech. Its Appl. 509 (2018) 1023–1033, https://doi.org/10.1016/j.physa.2018.06.079.
[118] S. Cao, P. Wang, M. Yao, W. Song, Dynamic analysis of pedestrian movement in single-file experiment under limited visibility, Commun, Nonlinear Sci. Numer. Simul. 69 (2019) 329–342, https://doi.org/10.1016/j.cnsns.2018.10.007.
[119] Y. Hu, J. Zhang, W. Song, Experimental study on the movement strategies of individuals in multidirectional flows, Phys. A Stat. Mech. Its Appl. 534 (2019), https://doi.org/10.1016/j.physa.2019.122046, 122046.
[120] Y. Xiao, Z. Gao, R. Jiang, X. Li, Y. Qu, Q. Huang, Investigation of pedestrian dynamics in circle antipode experiments: analysis and model evaluation with macroscopic indexes, Transport. Res. C Emerg. Technol. 103 (2019) 174–193, https://doi.org/10.1016/j.trc.2019.04.007.
[121] D. Versluis, Microscopic interaction behavior between individual pedestrians. https://doi.org/10.1007/978-3-319-02447-9, 2010.
[122] M. Moussaïd, E.G. Guillot, M. Moreau, J. Fehrenbach, O. Chabiron, S. Lemercier, J. Pettré, C. Appert-Rolland, P. Degond, G. Theraulaz, Traffic instabilities in self-organized pedestrian crowds, PLoS Comput, Biol. 8 (2012), https://doi.org/10.1371/journal.pcbi.1002442.
[123] M. Huber, Y.H. Su, M. Krüger, K. Faschian, S. Glasauer, J. Hermsdörfer, Adjustments of speed and path when avoiding collisions with another pedestrian, PLoS One 9 (2014), https://doi.org/10.1371/journal.pone.0089589.
[124] D.R. Parisi, P.A. Negri, L. Bruno, Experimental characterization of collision avoidance in pedestrian dynamics, Phys. Rev. E E. 94 (2016) 1–8, https://doi.org/10.1103/PhysRevE.94.022318.
[125] X. Liu, W. Song, L. Fu, Z. Fang, Experimental study of pedestrian inflow in a room with a separate entrance and exit 442, 2016, pp. 224–238, https://doi.org/10.1016/j.physa.2015.09.026.
[126] H. Li, J. Zhang, L. Xia, W. Song, N.W.F. Bode, Comparing the route-choice behavior of pedestrians around obstacles in a virtual experiment and a field study, Transport. Res. C Emerg. Technol. 107 (2019) 120–136, https://doi.org/10.1016/j.trc.2019.08.012.
[127] W. Daamen, S. Hoogendoorn, Capacity of doors during evacuation conditions, Procedia Eng 3 (2010) 53–66, https://doi.org/10.1016/j.proeng.2010.07.007.
[128] W. Tian, W. Song, J. Ma, Z. Fang, A. Seyfried, J. Liddle, Experimental study of pedestrian behaviors in a corridor based on digital image processing, Fire Saf. J. 47 (2012) 8–15, https://doi.org/10.1016/j.firesaf.2011.09.005.
[129] A. Jo, T. Sano, Y. Ikehata, Y. Ohmiya, Analysis of crowd flow capacity through a door connected to a crowded corridor, Transp. Res. Procedia. 2 (2014) 10–18, https://doi.org/10.1016/j.trpro.2014.09.003.
[130] F. Huo, W. Song, L. Chen, C. Liu, K.M. Liew, Experimental study on characteristics of pedestrian evacuation on stairs in a high-rise building, Saf. Sci. 86 (2016) 165–173, https://doi.org/10.1016/j.ssci.2016.02.025.
[131] S. Cao, L. Fu, P. Wang, G. Zeng, W. Song, Experimental and modeling study on evacuation under good and limited visibility in a supermarket, Fire Saf. J. 102 (2018) 27–36, https://doi.org/10.1016/j.firesaf.2018.10.003.
[132] Y. Zhao, T. Lu, L. Fu, P. Wu, M. Li, Experimental verification of escape efficiency enhancement by the presence of obstacles, Saf. Sci. 122 (2020), https://doi.org/10.1016/j.ssci.2019.104517, 104517.
[133] Z. Ding, Z. Shen, N. Guo, K. Zhu, J. Long, Evacuation through area with obstacle that can be stepped over: experimental study, J. Stat. Mech. Theor. Exp. 2020 (2020), https://doi.org/10.1088/1742-5468/ab6a01.
[134] Z. Fang, W. Song, J. Zhang, H. Wu, Experiment and modeling of exit-selecting behaviors during a building evacuation, Physica A 389 (2010) 815–824, https://doi.org/10.1016/j.physa.2009.10.019.
[135] R.Y. Guo, H.J. Huang, S.C. Wong, Route choice in pedestrian evacuation under conditions of good and zero visibility: experimental and simulation results, Transp. Res. Part B Methodol. 46 (2012) 669–686, https://doi.org/10.1016/j.trb.2012.01.002.
[136] K.-J. Zhu, Q. Shi, Experimental study on choice behavior of pedestrians during building evacuation, Procedia Eng 135 (2016) 206–215, https://doi.org/10.1016/j.proeng.2016.01.110.
[137] K. Fridolf, E. Ronchi, D. Nilsson, H. Frantzich, Movement speed and exit choice in smoke-filled rail tunnels, Fire Saf. J. 59 (2013) 8–21, https://doi.org/10.1016/j.firesaf.2013.03.007.
[138] E.R. Galea, H. Xie, S. Deere, D. Cooney, L. Filippidis, Evaluating the effectiveness of an improved active dynamic signage system using full scale evacuation trials, Fire Saf. J. 91 (2017) 908–917, https://doi.org/10.1016/j.firesaf.2017.03.022.
[139] M. D'Orazio, G. Bernardini, S. Tacconi, V. Arteconi, E. Quagliarini, Fire safety in Italian-style historical theatres: how photoluminescent wayfinding can improve occupants' evacuation with no architecture modifications, J. Cult. Herit. 19 (2016) 492–501, https://doi.org/10.1016/j.culher.2015.12.002.
[140] E. Ronchi, K. Fridolf, H. Frantzich, D. Nilsson, A.L. Walter, H. Modig, A tunnel evacuation experiment on movement speed and exit choice in smoke, Fire Saf. J. 97 (2018) 126–136, https://doi.org/10.1016/j.firesaf.2017.06.002.
[141] J. Porzycki, N. Schmidt-Polończyk, J. Wąs, Pedestrian behavior during evacuation from road tunnel in smoke condition—empirical results, PLoS One 13 (2018) 1–20, https://doi.org/10.1371/journal.pone.0201732.
[142] S. Cao, X. Liu, M. Chraibi, P. Zhang, W. Song, Characteristics of pedestrian's evacuation in a room under invisible conditions, Int. J. Disaster Risk Reduct. 41 (2019), https://doi.org/10.1016/j.ijdrr.2019.101295, 101295.
[143] S. Heliövaara, J.M. Kuusinen, T. Rinne, T. Korhonen, H. Ehtamo, Pedestrian behavior and exit selection in evacuation of a corridor - an experimental study, Saf. Sci. 50 (2012) 221–227, https://doi.org/10.1016/j.ssci.2011.08.020.
[144] C. von Krüchten, A. Schadschneider, Empirical study on social groups in pedestrian evacuation dynamics, Phys. A Stat. Mech. Its Appl. 475 (2017) 129–141, https://doi.org/10.1016/j.physa.2017.02.004.
[145] M. Haghani, M. Sarvi, Following the crowd or avoiding it? Empirical investigation of imitative behaviour in emergency escape of human crowds, Anim. Behav. 124 (2017) 47–56, https://doi.org/10.1016/j.anbehav.2016.11.024.
[146] W. Xie, E.W.M. Lee, Y. Cheng, M. Shi, R. Cao, Y. Zhang, Evacuation performance of individuals and social groups under different visibility conditions: experiments and surveys, Int. J. Disaster Risk Reduct. 47 (2020), https://doi.org/10.1016/j.ijdrr.2020.101527, 101527.
[147] D. Reid, Virtual reality and the person–environment experience, Cyberpsychol. Behav. 5 (2003) 559–564, https://doi.org/10.1089/109493102321018204.
[148] A.A.W.W. Tan, B. De Vries, H.J.P. Timmermans, Using a stereo panoramic interactive navigation system to measure pedestrian activity scheduling behaviour: a test of validity, Environ. Plann. Plann. Des. 33 (2006) 541–557, https://doi.org/10.1068/b31092.
[149] A. Natapov, D. Fisher-Gewirtzman, Visibility of urban activities and pedestrian routes: an experiment in a virtual environment, Comput. Environ. Urban Syst. 58 (2016) 60–70, https://doi.org/10.1016/j.compenvurbsys.2016.03.007.
[150] Y. Feng, D.C. Duives, S.P. Hoogendoorn, Developing a VR tool for studying pedestrian movement and choice behavior, IEEE Conf. Virtual Real. 3D User Interfaces Abstr. Work. Dev. (2020) 814–815, https://doi.org/10.1109/VRW50115.2020.00258, 2020.
[151] Philip W. Fink, Patrick S. Foo, William H. Warren, Obstacle avoidance during walking in real and virtual environments, ACM Transactions on Applied Perception (TAP) 4 (1) (2007), https://doi.org/10.1145/1227134.1227136, 2-es.
[152] F.A. Sanz, A.H. Olivier, G. Bruder, J. Pettre, A. Lecuyer, Virtual proxemics: locomotion in the presence of obstacles in large immersive projection environments, 2015 IEEE Virtual Real, Conf. VR 2015 - Proc (2015) 75–80, https://doi.org/10.1109/VR.2015.7223327.
[153] J. Bruneau, A.H. Olivier, J. Pettré, Going through, going around: a study on individual avoidance of groups, IEEE Trans. Visual. Comput. Graph. 21 (2015) 520–528, https://doi.org/10.1109/TVCG.2015.2391862.
[154] M. Kinateder, M. Müller, M. Jost, A. Mühlberger, P. Pauli, Social influence in a virtual tunnel fire - influence of conflicting information on evacuation behavior, Appl. Ergon. J. 45 (2014) 1649–1659, https://doi.org/10.1016/j.apergo.2014.05.014.
[155] M. Kinateder, E. Ronchi, D. Gromer, M. Müller, M. Jost, M. Nehfischer, A. Mühlberger, P. Pauli, Social influence on route choice in a virtual reality tunnel fire, Transport. Res. F Traffic Psychol. Behav. 26 (2014) 116–125, https://doi.org/10.1016/j.trf.2014.06.003.
[156] M. Kinateder, W.H. Warren, Social influence on evacuation behavior in real and virtual environments, Front. Robot. AI. 3 (2016) 1–8, https://doi.org/10.3389/frobt.2016.00043.
[157] N.W.F. Bode, A.U. Kemloh Wagoum, E.A. Codling, Information use by humans during dynamic route choice in virtual crowd evacuations, R. Soc. Open Sci. 2 (2015), https://doi.org/10.1098/rsos.140410.
[158] M. Moussaïd, M. Kapadia, T. Thrash, R.W. Sumner, M. Gross, D. Helbing, C. Hölscher, C. Ho, Crowd behaviour during high-stress evacuations in an immersive virtual environment, J. R. Soc. Interface 13 (2016) 414, https://doi.org/10.1098/rsif.2016.0414.
[159] M. Kinateder, B. Comunale, W.H. Warren, Exit choice in an emergency evacuation scenario is influenced by exit familiarity and neighbor behavior, Saf. Sci. 106 (2018) 170–175, https://doi.org/10.1016/j.ssci.2018.03.015.
[160] J. Lin, L. Cao, N. Li, How the completeness of spatial knowledge influences the evacuation behavior of passengers in metro stations : a VR-based experimental study Client, Autom. ConStruct. 113 (2020), https://doi.org/10.1016/j.autcon.2020.103136, 103136.
[161] C.-H. Tang, W.-T. Wu, C.-Y. Lin, Using virtual reality to determine how emergency signs facilitate way-finding, Appl. Ergon. 40 (2009) 722–730, https://doi.org/10.1016/j.apergo.2008.06.009.
[162] M. Kobes, I. Helsloot, B. De Vries, J. Post, Exit choice, (pre-)movement time and (pre-)evacuation behaviour in hotel fire evacuation - behavioural analysis and validation of the use of serious gaming in experimental research, Procedia Eng 3 (2010) 37–51, https://doi.org/10.1016/j.proeng.2010.07.006.
[163] J. Ahn, R. Han, RescueMe, An indoor mobile augmented-reality evacuation system by personalized pedometry, Proc. - 2011 IEEE Asia-Pacific Serv, Comput. Conf. APSCC (2011) 70–77, https://doi.org/10.1109/APSCC.2011.26, 2011.
[164] J. Ahn, R. Han, An indoor augmented-reality evacuation system for the Smartphone using personalized Pedometry, Human-Centric Comput, Inf. Sci. 2 (2012) 1–23, https://doi.org/10.1186/2192-1962-2-18.
[165] J.F. Silva, J.E. Almeida, R.J.F. Rossetti, A.L. Coelho, A serious game for EVAcuation training, IEEE 2nd International Conference on Serious Games and Applications for Health (SeGAH) (2013), https://doi.org/10.1109/SeGAH.2013.6665302.
[166] E. Duarte, F. Rebelo, J. Teles, M.S. Wogalter, Behavioral compliance for dynamic versus static signs in an immersive virtual environment, Appl. Ergon. 45 (2014) 1367–1375, https://doi.org/10.1016/j.apergo.2013.10.004.

[167] G. Cosma, E. Ronchi, D. Nilsson, Way-finding lighting systems for rail tunnel evacuation: a virtual reality experiment with Oculus Rift®, J. Transport. Saf. Secur. 8 (2016) 101–117, https://doi.org/10.1080/19439962.2015.1046621.

[168] M. Kinateder, W.H. Warren, K.B. Schloss, What color are emergency exit signs? Egress behavior differs from verbal report, Appl. Ergon. 75 (2019) 155–160, https://doi.org/10.1016/j.apergo.2018.08.010.

[169] L. Cao, J. Lin, N. Li, A virtual reality based study of indoor fire evacuation after active or passive spatial exploration, Comput. Hum. Behav. 90 (2019) 37–45, https://doi.org/10.1016/j.chb.2018.08.041.

[170] R. Zhu, J. Lin, B. Becerik-gerber, N. Li, Influence of architectural visual access on emergency wayfinding : a cross-cultural study in China , United Kingdom and United States, Fire, Saf. J. 113 (2020), https://doi.org/10.1016/j.firesaf.2020.102963, 102963.

[171] Y. Feng, D. Duives, W. Daamen, S. Hoogendoorn, Pedestrian exit choice behavior during an evacuation - a comparison study between field and VR experiment, in: Transp. Res. Board 98th Annu. Meet, Transporation Res. Board, 2019.

[172] M. Haghani, M. Sarvi, Z. Shahhoseini, M. Boltes, How simple hypothetical-choice experiments can be utilized to learn humans' navigational escape decisions in emergencies, PLoS One 11 (2016) 1–24, https://doi.org/10.1371/journal.pone.0166908.

[173] A. Falk, J. Heckman, Lab experiments are a major source of knowledge in the social sciences, Science 326 (2009) 535–538, https://doi.org/10.1126/science.1168244.

[174] D.C. Schwebel, J. Gaines, J. Severson, Validation of virtual reality as a tool to understand and prevent child pedestrian injury, Accid. Anal. Prev. 40 (2008) 1394–1400, https://doi.org/10.1016/j.aap.2008.03.005.

[175] D. Cohen, N. Sevdalis, D. Taylor, K. Kerr, M. Heys, K. Willett, N. Batrick, A. Darzi, Emergency preparedness in the 21st century: training and preparation modules in virtual environments, Resuscitation 84 (2012) 78–84, https://doi.org/10.1016/j.resuscitation.2012.05.014.

[176] I. Feldstein, A. Dietrich, S. Milinkovic, K. Bengler, A pedestrian simulator for urban crossing scenarios, IFAC-PapersOnLine. 49 (2016) 239–244, https://doi.org/10.1016/j.ifacol.2016.10.531.

[177] N.W.F. Bode, E.A. Codling, Human exit route choice in virtual crowd evacuations, Anim. Behav. 86 (2013) 347–358, https://doi.org/10.1016/j.anbehav.2013.05.025.

[178] S. Deb, D.W. Carruth, R. Sween, L. Strawderman, T.M. Garrison, Efficacy of virtual reality in pedestrian safety research, Appl. Ergon. 65 (2017) 449–460, https://doi.org/10.1016/j.apergo.2017.03.007.

[179] M. Haghani, M. Sarvi, Pedestrian crowd tactical-level decision making during emergency evacuations, J. Adv. Transport. 50 (2016) 1870–1895, https://doi.org/10.1002/atr.1434.

[180] J. Olander, E. Ronchi, R. Lovreglio, D. Nilsson, Dissuasive exit signage for building fire evacuation, Appl. Ergon. 59 (2017) 84–93, https://doi.org/10.1016/j.apergo.2016.08.029.

[181] L. Chen, T.Q. Tang, H.J. Huang, Z. Song, Elementary students' evacuation route choice in a classroom: a questionnaire-based method, Phys. A Stat. Mech. Its Appl. 492 (2018) 1066–1074, https://doi.org/10.1016/j.physa.2017.11.036.

[182] M. Aleksandrov, A. Rajabifard, M. Kalantari, R. Lovreglio, V.A. González, People choice modelling for evacuation of tall buildings, Fire Technol. 54 (2018) 1171–1193, https://doi.org/10.1007/s10694-018-0731-1.

[183] X. Chen, H. Li, J. Miao, S. Jiang, X. Jiang, A multiagent-based model for pedestrian simulation in subway stations, Simulat. Model. Pract. Theor. 71 (2017) 134–148, https://doi.org/10.1016/j.simpat.2016.12.001.

[184] J. Ma, W.G. Song, S.M. Lo, Z.M. Fang, New insights into turbulent pedestrian movement pattern in crowd-quakes, J. Stat. Mech. Theor. Exp. 2013 (2013), https://doi.org/10.1088/1742-5468/2013/02/P02028.

[185] I.M. Shochet, M.R. Dadds, D. Ham, R. Montague, Road-crossing safety in virtual reality: a comparison of adolescents with and without adhd, J. Clin. Adolesc. Psychol. 4416 (2010) 37–41, https://doi.org/10.1207/s15374424jccp3502.

[186] T. Maheshwari, J. Kupferschmid, A. Erath, M. Joos, Virtual Reality as a Tool to Assess Perception of Safety and Comfort for Cyclists in singapore, in: Gt. Asian Streets Symp., GASS, 2016, pp. 59–66, 2016.

[187] F. Rebelo, P. Noriega, Indoor human wayfinding performance using vertical and horizontal signage in virtual reality, Hum. Factors Ergon. Manuf. Serv. Ind. 24 (2014) 601–615, https://doi.org/10.1002/hfm.