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CHAPTER ELEVEN

How crowd management strategies influence pedestrian choice behavior and movement dynamics: A state-of-the-art overview

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Abstract

This chapter aims to provide crowd operators with an overview, including the effects of crowd management strategies on the pedestrian choice behavior and movement dynamics. Crowd management strategies are commonly considered as the deployment of steering mechanism. The overview also includes how the profile of a crowd and environment influences pedestrian choice behavior and movement dynamics. Specifically, the study focuses on the impact of different steering mechanisms and profiling factors on pedestrian walking speed, flow rate, pedestrian route choice behavior, and pedestrian wayfinding performance. This overview is based on a review of the state-of-the-art literature, which is also presented within this chapter. It demonstrates the opportunity to employ particular steering mechanisms to manage crowds within a given environment. However, the overview also highlights some limitations in the state-of-the-art regarding the effects of the steering mechanisms, or even in the broader context of crowd management. Specific challenges for future crowd management research are discussed, which could provide crowd operators with more insights into the quantitative effect of crowd management strategies in a given environment.

1. Introduction

Crowd management is becoming more pressing within pedestrian infrastructures over the years. The infrastructures are often constrained in size, while witnessing a continuous increase in their pedestrian traffic. This leads to congestions and concerns regarding the pedestrian safety. To address these issues, crowd management strategies are employed.

The wide variation of crowd management strategies ensure that crowd operators have many opportunities to manage the pedestrian in their infrastructures. Ideally, state-of-the-art provides empirical studies featuring quantitative influences of each crowd management strategy on pedestrian behavior. In that case, crowd operators are able to tailor strategies for the specific need of their infrastructure, whether it is to prevent congestions from happening or to enhance the pedestrians' level of safety within that infrastructure. For example, previous empirical studies have shown that strategies such as signage (O'Neill, 1991; Tucker et al., 2018), illumination (Taylor and Socov, 1974; Vilar et al., 2013), and built environment features (Shahhoseini and Sarvi, 2019; Wang et al., 2020; Zhao et al., 2020) have an impact on pedestrian choice behavior and movement dynamics.

Unfortunately, extracting this type of information from the state-of-the-art is not straightforward for crowd operators. There are two key reasons that make it complicated to do so. Firstly, the state-of-the-art lacks a comprehensive overview of crowd management strategies and their corresponding influence on pedestrian behavior. Secondly, the state-of-the-art is not complete regarding the effect of crowd management strategies, indicating a large range of research gaps. This chapter seeks to address the lack of such an overview by providing crowd operators with an overview based on the state-of-the-art. Specifically, it focuses on the effects of crowd management strategies on different types of pedestrian choice behavior and movement dynamics. Within this chapter, the crowd management strategies are defined as the deployment of steering mechanisms to manage crowds. Although it is not the aim of this chapter, the overview should also identify the research gaps in the literature.

In order to provide an overview featuring the effects of crowd management strategies on pedestrian choice behavior and movement dynamics, the crowd dynamics literature should be reviewed. Haghani (2021) introduces an extensive network mapping the full scope of crowd dynamics literature, separating studies into distinct clusters for systematic analysis of the literature. The largest clusters in size include pedestrian evacuation (e.g., in Chowdhury et al. (2000), Helbing and Molnar (1995), Helbing (2001), Kirchner and Schadschneider (2002)), pedestrian dynamics (e.g., in Chraibi et al. (2011), Hoogendoorn and Bovy (2004), Moussaid et al. (2010), Xia et al. (2009)), pedestrian walking behavior (e.g., in Blue and Adler (2001); Gipps and Marksjö (1985), Helbing (1991), Schreckenberg and Sharma (2002)), decision analysis (e.g., in Ando et al. (1988), Gwynne et al. (1999); Kobes et al. (2010b), Thompson and Marchant (1995)), and empirical method (e.g., in Daamen (2002), Haghani and Sarvi (2018), Kinateder et al. (2014), Lovreglio et al. (2016b)). The provided references are the most cited articles within each cluster, offering a rough understanding of their content. The first three clusters primarily consists of modeling and simulation studies, while the decision analysis cluster is strongly associated with fire safety and crowd dynamics in emergency situations. This chapter is mostly correlated to the empirical methods cluster, although it is not limited to solely this cluster. Since this chapter aims to provide crowd operators with relevant information regarding the effects of crowd management strategies, this overview focuses on empirical findings, as crowd operators require relationships that have been validated through experiments.

Yet, next to the effects of crowd management strategies, this chapter includes how the profile of the crowd and the environment can affect the pedestrian choice behavior and movement dynamics. Generating a profile of the crowd and environment is an essential step in effective crowd management, and is taken before selecting an appropriate crowd management strategy. Although the profiling factors of the crowd and the environment are not a strategy in itself, they are important input variables when employing such a strategy to manage crowds. Crowd operators need to know which type of pedestrians are within the environment, because of the characteristics of the crowd impact the efficiency of the steering mechanisms. Therefore, this chapter includes the influence of both the profiling factors and steering mechanisms on pedestrian choice behavior and movement dynamics.

Altogether, the aim of this chapter is twofold. Firstly, to provide crowd operators with state-of-the-art information regarding the effects of crowd management strategies on pedestrian choice behavior and movement dynamics. Secondly, to inform them about how the profile of the crowd and the environment can influence that behavior as well. This is achieved by providing an overview that include all the effects of the crowd management strategies and profiling factors established in the state-of-the-art literature.

This chapter continues with three definitions in Section 2. These definitions give more clarity regarding the pedestrian choice behavior and movement dynamics, the profiling of both the crowd and the environment, and the steering mechanisms to manage crowds. Thereafter, in Section 3, the methodology of this study is introduced, which includes the scope of this review, the employed search strategy, and the structure of the overview. Accordingly, Section 4 presents a comprehensive review of the existing literature with respect to the effects of steering mechanisms and profiling factors on pedestrian choice behavior and movement dynamics. An overview of the state-of-the-art is given in Section 5. This overview is discussed in Section 6, highlighting what has been established in the state-of-the-art and some challenges for future crowd management research. Finally, this chapters ends with a short summary in Section 7.

2. Definitions

This study examines the influence of both steering mechanisms and the profile of the crowd and the environment on pedestrian choice behavior and movement dynamics. This section is going to provide the

definitions of these properties. That is, this section emphasizes what is included within the overview and what not. Section 2.1 introduces the distinct types of pedestrian choice behavior and movement dynamics that are examined within this chapter. Moreover, the specific subset of profiling factors are presented in Section 2.2, while the different steering mechanisms are outlined in Section 2.3.

2.1 Pedestrian choice behavior and movement dynamics

In Chapter 8, the most detailed level of pedestrian movement behavior is divided into three levels, namely strategic choice behavior, tactical choice behavior, and operational movement dynamics (Hoogendoorn and Bovy, 2004). At the strategic and tactical level, pedestrians predominantly make decisions regarding the planning of their trip. At the operational level, pedestrians predominantly make decisions regarding their next few steps moving through a space. Decisions on the operational level are influenced by both their direct environment and the higher-level goals that result from the strategic and tactical levels.

In this chapter, the crowd and pedestrian behavior are examined based on the above-mentioned levels of pedestrian choice behavior and movement dynamics. In Section 2.1.1, the strategic and tactical choice behavior that is considered within this chapter are discussed. Thereafter, the same is done for the operational movement dynamics in Section 2.1.2. The types of pedestrian behavior that are considered in this chapter are highlighted in bold.

2.1.1 Strategic and tactical choice behavior

Pedestrians make decisions at different levels with respect to pedestrian route choice, including strategic choice behavior within a road network, and tactical choice behavior within complex parts of the infrastructure (e.g., intersections). Decisions on both the strategic and tactical level are closely linked to pedestrian route choice behavior, but at different levels of decision-making. In this chapter, route choice behavior refers to all decisions related to local and global path planning of pedestrians, while being within a pedestrian infrastructure. This includes, but is not limited to, exit choice behavior, path choice inside rooms, path planning within entire buildings, and route choice in street networks. To reduce the complexity of this chapter, all types of choice behavior at these two levels are defined as **pedestrian route choice**. Thus, this chapter does not distinguish between strategic choice behavior and tactical choice behavior, or between the different types of route choice behavior.

It is crucial to establish a distinct definition of what constitutes a positive and a negative influence on pedestrian route choice. If a factor influences pedestrians to choose route A more often compared to a scenario without that factor, the factor is considered to have a positive impact on pedestrian route choice. In other words, pedestrians are more likely to adopt routes that include this factor. Conversely, if pedestrians choose route A less frequently due to the presence of a particular factor, the factor is considered to have a negative impact on the route choice.

2.1.2 Operational movement dynamics

At the operational level, pedestrians make short-term decisions on their instantaneous response to their intermediate static objects (e.g., doors, tables, or pillars) and dynamic environment (e.g., light, moving obstacles, or other pedestrians). Within the traffic engineering domain, three variables are often used to describe the instantaneous response of pedestrians to their dynamically changing environment, namely velocity, acceleration, and distance headway. Velocity is a two-dimensional vector that can be translated into a magnitude (e.g., walking speed) and directional vector (e.g., rotation angle). This chapter only examines the **pedestrian walking speed**, because it is most relevant for crowd operators due to its relation with flow rate in the fundamental diagram and capacity. This means that this overview excludes studies focusing on the rotational behavior of pedestrians (e.g., in Bao (2021), Jin et al. (2017), Yamamoto et al. (2019), Zhang et al. (2021)).

Pedestrian walking speed is considered as a microscopic variable. In addition to the microscopic variable, this chapter examines two macroscopic variables to assess pedestrian movement dynamics, namely the flow rate and the pedestrian wayfinding performance. The **flow rate** is defined as the average number of pedestrians passing a cross-section of the infrastructure within a defined time period. A high flow rate indicates efficient demand processing, whereas a low flow rate in high-demand scenarios is correlated with inefficient processing, such as queuing, crowd locks and turbulence. As mentioned in earlier chapters, the flow rate is directly correlated to the pedestrian walking speed and the crowd density through the fundamental diagrams (e.g., in Buchmueller and Weidmann (2006), Cao et al. (2018), Fruin (1971), Rastogi et al. (2013)).

Pedestrian wayfinding performance identifies how effectively pedestrians find their way from their origin A to their destination B (Kuliga et al., 2019). Various operational properties are encountered in the literature to

assess wayfinding performance. Most often, wayfinding performance is accounted for in walking time, indicating the time it takes to get from A to B (Suzer et al., 2018). Other properties are the walking distance (i.e., the total distance of the pedestrians' path between A and B), number of detours (i.e., how often the pedestrian deviated from the most direct route between A and B), and number of turns (i.e., number of turns in the route between A and B). In all cases, higher numbers for these properties result in a less effective performance. Therefore, this review does not differentiate between the four measures, but instead examines the pedestrian wayfinding performance in a more universal context.

This chapter distinguishes two types of pedestrian wayfinding performance, as it can severely differ based on the context. Wayfinding performance is considered in both normal and emergency conditions. Here, normal conditions are identified as day-to-day scenarios where pedestrians can perform wayfinding on a regular basis. Emergency scenarios are identified as any scenario where pedestrians were urged to quickly leave their current location and find the (nearest) exit because of potential dangers (e.g., fire, flooding and active shooter scenarios). The factors influencing wayfinding performance may vary in magnitude between the emergency scenario and the 'standard' situations. For example, Daamen and Hoogendoorn (2012) show that the capacity of the exit is higher in the evacuation scenario than in the standard scenario without any signal. Therefore, pedestrian wayfinding performance is divided into two types, namely **pedestrian wayfinding performance under 'normal' conditions** and **pedestrian wayfinding performance under evacuation conditions**. This allows crowd operators to distinguish the impact of the context (i.e., normal or emergency scenario) from the impact of the profiling factors and steering mechanisms.

This chapter includes both evacuations of buildings and emergency scenarios in urban spaces. Even though, the majority of empirical studies on pedestrian choice behavior and movement dynamics in emergency conditions correlates to indoor evacuations, most of these properties can be translated to emergency situations in outdoor urban spaces.

2.2 Profiling the crowd and its environment

Crowd operators should profile the crowd and the surrounding pedestrian infrastructure before employing any steering mechanism to manage this crowd within their infrastructure. For example, crowd operators often employ different strategies to affect choice behavior of young adults attending

a musical festival in a rural area compared to that of an elderly crowd moving through a city center. Once operators have a profile of their crowd and its environment, they should assess the pedestrian choice behavior and movement dynamics corresponding to that profile before deciding on any strategy. Chapter 5 provides an overview of human factors that influence different behavioral aspects of pedestrians. Human factors are an ideal guideline to profile a specific crowd and partially the environment. They are considered to be either on the individual, social, and contextual level, from which the contextual level human factors are primarily about the environment. The individual and social level human factors can be used to profile the crowd. In Section 2.2.1, the profile of the crowd is discussed in more detail, including the profiling factors that are considered and excluded from this chapter. Thereafter, the profile of the environment is discussed in Section 2.2.2.

2.2.1 Profiling the crowd

The profile of a crowd can be assessed based on the individual and social level of human factors as identified in Chapter 5, from which the social level can be separated into the culture characteristics of pedestrians and the group characteristics within a crowd. This leads to the three characteristics that need to be considered when profiling a crowd, namely the individual and cultural characteristics of pedestrians, and the group characteristics within the crowd. This chapter does add one restriction to using these human factors to profile crowds. Certain properties are difficult to derive from a crowd. For instance, crowd operators do not always have the knowledge and expertise to directly assess the personality traits within the crowd. Therefore, this chapter focuses on profiling the crowd based on properties that are directly observable from an individual or the crowd, or at least, accurately estimated.

Following this restriction, the profile of the crowd regarding the individual characteristics are limited to ones that can easily be estimated by the crowd operators. These characteristics include, but are not limited to, pedestrians' physical characteristics (e.g., age, gender, height, and weight), social characteristics (e.g., cultural background), and intellectual characteristics (e.g., educational background, and spatial knowledge). Additionally, the culture characteristics of pedestrians are excluded in this chapter. Chapter 5 defines the culture of pedestrians as the collective programming of the mind that separates people into groups. Since the collective programming or social mindset cannot be directly derived, or even estimated, from a crowd, the culture characteristics of the pedestrians are excluded from the profiling of a crowd in this chapter.

The group characteristics within the crowd include all factors that affect pedestrians' interactions with other pedestrians in their direct environment. Specifically, the properties of these interactions that influence pedestrian choice behavior and movement dynamics. State-of-the-art literature indicates different properties, such as the composition of groups (i.e., group formation and size), the type of interactions between the global flow directions (i.e., flow ratio), and the microscopic interactions between groups of people (e.g., herding and leader-follower behavior). Among these properties of group characteristics, this chapter focuses on the composition of groups and their impact on pedestrian choice behavior and movement dynamics. Readers can expect there is an overlap between this literature review and Chapter 5. For other properties, readers are referred to other literature, such as flow ratio (e.g., in Alhajyaseen et al. (2011), Feliciani and Nishinari (2016), Zhang et al. (2012, 2018)), herding (Haghani and Sarvi, 2019), and leader-follower behavior (e.g., in Irnich et al. (2022), Jones and Hewitt (1986), Moussaid et al. (2010), van der Wal et al. (2021)).

2.2.2 Profiling the environment

When crowd operators determine the profile of their respective environments, they focus on two key characteristics, namely the built environment and the physiological and natural environment. As this chapter considers the built environment as a steering mechanism, the physiological and natural environment remains the sole characteristic to profile the respective environment. The built environment features are considered steering mechanisms following the DIM-ICE model of Still (2014). He considers the built environment to be one of the characteristics to influence crowds. In particular, when designing a new or improving pedestrian infrastructure, the built environment can be used as a strategic tool to manage crowds. For that reason, the authors have decided to include the built environment features in the category of steering mechanisms. That is, the profiling of the environment is considered by analyzing the physiological and natural environment. This characteristic assesses the climate within the respective environment. Here, climate is defined as the general environmental conditions inside a pedestrian infrastructure. These conditions include, but are not limited to, rain, snow, humidity, and temperature. Moreover, the presence of smoke and fire are included in the profiling of the environment.

2.3 Steering mechanisms to manage crowds

Steering mechanisms are measures that can be used to steer pedestrian choice behavior and movement dynamics. They can be employed as a strategy to manage crowds in a given environment. This chapter accounts for steering mechanisms that can impact the types of pedestrian behavior introduced in Section 2.1. That is, the steering mechanisms that are able to influence either pedestrian walking speed, flow rate, route choice, or wayfinding performance. The DIM-ICE model distinguishes three elements that are able to influence crowds (Still, 2014), including design, information, and management. Here, the design refers to the physical and spatial characteristics of the built environment, information consists of any information provision method (e.g., signage), and management refers to all other types of steering mechanisms (e.g., visual and aural stimuli). This chapter includes all three elements as potential steering mechanisms to manage and control crowds in a given environment.

3. Methodology

This chapter aims to provide crowd operators with information regarding the influence of crowd management strategies and corresponding profiling factors on pedestrian choice behavior and movement dynamics. To achieve this, a literature review was conducted to provide an overview of studies featuring empirical findings regarding the relationship between pedestrian behavior and profiling factors, as well as pedestrian behavior and steering mechanisms. Specifically, the review examines relationships that align with the types of pedestrian behavior listed in Section 2.1, the profiling factors described in Section 2.2, and the steering mechanisms defined in Section 2.3. The literature review is conducted based on the scope described in Section 3.1, and the search strategy introduced in Section 3.2. Finally, the structure of the overview is presented in Section 3.3.

3.1 Scope

Pedestrian research is a very interdisciplinary field, which features, amongst other things, physics and engineering-related (Feng et al., 2022; Fruin, 1971; Older, 1968; Rastogi et al., 2013), sociological (Bode, 2016; Gorrini et al., 2016; Moussaid et al., 2010; Zhao et al., 2016), architectural (Corbetta et al., 2016; Liu et al., 2020; Stoker et al., 2015; Sun, 2009) and psychological perspective (Drury, 2020; Franek et al., 2014; Sieben et al., 2017; Templeton et al., 2018). This chapter is written from an engineering and planning perspective, although

the included studies are not necessarily limited to studies from this field. The selection of studies for the literature review is entirely based on the defined types of pedestrian choice behavior and movement dynamics in Section 2.1, the profiling factors in Section 2.2, and the steering mechanisms in Section 2.3.

Crowd operators are primarily interested in relationships that have been established with experimental work, as empirical work confirms whether an effect exists. Thus, this chapter only accounts for empirical findings that identify quantitative relationships between pedestrian choice behavior and movement dynamics with the steering mechanisms or profiling factors that have been explained in Section 2.

The authors want to highlight that this chapter aims to provide crowd operators with sufficient information to employ crowd management strategies. For this purpose, this chapter provides an overview of crowd management strategies and their impact on pedestrian choice behavior and movement dynamics according to the state-of-the-art. By analyzing this overview, crowd operators are able to determine whether particular relationships are established in the state-of-the-art.

3.2 Employed search strategy

Based on the identified scope, a set of keywords was selected to capture relevant studies for this literature review. The adopted keywords include 'pedestrian', 'crowd', 'behavior', 'dynamics', 'movement dynamics', 'walking speed', 'route choice', 'flow rate', 'wayfinding performance', 'evacuation', 'personal characteristics', 'social groups', 'built environment', 'climate', 'crowd management measures, 'illumination', 'lighting', and 'aural stimuli'. Accordingly, the selected keywords are used individually and in combination to identify as many studies as possible that satisfy the predefined inclusion criteria. There were no criteria regarding the publication date of the article, but only articles published in English, German or Dutch were included in the literature review. The search engines Google Scholar and Scopus were adopted to perform the literature review search. Furthermore, the snowballing technique, including both backward and forward snowballing, was used frequently to expand the number of studies.

For particular relationships, the state-of-the-art includes many studies. In these instances, the literature review in Section 4 only shows a limited amount of these studies to avoid dozens of references for a single relationship. It is worth noting that the literature review features a variety of findings in the state-of-the-art. That is, if a contradiction for a specific relationship exists in literature, the literature review presents both perspectives.

Accordingly, the criteria regarding the scope were adopted to filter the studies. After filtering, 171 papers fit within the scope of this research, and are presented in the literature review (see Section 4). These papers comprise the period spanning from 1972 to 2024, and are written by 444 different authors, 140 of whom were first authors. Table 1 gives descriptive statistics of the papers in Section 4, including the authors, the publication year, the type of pedestrian choice behavior and movement dynamics, the profiling factors, and the steering mechanisms.

Table 1 Descriptive statistics of the literature that has been selected for this literature review. It indicates the number of papers per time period, per type of pedestrian choice behavior and movement dynamics, per group of profiling factors, and per steering mechanisms.

Descriptive information	Classification	Number of papers
Articles	Number of articles	171
First author's affiliation continent	Africa	0
	Asia	60
	Europe	75
	Oceania	7
	North America	29
	South America	1
Publication year	1971–1980	3
	1981–1990	8
	1991–2000	8
	2001–2010	36
	2011–2020	95
	2021–2024	22
Type of pedestrian behavior	Walking speed	52
	Flow rate	36
	Route choice	58
	Wayfinding performance	33
	Wayfinding performance in evacuation	20

Profiling factors	Individual characteristics	65
	Social characteristics	19
	Physiological and natural environment	21
Steering mechanisms	Built environment	71
	Information and management	37

3.3 Introduction to the systematic overview

Based on the identified studies, this chapter provides systematic overview of the relation between the types of pedestrian choice behavior and movement dynamics (see Section 2.1) and profiling of the crowd and environment (see Section 2.2) as well as the steering mechanisms (see Section 2.3). Within this chapter, these relationships will be referred to as 'factor-behavior pairs'. Here, the term 'factor' refers to the profiling and steering mechanisms, whereas 'behavior' addresses the types of pedestrian choice behavior and movement dynamics. The purpose of this overview is (1) to indicate that quantitative information exists regarding a factor-behavior pair, (2) to record the nature of that relationship, and (3) to provide the studies including that information.

The structure of the overview is presented in Table 2. Here, the profiling factor (PF) and steering mechanisms (SM) are expressed against the pedestrian walking speed (WS), flow rate (FR), route choice (RC), wayfinding performance in normal scenarios (WP), and wayfinding performance in

Table 2 The structure of an overview of profiling factors (PF) and steering mechanisms (SM) in relation to the walking speed (WS), flow rate (FR), route choice (RC), wayfinding performance (WP), and wayfinding performance in evacuation (WPe).

	Classification	WS	FR	RC	WP	WPe
PF	…					
	…					
SM	…					
	…					

evacuation scenarios (WPe). The distinct types of profiling factors and steering mechanisms will be added to the column 'classifications' based on the information presented in the literature review (see Section 4).

If a specific factor-behavior pair has not been studied, its corresponding cell remains white and empty. When literature provides quantitative information regarding a factor-behavior pair, the respective cell is colored and the relevant studies are indicated. This overview distinguishes five types of relationships: no relationship, monotone decreasing, monotone increasing, inconsistent findings, and a relationship that is not necessary positive or negative. A more in-depth explanation of these classifications can be found in Section 5.

4. Review of state-of-the-art literature

This section provides the key findings from the state-of-the-art literature review. Within this section, the influences of the profiling factors and the steering mechanisms on each type of pedestrian choice behavior and movement dynamics are examined. Studies featuring the effects on pedestrian walking speed are discussed in Section 4.1. Thereafter, Section 4.2 introduces the studies regarding the effects on flow rate. Section 4.3 discusses the observed impact on pedestrian route choice. Finally, the effect on pedestrian wayfinding performance in normal and emergency conditions is discussed in Sections 4.4 and 4.5. For each type of pedestrian choice behavior and movement dynamics, the findings are organized into four segments; profiling the crowd, profiling the environment, built environment features, and other steering mechanisms.

Two remarks should be made. Firstly, this literature review considers the influence of pedestrian stress levels. While precise stress levels cannot be directly derived from a crowd, there is an element in the environment with an association with stress levels. This literature review defines stress levels as a condition that triggers people to hurry and is caused by any type of evacuation signal (e.g., evacuation alarms). This signal is directly identifiable from the scenario, and therefore part of this overview. Secondly, signage is considered to be one of the other steering mechanisms. It is not considered as a built environment feature, as signage can be dynamically changed in the infrastructure.

4.1 Effects on pedestrian walking speed

Profiling the crowd — The impact of age and gender on pedestrian walking speed is homogeneous in literature. Pedestrian walking speed increases for

an increment in age for children and decreases for an increment in age for adults (e.g., in Cabrera et al. (2016), Gorrini et al. (2015), Pinna and Murrau (2018), Subaih et al. (2020), Zhao et al. (2016)). In addition, males walk faster than females in different environments, including buildings (Zanlungo et al., 2020), parks (Cabrera et al., 2016), and city centers on walkways (Laxman et al., 2010), sidewalks (O'Flaherty and Parkinson, 1972; Polus et al., 1983), and signalized intersections (Montufar et al., 2007). In contrast to the clearly established influence of age and gender on walking speed, the impact of the cultural background is still up for debate. Rastogi et al. (2013) and Tanaboriboon et al. (1986) show that Indian pedestrians walk slower on sidewalks than those in the UK or the USA, whereas Subaih et al. (2020) states that both Indian and Palestinian pedestrians walk faster than German ones in a controlled experiment. The latter directly contrasts with the findings of the controlled experiment of Chattaraj et al. (2009), which shows an equal walking speed for pedestrians of India and Germany. The results cannot state whether the contradiction originates from other factors, such as the number of males and females in the experiment.

Literature also indicates that the context of the scenarios influences the pedestrian walking speed (Feng et al., 2022). For instance, Daamen and Hoogendoorn (2012) and Dachner and Kinateder (2016) find that pedestrians increase their walking speed toward and through an emergency exit when exposed to emergency conditions compared to normal conditions. The same statement holds true on stairways (Yang et al., 2012). Moreover, some studies indicate that individual pedestrians walk faster than a group of pedestrians (e.g., dyads or triads) in uni-directional and multi-directional flows (Gorrini et al., 2015,2016; Moussaid et al., 2010; Zhao et al., 2016), highlighting the influence of group size on pedestrian walking speed. However, Hu et al. (2020) show that the walking speed of individuals is not always higher than that of social groups for a multi-directional flow.

Profiling the environment — A small body of research has been performed on the impact of climate on pedestrian walking speed. In particular, it has been shown that the effect of temperature on pedestrian walking speed should be taken into account (Liang et al., 2020; Rotton et al., 1990). For instance, Kimura et al. (2015) show that the average pedestrian walking speed is higher in winter than in summer, i.e., the pedestrian walking speed is higher at lower temperatures. Pedestrian walking speed increases even more when the temperatures are below 0 °C (Dong et al., 2022; Weidmann, 1993). However, these two studies are in contrast regarding

the pedestrian walking speed at higher temperatures. Weidmann (1993) states that pedestrian walking speed decreases with higher temperatures (i.e., temperatures above 25 °C), while Dong et al. (2022) find a small increase in the pedestrian walking speed for high temperature (i.e., temperatures above 30 °C). The latter study also observes faster walking speed on rainy days than on sunny ones (Dong et al., 2022).

For indoor environments, literature shows that pedestrians reduce their walking speed when smoke is present in the environment due to the lack of visibility (e.g., in Fridolf et al. (2014), Jeon et al. (2011), Ronchi et al. (2018), Xie et al. (2020)).

Built environment features — Literature provides various aspects of the built environment that influence pedestrian walking speed. For instance, pedestrian walking speed significantly decreases at high-degree bends of at least 90° (e.g., in Adrian et al. (2018), Dias et al. (2013), Hannun et al. (2022), Zhang et al. (2011)). Additionally, previous studies showed that the pedestrian walking speed changes when they encounter a bottleneck (e.g., in Hoogendoorn and Daamen (2005), Seyfried et al. (2009)). Pedestrians also walk faster through urban areas without greenery in comparison to urban areas with lots of greenery (Franek, 2013). Next to that, some studies investigate pedestrian walking speed on and around stairways (e.g., in Burghardt et al. (2013), Corbetta et al. (2016), Frantzich (1996), Köster et al. (2019)). For instance, Köster et al. (2019) show that pedestrians walk faster on the landing in between stairs than on the stairs themselves. Moreover, Corbetta et al. (2016) find that pedestrians walk slower after ascending a stairway than when they just descended one. Altogether, one can conclude that built environment features impact pedestrian walking speed. Nonetheless, a lot of built environment features have not yet been well studied, such as the impact of visual accessibility, natural lighting, and water bodies on pedestrian walking speed. Thus, much remains to be researched about the complex relationship between the built environment and pedestrian walking speed.

Other steering mechanisms — Some research has been performed on the impact of other steering mechanisms on pedestrian walking speed. Prior research indicates that pedestrians decrease their walking speed under dimmed lighting conditions in two laboratory experiments (Choi et al., 2014; Pedersen and Johansson, 2018) and a Virtual Reality experiment (Duives et al., 2024). Kesler et al. (2005) also show that older pedestrians lower their gait when walking over pathways with almost no lighting. However, the field study of Donker et al. (2011) indicate that pedestrians

walk faster along dark pathways than along well-lit pathways. Regarding the light color, the state-of-the-art does not provide much information. Only Duives et al. (2024) find that pedestrians walk faster under colored light conditions than under normal light conditions. Here, they compared the walking speed of pedestrians between similar environments with white (i.e., normal), green, red, and blue colored lights. There was no significant difference in walking speed among the three colored light conditions.

In addition, there are some studies regarding the effects of aural stimuli (e.g., metronome or background music) on pedestrian walking speed. Styns et al. (2007) show that pedestrians walk faster when they synchronize to music than when they synchronize to simple rhythmic beats (i.e., metronome). For more realistic scenarios, in which pedestrians are clueless about the intention of the aural stimuli, pedestrians walk slower with background music than without at high densities, i.e., density ρ above 1.0 pedestrians per meter (Zeng et al., 2019, 2020). They also observe that there was no difference in pedestrian walking speed between both scenarios below this threshold. Also, Meng et al. (2018) show that the average walking speed of pedestrians on an urban square is lower with background music than without. Moreover, Franek et al. (2014) find that pedestrians increase their walking speed when exposed to fast and motivational background music, and pedestrians decrease their walking speed when exposed to slow and relaxing background music. Another study shows that pedestrians walk faster with traffic noises in the background than with relaxation sounds (Franek et al., 2018). In contrast to the effects of lighting conditions and aural stimuli, the impact of signage on pedestrian walking speed is unknown.

4.2 Effects on flow rate

Profiling the crowd — In contrast to the extensively studied relationship between pedestrian walking speed and the individual characteristics of pedestrians, only a few studies feature findings about the relationship between flow rate and these characteristics. The lack of research is surprising, given that walking speed and flow rate are directly related through a fundamental diagram (e.g., in Laxman et al. (2010), Ren et al. (2019), Sarkar and Janardhan (2001)).

Alhajyaseen et al. (2011) find that the maximum flow rate reduced with an increment in the age of the pedestrians at cross walks. Similarly, Daamen and Hoogendoorn (2012) show that there is a negative relationship between the average age of the crowd and the maximum flow rate through emergency doors. It is worth noting that both studies focus on the

maximum flow rate (i.e., the capacity of the environment), rather than the flow rate in general. Furthermore, research provides information regarding the impact of pedestrian stress levels on the flow rate. Daamen and Hoogendoorn (2012) show that the capacity of an exit is higher during an evacuation scenario than during normal scenarios. Also, Yang et al. (2012) show that both the flow rate and the capacity on stairways are higher during emergency conditions.

Some earlier studies have looked at the relationship between flow rate and social grouping. Moussaid et al. (2010) show that the flow rate reduces because of social grouping due to their 'non-aerodynamic' shape (i.e., V-pattern and U-pattern at higher densities). Flow rate is also lower in crowds with individuals and dyads than in crowds with only individual pedestrians for a bidirectional flow with densities above 0.5 pedestrians per square meter (Crociani et al., 2019). In contrast, the findings of Bode (2016) show that membership in a social group does not affect the flow rate in front of bottlenecks.

Profiling the environment — To the best of the authors' knowledge, the state-of-the-art studies do not provide findings regarding the climate's influence on flow rate. As literature clearly indicates a relation between climate and pedestrian walking speed (see Section 4.1), one would expect a direct relation between climate (e.g., temperature, precipitation, and other natural factors) and flow rate. The same holds true for the impact of smoke and reduced visibility on flow rate. Though numerous studies address their impact on individual walking speed and exit choice (e.g., in Fridolf et al. (2013), Ronchi et al. (2018)), the existing literature does not provide any research featuring the impact of smoke on the flow rate.

Built environment features — A wide variety of built environment features has been studied in relation to flow rate. Previous research has focused on the effects of corridor width (e.g., in Adrian et al. (2020), Jin et al. (2021)) and exit width (e.g., in Hoogendoorn and Daamen (2005), Ren et al. (2021), Wang et al. (2020)) on flow rate in different types of environment. Here, the exit width is often studied with controlled experiments at a bottleneck (Kretz et al., 2006, Seyfried et al., 2009, Tian et al., 2012). Specifically, Adrian et al. (2020) find that the flow rate is not affected by the corridor width in front of a bottleneck. The flow rate does increase with an increase in the exit door width (e.g., in Kretz et al. (2006), Seyfried et al. (2009), Tian et al. (2012)). Notably, Gwynne et al. (2009) point out that the flow rate is not only affected by the door width, but also by the design of the door (e.g., closing mechanism of the door). Also, Wang et al. (2020)

show that the flow rate is higher when the exit is located in the middle of a wall than in the corner. Another angle in relation to the flow rate and exits is studied by Zhao et al. (2020). They showed that the flow rate of the Love Parade disaster could have been improved by opening an additional exit.

Another body of studies focuses on the effect of corners on flow rate. These studies find that the angle of the corner influences flow rate (e.g., in Aghabayk et al. (2020), Dias et al. (2014), Dias and Sarvi (2016), Shiwakoti et al. (2011)). For instance, Dias and Sarvi (2016) find that the fundamental diagram of density-flow rate was similar for pedestrians walking along straight corridors or corridors with a 45° angle. They also show that flow rate decreases when the turning angle becomes larger than 45° in comparison to the straight corridor. That is, the fundamental diagram of a straight corridor does not apply to corridors with sharper angles.

Additionally, existing literature has investigated the impact of the merging process of two pedestrian flows (e.g., in Lian et al. (2017), Shi et al. (2016), Shiwakoti et al. (2015), Zhang et al. (2011)). In particular, the impact of the configuration of pedestrian infrastructure on flow rate. For instance, Shahhoseini and Sarvi (2019) show that the flow rate of merging streams is higher when the configuration of the infrastructure is symmetrical instead of asymmetric.

Previous studies also provide information regarding the impact of stairways on the flow rate (e.g., in Burghardt et al. (2013), Chen et al. (2010), Huo et al. (2016), Yang et al. (2012)). Both the influence of the slope of the stairs and the direction of movement on the stairs have been studied. Yang et al. (2012) observe variations in flow rate among stairs with different slopes, but they could not attribute the difference in flow rate to the slope of the stair due to the presence of other factors. However, other studies suggest that both the flow rate and the capacity decrease with increasing slope of the stairs (Burghardt et al., 2013; Graat et al., 1999). Regarding the direction of movement, the findings in the literature are inconclusive. Ye et al. (2008) show that the flow rate is higher on a descending stairway than an ascending stairway, while Chen et al. (2010) finds a slightly higher flow rate for an ascending stairway than for a descending stairway.

Altogether, state-of-the-art literature provides numerous studies regarding the impact of built environment features on pedestrian flow rate. Specifically, the influence of corridor and exit widths, corners and stairways on the flow rate has been studied intensively over the last couple of decades.

Other steering mechanisms — There is only a limited number of studies featuring the impact of other steering mechanisms (i.e., steering mechanisms considering the information or management of the DIM-ICE model). Two studies demonstrate that the flow rate improves by synchronizing the step frequency of pedestrians to a slower rhythmic beat (Ikeda et al., 2017; Yanagisawa et al., 2012). In a more realistic scenario (i.e., pedestrians were not asked to synchronize their step frequency with a rhythmic beat), Zeng et al. (2019) find that background music has a negative influence on flow rate for densities above 1 pedestrian per meter. Specifically, above this density level, flow rate is lower with music of 120 BPM (i.e., beats per minute) than with no music or music of 90 and 150 BPM (Zeng et al., 2020). Also, the type of background music can influence the flow rate. Motivational music can increase the flow rate, while non-motivational music can decrease the flow rate (Zeng et al., 2022). Notably, the impact of other steering mechanisms, such as informational (e.g., signage) and visual stimuli (e.g., lighting), on flow rate remains unknown.

4.3 Effects on pedestrian route choice behavior

Profiling the crowd — Previous research has especially studied the impact of age and gender on route choice behavior. Most likely because these can be easily recorded in experimental settings. Findings of Bernhoft and Carstensen (2008) and Hill (1982) show that young adults take more complex (e.g., a route with more turns) and dangerous routes (e.g., a path where cars are allowed to drive) than elderly. Another study shows that children and young adults chose differently when encountering a path with red-running lights; adults are more likely to follow the path with red-running lights (Künzer et al., 2020). Also, adults above 65 years are more likely to walk in routes with higher walkability (Brookfield and Tilley, 2016). Regarding the pedestrians' gender, findings show that females take both shorter and more complex routes than males (Hill, 1982; Liu et al., 2020). Also, the used strategy to find their way is different for both genders. Women are more likely to rely on landmark-based route information, while males are more likely to rely on global reference points (Lawton, 1994). Others have indicated that males have a better performance and accuracy in wayfinding strategy (Lawton and Kallai, 2002; Miller and Santoni, 1986; Ward et al., 1986). For elementary students, the gender does not affect their route choice (Chen et al., 2010). Notably, the motivation to follow a certain path is similar for both genders (Seneviratne and Morrall, 1985).

Literature also shows that the cultural background affects pedestrian choice behavior. Pedestrians originated from Japan and the UK have a left-handed tendency (Brscić et al., 2014), whereas pedestrians from other European countries and the USA prefer to walk on the right side (Corbetta et al., 2016). Also, the findings of van Beek et al. (2024b) and Taylor and Socov (1974) suggest that pedestrians prefer to follow the right path at a T-intersection in the Netherlands and the USA. In addition, pedestrians rely on their experiences. Specifically, pedestrians tend to use 'familiar' exits during evacuations. Here, a 'familiar' exit is either the exit they entered the building through or the exit they knew from prior knowledge (Benthorn and Frantzich, 1999; Kinateder et al., 2018). In contrast to most individual characteristics of pedestrians, the literature does not provide insights regarding the relationship between the educational background of pedestrians and their route choice behavior.

Next to all these characteristics, research shows that pedestrian route choice is affected by the stress levels of pedestrians. Pedestrian are more likely to choose the nearest exit and take the shortest route to the exit during evacuation scenarios (e.g., in Fang et al. (2010, 2020), Feng et al. (2022), Kobes et al. (2010a)). Pedestrian also tend to follow routes without vertical movement if possible during these evacuation scenarios (Lin et al., 2020b; Shiwakoti et al., 2017).

Although some studies have shown that social influences affect pedestrian route choice, there is not much known with respect to the influence of group size on pedestrian route choice. While the following studies are not within the scope of this chapter, they have been included in the literature overview due to their potential use for crowd operators. Kinateder and Warren (2021) suggests that three types of social influence play a role in pedestrian exit choice during evacuation. Firstly, the well-known leader-follower behavior, i.e., pedestrians are likely to follow both their neighbor and the majority of the crowd (e.g., in Feng et al. (2021), Kinateder et al. (2018), Moussaid et al. (2016), Nilsson and Johansson (2009)). Secondly, pedestrians tend to avoid exits with congestion (Guo et al., 2012; Haghani and Sarvi, 2019; Lovreglio et al., 2016a). Lastly, pedestrians prefer to avoid exits that nobody is using (Lovreglio et al., 2016b). It is worth noting that these studies are not incorporated in Table 1.

Profiling the environment — Little literature studies the impact of the climate on pedestrian choice behavior in outdoor environments. State-of-the-art indicates that there is a distinct relation between climate and activity choice. The pedestrian volume (i.e., the number of pedestrians per time period) is

affected by both the temperature and the precipitation, especially during the winter months (Aultman-Hall et al., 2009; Fishman et al., 2015; Miranda-Moreno and Lahti, 2013). However, these studies are outside the scope, and therefore, excluded from the overview in this chapter.

In contrast to the climate, state-of-the-art studies contain insights regarding the impact of smoke on pedestrian route choice in indoor environments. An experimental study in a hotel shows that smoke drives pedestrians toward the nearest exit (Kobes et al., 2009, 2010a). Other studies indicate that pedestrian choice behavior is affected by smoke and fire, as pedestrian prefer to avoid both of them (Fang et al., 2020; Fu et al., 2021b, 2021c). Furthermore, pedestrians are likely to walk along the walls of smoke-filled tunnels during evacuations (Frantzich and Nilsson, 2004; Fridolf et al., 2013; Jin, 2002; Ronchi et al., 2018). Guo et al. (2012) find similar behavior during an evacuation drill conducted in a classroom.

Built environment features — Numerous studies show the impact of built environment features on pedestrian route choice. The geometrical layout of corridors influences pedestrian route choice, as pedestrians prefer to take wider paths over narrower one (Feng et al., 2019; Vilar et al., 2013, 2014) and to follow a corridor with longer line of sight (Frankenstein et al., 2012; Wiener et al., 2012). The local route choice of pedestrians is also affected by objects in the corridors, such as walls and obstacles. Pedestrians maintain a certain distance from both the walls of the corridor (e.g., in Bosina et al. (2016), Habicht and Braaksma (1984), Ma et al. (2010), Moussaid et al. (2009)) and the obstacles in the corridors (e.g., in Bosina et al. (2016, 2020), Chen et al. (2019), Jia et al. (2020)) in order to avoid collisions. They also show that the impact of the obstacle on pedestrian locomotion varies across different types and configurations of obstacles. For instance, the effect of small-scale obstacles (e.g., benches and advertisement boards) is relatively small in comparison to the large-scale obstacles, such as pillars (Bosina et al., 2020). Even the facade of the building can deviate the pedestrians' path (Sun et al., 2021). Liu et al. (2020) show that the pedestrian route choice is strongly influenced by the 'larger' built environment, such as exhibitions and shops, at big events.

Others have looked into the pedestrian wayfinding strategy, which is a more global route choice. Literature shows contradicting findings regarding the pedestrian wayfinding strategy in multi-story buildings, where pedestrians had to use stairs along their route. (van Beek et al., 2024a; Feng et al., 2022; Hölscher et al., 2006a) observe that a pedestrian prefers the so-called 'floor strategy', i.e., they initially move toward the floor level of their

destination. However, other findings suggest that pedestrians prefer the 'direction strategy', i.e., they start walking to the horizontal position of their destination before changing floors (Büchner et al., 2007; Hölscher et al., 2009).

Other steering mechanisms — State-of-the-art provides a few studies focusing on the impact of lighting on pedestrian route choice. Prior research suggests that the brightness of lighting influences the pedestrian route choice in two Virtual Reality experiments (van Beek et al., 2024b; Vilar et al., 2014), one controlled experiment (Taylor and Socov, 1974), and one field experiment Feliciani et al. (2024). They all show that pedestrians prefer to follow a path with brighter light conditions over one with dimmed conditions. Here, the influence of light brightness has been studied on path choice (van Beek et al., 2024b; Taylor and Socov, 1974; Vilar et al., 2013) and exit choice (Feliciani et al., 2024). Their findings are in contrast to the findings of an experiment at a light festival in the Netherlands, which has been described in Buikstra (2021). Regarding the influence of light color on pedestrian route choice behavior, Künzer et al. (2020) show that pedestrians, especially adults, tend to follow green-running lights into the direction indicated by the lights in a metro station. A similar result is found in van Beek et al. (2024b), in which the findings indicate a strong preference for a green-lit path within a virtual maze. The participants in their study also tend to avoid red-lit paths. Similarly, green-flashing lights can influence the pedestrian exit choice positively in evacuation scenarios (Nilsson et al., 2008).

Furthermore, a distinct relation between pedestrian route choice and signage is presented in the literature. Pedestrian route and exit choice are positively affected by different types of signage, i.e., pedestrian often follow the path or exit that is being directed by the signage (e.g., in Duarte et al. (2014); Feliciani et al. (2024); Filippidis et al. (2009); Galea et al. (2014); Nilsson et al. (2008); Rousek and Hallbeck (2011)). Differences in the effect of the signage on the pedestrian choice behavior has been found for various types of signage. Dynamic signage is observed and followed more often by pedestrians than static signage (Duarte et al., 2014; Galea et al., 2014). Here, the dynamic signage features lit, flashing and running lights within an emergency exit sign, whereas the static signage is the standard emergency exit sign without any lights. In addition, signage is considered clearer when humanoid images are used on it (Rousek and Hallbeck, 2011). Another method is to direct pedestrians toward a certain exit with arrows on LED screens (Feliciani et al., 2024).

State-of-the-art literature also shows a relation between pedestrian route choice behavior and information provision by the crowd operators. Information provision varies from static information, such as city maps and information booklets, to dynamic information, such as verbal communication by operators or smartphone notifications (Zomer et al., 2015). Their findings indicate that WhatsApp notification and LED screens were most effective in adapting and confirming location choice behavior. In addition, research shows that pedestrians comply with verbal information when evacuating that has been provided through a broadcast (Xia et al., 2021). Their findings indicate that pedestrians change their route choice based on the provided information, even when their spatial knowledge is in contrast with the provided information. Zomer et al. (2015) highlight that pedestrians might misinterpret the information.

4.4 Effects on pedestrian wayfinding performance in normal scenarios

Profiling the crowd — Research has been performed regarding the influence of individual characteristics on pedestrian wayfinding performance. With respect to the age of pedestrians, the wayfinding performance is better for younger adults than for older adults (Lee and Kline, 2011; Taillade et al., 2013; Wang et al., 2018). Additionally, younger pedestrians have a better wayfinding performance in terms of route learning, while older pedestrians do better in terms of recalling landmarks (Head and Isom, 2010; Lee, 2010). Moreover, earlier research shows that males have a better wayfinding performance than females (e.g., in Allen and Hogeland (1978), Chen et al. (2009), Malinowski and Gillespie (2001)). However, others indicate that the wayfinding performance in terms of the use of landmarks, self-location, route memorization, and route following is similar for male and female pedestrians in indoor environments (e.g., in Harrell et al. (2000), Wang et al. (2018)). In contrast to the age and gender of pedestrians, there are no studies featuring the impact of cultural and educational background on the pedestrian wayfinding performance in the state-of-the-art.

Some studies focus on the impact of spatial knowledge, or familiarity with the environment, on pedestrian wayfinding performance. All of them find that spatial knowledge positively influences wayfinding performance, i.e., pedestrians with more spatial knowledge have a better performance (e.g., in Chebat et al. (2005), Ewart and Johnson (2021), Iachini et al. (2009), Lin et al. (2019), O'Neill (1992)). For example, the wayfinding performance of pedestrians improved significantly when repeatedly exposed to the same

environment (Lin et al., 2019). Furthermore, pedestrian wayfinding performance is worse when the 'stress levels' of pedestrians are increased. Thus, the wayfinding performance is worse (e.g., slower egress times) for pedestrians in evacuation scenarios than in standard ones (Cao et al., 2019; Feng et al., 2022; Lin et al., 2019; Meng and Zhang, 2014).

Moreover, social groups seem to have an influence on pedestrian wayfinding performance (Bode et al., 2015; Bode, 2016; Köster et al., 2011). Social groups have lower egress times compared to individual pedestrians (Bode et al., 2015; Köster et al., 2011). This is caused by slower pre-movement times for social groups at the start of an evacuation, and by taking longer to reach an exit (Bode et al., 2015). However, the findings of the two experiments in Bode (2016) are inconclusive where one experiment shows slower egress times for individuals, while the other experiment shows the opposite. They suggest this contradiction might be influenced by the learning effect of the participants, that is, participants egress faster when running the experiment for the second time. The authors want to highlight two overviews featuring pedestrian wayfinding performance. Hu and Bode (2023) present a comprehensive overview with respect to the influence of group size on the egress time, whereas Dalton et al. (2019) focus on pedestrian wayfinding performance from a broader perspective.

Profiling the environment — To the author's knowledge, existing literature does not provide any studies featuring the influence of climate on pedestrian wayfinding performance.

Built environment features — Pedestrian wayfinding performance has been extensively studied in various types of infrastructures. These infrastructures include, but are not limited to, mazes (Goldiez et al., 2007; Shi et al., 2021), healthcare facilities (Kalantari et al., 2022; Pouyan et al., 2021), library (Kuliga et al., 2019), conference centers (Hölscher et al., 2006a, 2006b) and university buildings (Feng et al., 2022; O'Neill, 1991). Though there is an abundance of studies featuring pedestrian wayfinding performance, there are fewer studies pinpointing the cause of potential differences between the different types of infrastructures.

Earlier research does show that visual accessibility of the space influences pedestrian wayfinding performance. Natapov et al. (2022) find that wall transparency positively affected wayfinding performance, but only when pedestrians were still constructing their initial route. Furthermore, findings of Lee (2010) show that wayfinding performance was enhanced with architectural wayfinding features, such as wall colors, doors, and logos. Other significant factors in wayfinding performance are the number of

floors (Feng et al., 2022; Hölscher et al., 2006b; Kuliga et al., 2019) and floor complexity (O'Neill, 1991).

Other steering mechanisms — There is only one study featuring the impact of lighting on pedestrian wayfinding performance. Suzer et al. (2018) find that the wayfinding performance is similar for three different white-colored lights in terms of travel time and number of errors. Though the number of hesitations is different for each light condition, the number of hesitations decreased when the correlate color temperature increased from 3000 K to 12000 K (i.e., from yellowish-white to blueish-white). Further than that, the literature does not provide studies featuring the impact of lighting and aural stimuli.

Pedestrian decision-making is positively affected by the presence of signage, i.e., pedestrians tend to move in the direction that is directed by the signage (e.g., in Rousek and Hallbeck (2011)). While the relation between pedestrian egress time and signage has been studied more frequently in evacuation scenarios (e.g., in Duarte et al. (2014)), it is not the case for pedestrian wayfinding performance in normal conditions. For normal conditions, a single study has been found showing that signage improved pedestrian wayfinding performance under normal conditions O'Neill (1991).

4.5 Effects on wayfinding performance in evacuation scenarios

Profiling the crowd — Though the literature review already shows distinct influences of both the age and gender of the pedestrian wayfinding performance in normal conditions, there are limited studies regarding individual characteristics of pedestrians in evacuation scenarios. Findings of Fang et al. (2020) showed that younger, male and higher-educated individuals have a better wayfinding performance in terms of evacuation time compared to older, female and lower-educated individuals in a virtual square room with multiple obstacles. In addition, there is no difference in wayfinding performance in terms of evacuation time between children between the ages of 11 and 15 years old (Vanumu et al., 2020). Regarding the cultural background, Lin et al. (2020b) find that the wayfinding performance was similar in three cultures; Chinese, American, and English. In addition, pedestrians also demonstrated improved wayfinding performance during evacuations when they had pre-existing spatial knowledge of the building (Lin et al., 2020a).

Laboratory experiments indicate that pedestrian wayfinding performance in terms of egress time depends on the group size. Crowds composed of smaller groups of 2 or 3 pedestrians have slower egress times than a crowd of individuals (Bode et al., 2015; Haghani and Sarvi, 2019; Lu et al., 2017). However, when considering groups of 4 or more pedestrians, the egress time becomes faster in comparison to crowds composed of individuals (Cuesta et al., 2021; Haghani et al., 2019; Von Krüchten and Schadschneider, 2017). Additionally, the findings of Xie et al. (2020) indicate that the influence of group size on the egress time differs for different visibility levels. Social groups have slower egress times than individuals when normal visibility is considered, however, these groups have faster egress times with lower levels of visibility. Meanwhile, other studies show pedestrian wayfinding performance is affected by social influence in terms of leader-follower behavior during emergency conditions (e.g., in Fu et al. (2021b, 2021c); Kinateder et al. (2014); Lin et al. (2020b)).

Profiling the environment — Yet, wayfinding performance in evacuation scenarios is not studied in relation to the impact of climate. The impact of smoke has been considered in the literature, though not by many, as most studies focus on the individual walking speed. Research shows that the presence of smoke reduces the wayfinding performance in terms of egress time (Kobes et al., 2010a). The findings of Xie et al. (2020) show slower egress time when the visibility of participants is reduced in emergencies, although they did not use smoke within the laboratory experiment. They use eye patches to simulate the vision loss caused by smoke.

Built environment features — The state-of-the-art literature presents various built environment features that affect pedestrian wayfinding performance in evacuation. Lin et al. (2020b) showed that pedestrians tend to follow hallways rather than stairs when directional information, such as signage and crowds, are excluded from the environment. It has also been found that pedestrians tend to find their way, especially based on vertical outdoor light, ascending stairs, and doorways during evacuations (Sun, 2009). In addition, the wayfinding performance in terms of evacuation time is also positively impacted by the width of the door (Vanumu et al., 2020), width of the corridors (Vilar et al., 2013, 2014) and the walls of the environment (Fridolf et al., 2013).

Steering mechanisms — There are barely any studies focusing on the impact of both visual and aural stimuli on pedestrian wayfinding performance in evacuation scenarios. Only the findings of Kinkel et al. (2017) indicate that the wayfinding performance in terms of the egress time is negatively influenced by darkness.

The influence of signage on pedestrian wayfinding performance in evacuation scenarios is studied more often, in contrast to its impact on wayfinding performance in normal conditions. All findings agree that the wayfinding performance improves when signage is present in the pedestrian infrastructure (e.g., in Duarte et al. (2014), Fridolf et al. (2013), Kinkel et al. (2017), Tang et al. (2009), Tucker et al. (2018)). In addition, information provision helps pedestrians, and especially wheelchair users, to make the correct decision regarding the route choice, leading to fewer mistakes and a lower egress time (Feliciani et al., 2020). The pedestrian egress time also decreases when verbal information is provided when evacuating (Tucker et al., 2018).

5. An overview of the state-of-the-art

Section 4 presents an overview of the literature, highlighting the state-of-the-art knowledge concerning the relationship between pedestrian choice behavior and movement dynamics with the profiling factors, as well as with the steering mechanisms. Specifically, the factor-behavior pairs that fall within the definitions that are introduced in Sections 2.1, 2.2, and 2.3. To provide crowd operators with an overview of the literature, this section organizes the reviewed literature according to the systematic structure in Table 2 and integrates it to Table 3. This table

Table 3 An overview of literature regarding the factor-behavior pairs within identified literature. Here, the numerical identifiers refer to the references in Appendix A. Symbol * means that there are more studies regarding the specific factor-behavior pair, whereas ∧ indicates that one or more studies are related to the impact on the pedestrian capacity (i.e., the maximum flow rate). This overview accounts for five distinct types of factor-behavior pairs: (1) positive influence (green cells), (2) negative influence (red cells), (3) no influence (yellow), (4) inconclusive influence (magenta cells), and (5) other influence (cyan cells).

	Classification	WS	FR	RC	WP	WPe
Profiling factors	Age (older)	1-4 (∗)	13; 39 (∧)	49-52	83-86 (∗)	63; 103
	Gender (males)	5-8 (∗)		52-55 (∗)	86-89 (∗)	63
	Cultural background (Asian)	4; 9-11 (∗)		56-59		104
	Educational background (higher)					63
	Spatial knowledge (increasing)			60-61	90-93 (∗)	105
	Stress level (-)	12-15	13-14	62-65 (∗)	64; 93-95	
	Grouping (-)	2; 16-18 (∗)	16; 40-41		40; 96-97	106-109 (∗)
	Climate (-)	19-22 (∗)				
	Smoke or fire (-)	23-26		66-69 (∗)		26; 66
Steering mech.	Built environment features	27-30 (∗)	42-44 (∗,∧)	70-73 (∗)	64; 98-100 (∗)	68; 103-104; 110 (∗)
	Lighting' brightness (higher)	31-34 (∗)		58-59; 74-75 (∗)		111
	Lighting' color (-)	32		51; 58; 76	101	
	Aural stimuli (-)	35-38	38; 46-48			
	Signage (-)			77-80 (∗)	102	68; 77; 112-113 (∗)
	Other information provision			81-82		113-114

serves as a structured overview to summarize the literature for the factor-behavior pairs within the scope of this study. It highlights the effects of both the profiling factors and the steering mechanisms on the different types of pedestrian choice behavior and movement dynamics, including pedestrian walking speed, flow rate, route choice behavior, wayfinding performance in normal conditions, and wayfinding performance in evacuation conditions.

To facilitate a better understanding of the overview in Table 3, baseline conditions are added in brackets next to the factors. They specify how these factors should be interpreted in relation to the different types of pedestrian choice behavior and movement dynamics. For instance, the word 'older' in brackets behind the factor 'age' indicates that the focus of the relation should be on the impact of increasing age when examining the factor-behavior pair. That is, the different types of pedestrian choice behavior and movement dynamics of older pedestrians are compared to those of younger ones. Similarly, the word 'Asian' in brackets behind the factor 'cultural background' emphasizes that one should consider the impact of Asian pedestrians on the pedestrian choice behavior and movement dynamics relative to those from other continents. For example, the pedestrian walking speed of Asian pedestrians in comparison to the walking speed of European or American pedestrians. Notably, the stripe in brackets next to the factors indicates that it is about the presence of that specific factor.

Table 3 has three main purposes, which were introduced in Section 3.3. Firstly, to indicate that quantitative information exists in literature regarding a factor-behavior pair. When the cell of a factor-behavior pair is empty (i.e., a white cell without any textual content), it means the corresponding factor-behavior pair has not been established in the state-of-the-art literature. All not-empty cells indicate that some types of relationship of the respective factor-behavior pair have been established. This leads to the second function of Table 3, which is specifying the nature of each relationship. This overview classifies five different types of factor-behavior pairs, each visualized in a different color. A green-colored cell represents a positive impact of a particular 'factor' (i.e., a distinct profiling factor or steering mechanism) on a 'behavior' (i.e., a specific type of pedestrian choice behavior and movement dynamics), meaning that the behavior will increase or improve when the specific factor is implemented or increased. On the other hand, a red-colored cell indicates a negative impact of a factor on the behavior, meaning that the

behavior will decrease or deteriorate when the specific factor is implemented or increased. When the cell is yellow-colored, it means the factor does not impact that type of pedestrian behavior, i.e., the type is insensitive to that specific factor. A magenta-colored cell denotes that no clear statement can be drawn regarding the factor-behavior pair due to inconclusive results in the literature (e.g., both a positive and negative effect have been established in literature). Lastly, the cyan-colored cell indicates a distinct relation between the dynamic and the factor, although the relationship is not necessarily positive or negative. These classifications of the factor-behavior pairs allow for a more structured overview of the state-of-the-art literature.

The third purpose of the overview is to provide the scientific studies featuring the specific factor-behavior pairs. For each factor-behavior pair, the overview indicates which studies feature that relationship. All studies that have been integrated into the overview are allocated with a numerical identifier. The legend of these identifiers is presented in Appendix A. Moreover, this overview allows for a maximum of four studies per factor-behavior pair. If Section 4 includes more than four studies for a single factor-behavior pair, this abundance is indicated with the symbol *. Additionally, this overview denotes the deviation of the flow rate with the symbol ∧, meaning that some studies look at the impact of a factor on the maximum flow rate (i.e., the capacity) of the pedestrian infrastructure, rather than the flow rate.

The overview in Table 3 features the term 'built environment features' as one of the steering mechanisms. This term is adopted to identify all characteristics of the built environment that have been found to influence pedestrian choice behavior and movement dynamics. These features vary from static (i.e., non-movable) to dynamic (i.e., moveable) obstacles in the environment through which the pedestrians move. These include, but are not limited to static elements such as walls, doors, fences, stairs, and facades, as well as dynamic obstacles like fences and dynamic gates. These built environment features can be part of an outdoor and an indoor pedestrian infrastructure. Given the wide range of built environment features, the authors decided to accumulate the findings of all features into a single overarching influence to simplify the overview. This overarching term indicates whether the built environment can influence specific types of pedestrian behavior. Readers are referred to Section 4 when they require the effect of a specific built environment feature.

6. Discussion on the challenges for future crowd management research

The overview in Table 3 aims to (1) determine whether factor-behavior pairs are established in the existing literature, (2) identify the nature of this relationship, and (3) provide the studies that have empirically examined it. This section focuses on the relationships that are included in that overview, or in other words, it discusses the reviewed literature. This discussion is based on identified challenges for future crowd management research. Each of these challenges is discussed in its own section, with each section aiming (1) to summarize the findings within the overview, (2) to identify the challenge for crowd management research, and (3) to indicate the importance for crowd operators.

The potential research directions and challenges for crowd management studies are determined based on the overview in three ways. Firstly, the systematic overview identifies 29 empty cells, indicating that the respective factor-behavior pairs have not been established in the state-of-the-art literature. Secondly, the magenta-colored cells indicate that the state-of-the-art provides inconclusive findings regarding the particular factor-behavior pair (e.g., studies present findings that contradict each other). Table 3 shows six inconclusive factor-behavior pairs. Lastly, all cells without the symbol * shows there has been little research on that factor-behavior pair. Although the factor-behavior pair has been shown by one to four studies, the relationship needs more research to validate these findings. All three approaches will identify challenges for future crowd management research, however, not all of them are as relevant. Some factor-behavior pairs are less interesting from a scientific perspective, whereas some are less essential to crowd operators.

To this end, three challenges have been identified by the authors. The first challenge is about the steering mechanisms and their influence on pedestrian choice behavior and movement dynamics. The overview identifies that particular steering mechanisms are able to influence distinct types of pedestrians behavior, yet, many corresponding factor-behavior pairs are either not established or only examined from one perspective. Section 6.1 provides a discussion on these steering mechanisms by summarizing the established factor-behavior pairs and highlighting other pairs that require further study. Secondly, the second challenge is to study all types of crowds in future crowd management research. Therefore, the influence of the crowd's profile is discussed in Section 6.2. Specifically, the

effect of individual characteristics of pedestrians on the pedestrian choice behavior and movement dynamics will be discussed, highlighting both established and missing factor-behavior pairs. Thirdly, the overview identifies the lack of relation featuring the flow rate. This might be an issue, as the crowd flow rate is a commonly used property to manage crowds by crowd operators. Thus, the third challenge is to identify the effects of crowd management strategies on flow rate, and is discussed in Section 6.3. These challenges have been identified, as they are relevant for both researchers and crowd operators. Among these challenges, the first one is directly associated with the objective of this chapter, while the second is related to the profile of the crowd. The last challenge is discussed due to their relevance for crowd operators.

This discussion section is closed with an intermezzo, briefly deviating from the challenges for crowd management research. The authors want to emphasize the importance of case studies, in which multiple factors coherently influence pedestrian choice behavior and movement dynamics. This is briefly discussed in Section 6.4.

6.1 Challenge 1: Steering mechanisms are in its infancy

Crowd management strategies are of utmost importance to manage pedestrian flows efficiently in various environments. These strategies are already employed by crowd operators within their pedestrian infrastructures, often using specific steering mechanisms to guide the crowd. Although particular strategies have been shown to influence crowd dynamics within real-life environments, they are often employed without knowing the quantitative influence of each strategy. The effectiveness of these crowd management strategies can be improved by providing crowd operators with this quantitative relationship, such that they can utilize it in their pedestrian infrastructures.

This literature review identifies whether the effects of steering mechanisms on pedestrian choice behavior and movement dynamics are established, and if so, they are briefly reported. These steering mechanisms are commonly employed as a strategy to manage crowds. The reviewed literature indicates that each steering mechanism influences a particular type of pedestrian choice behavior and movement dynamics. However, it also indicates that certain factor-behavior pairs are either not validated by multiple findings or not studied at all. In order to systematically summarize the effects of the steering mechanisms on pedestrian choice behavior and movement dynamics, the steering mechanisms are reviewed and discussed one by one.

Firstly, the overview in Table 3 shows an abundance of studies on the effect of built environment features on pedestrian choice behavior and movement dynamics. This highlights the importance of profiling the existing pedestrian infrastructure and considering changes to the built environment as a strategy for crowd management. Readers are referred to Section 4 for a specific built environment feature.

Secondly, the overview shows that both the lighting brightness and lighting color influence pedestrian route choice. Specifically, the pedestrian route choice is positively affected by both well-lit paths and paths with green-colored paths. For now, crowd operators should notice these qualitative trends, rather than the quantitive details. The quantitative influence of lighting on pedestrian route varies between the different studies, which suggests that the effectiveness of light conditions is affected by its surroundings and the crowd navigating. In addition, the overview indicates that there are inconclusive findings regarding the effect of the lighting brightness on pedestrian walking speed. Some studies showed that pedestrians walked slower in dimmed conditions, while another research found the opposite. Again, the findings suggest that certain variables are affecting the relationship between lighting brightness and pedestrian walking speed. In contrast to the effects of lighting on pedestrian walking speed and pedestrian route choice, the relationship between lighting and pedestrian wayfinding performance is still missing from the state-of-the-art literature. Although lighting might play a crucial role in reducing egress time (e.g, by enhancing visibility of signs), little is known about the impact of ambient lighting on the pedestrian wayfinding performance. Overall, this highlights the need for further research: (1) to understand how light conditions influence pedestrian choice behavior and movement dynamics, and (2) to examine how the effectiveness of these influences varies across different types of crowds and environments. This is especially important, as lighting is an interesting steering mechanism for crowd operators. Managing crowds with lighting is cost-effective, easy to adopt within existing pedestrian infrastructure and offers a high degree of flexibility in its implementation, given that it is already present in most infrastructures.

Thirdly, the overview shows a relationship between aural stimuli and two types of pedestrian choice behavior and movement dynamics. Previous studies have shown that different aural stimuli (i.e., rhytmic beats, background music, and traffic noises) influence both pedestrian walking speed and flow rate. However, these findings are not validated with multiple studies. In addition, the relationships of aural stimuli with both the

pedestrian route choice and pedestrian wayfinding performance have not been established in the reviewed literature. Overall, more research is required regarding the effects of aural stimuli on pedestrian choice behavior and movement dynamics, such that crowd operators can employ crowd management strategies based on flow rate.

Lastly, the overview provides two established relationships with respect to signage and any other method of information provision. In particular, the presence of signage or other information provision positively affects both the pedestrian route choice behavior and the wayfinding performance in evacuation scenarios. Crowd operators can use these steering mechanisms to guide pedestrians into specific directions within their environments. Although the influence of information (e.g., signage) on the pedestrian walking speed and the flow rate remains unexplored, it is less interesting as the primary function of providing information is to help pedestrians navigate through the environment (i.e., influencing route choice behavior and wayfinding performance).

In conclusion, although crowd management strategies are often used in practice, the scientific literature is still in its infancy. While some studies provide quantitative arguments for specific crowd management strategies, more research is required to fully understand the effect of each strategy on pedestrian choice behavior and movement. This remains highly challenging due to the codependency between crowd management strategies and the infrastructure. Other elements influence the effectiveness of crowd management strategies. Crowd operators can use the state-of-the-art literature to identify suitable crowd management strategies, however, their decision to employ a specific strategy should not be based solely on it. For now, the state-of-the-art literature is not able to give quantitive relationships regarding the effects of steering mechanisms.

6.2 Challenge 2: Studying more individual characteristics of pedestrians

Profiling the crowd is an essential step before employing any steering mechanism as a strategy to manage the crowd. This overview includes the individual characteristics of the pedestrians that are directly observable in a crowd, or at least can be accurately estimated. The overview identifies numerous established relationships between the individual characteristics of pedestrians and their choice behavior and movement dynamics. The effects of age have been established on pedestrian walking speed and pedestrian wayfinding performance. Older adults walk slower and have worse

wayfinding performance compared to young adults. Additionally, males walk faster, make different route choices, and have mostly a better wayfinding performance than females, highlighting the effect of gender on pedestrian walking speed, route choice, and wayfinding performance. The cultural background of pedestrians also affects the pedestrian walking speed.

Despite all these established relationships, challenges remain in providing crowd operators with a more complete overview. The overview exposes different factor-behavior pairs that have either been explored in a few studies or not at all. Notably, the influence of individual characteristics on pedestrian wayfinding performance in evacuations is barely studied. This indicates that the state-of-the-art provides limited information on how specific groups (e.g., elderly crowd) behave in emergency scenarios. This lack in itself is already a research direction for future research. However, within this section, two other challenges regarding the individual characteristics are discussed. Both challenges are important to consider when reviewing the literature.

Firstly, the overview indicates that there is little studies featuring the impact of educational background on pedestrian choice behavior and movement dynamics. The findings of Fang et al. (2020) show that higher-educated pedestrians have a better ability to escape during a virtual evacuation compared to lower-educated pedestrians in terms of lower evacuation times. However, there are no other studies either validating this finding or demonstrating an impact of educational background on another type of pedestrian choice behavior and movement dynamics. One of the challenges of crowd management research is to study the effect of pedestrians' educational background on the different types of pedestrian choice behavior and movement dynamics. This is important as most laboratory students within pedestrian research are performed with university students, highlighting the importance to understand the effects of educational background on pedestrian choice behavior and movement dynamics.

Secondly, this section addresses a challenge not explicitly mentioned in the overview or literature review, but one that should still be considered. The majority of studies are conducted with young adults in good physical conditions, giving rise to a limitation in the state-of-the-art.

Firstly, the majority of studies are conducted with young adults in good physical conditions, giving rise to a limitation in the state-of-the-art. As crowd operators need to design safe environments satisfying the needs of a diverse population, knowledge of the pedestrian behavior of these

populations needs to be provided. For example, the pedestrian behavior of children, the elderly, and people with disabilities needs further study in order to design safe environments close to schools, nursing homes and special care facilities. By conducting these studies, architects can have a better understanding of how to design environments that satisfy the needs of all individuals within that environment. It should be noted that literature already provides some studies featuring children (e.g., in Biassoni et al. (2018), Künzer et al. (2020)), elderly (e.g., in Lee (2010), Ren et al. (2019)), and disabled people (e.g., in Fu et al. (2021a), Sharifi et al. (2017)). However, more studies are required to establish their relationships with the different types of pedestrian choice behavior and movement dynamics. Furthermore, there is a need to investigate the relationship between types of crowds (e.g., football hooligans and festival visitors) and pedestrian choice behavior and movement dynamics.

6.3 Challenge 3: Identifying the effects of crowd management strategies on flow rate

Crowd operators often use flow rate to determine how efficient their infrastructure is in managing the crowd. Therefore, it is essential to provide them with sufficient information regarding the flow rate, particularly how specific steering mechanisms, profiles of the crowd, and profiles of the environment influence it. Table 3 indicates that only three profiling factors and two steering mechanisms have been studied in relation to the flow rate. Yet, none of these relationships have been validated with multiple findings. This highlights the lack of studies regarding the effects of both profiling factors and steering mechanisms on crowd flow rate. In order to provide crowd operators with essential information and a more complete overview, future crowd management research should focus on flow rate as one of its research endeavors.

In traffic engineering, there are three metrics strongly correlated in the fundamental diagrams, namely density, walking speed, and flow rate (e.g., in Laxman et al. (2010), Rastogi et al. (2013), Sarkar and Janardhan (2001), Weidmann (1993)). While the influence of age, gender and cultural background on pedestrian walking speed has been established, there is little known about the effect of these characteristics on flow rate. For instance, while numerous studies show that the pedestrian's age influences their walking speed, a similar effect is expected for flow rate because of the flow-speed relationship in the fundamental diagram. However, two studies show that increasing age decreases both the flow rate and the capacity within the

environment. This indicates that the influence of a certain factor – either a profiling factor or a steering mechanism – on the pedestrian walking speed is rarely used to study its influence on the flow rate as well.

6.4 Intermezzo: Case studies consistently include different effects

The overview in Table 3 shows the wide variety of 'factors' that affect pedestrian choice behavior and movement dynamics. Here, the term 'factors' include different types of steering mechanisms and any property to profile the crowd or environment. However, these factors are often examined in isolation, whereas in real-life scenarios, all these factors are intertwined, leading to a complex interaction between different profiling factors and steering mechanisms shaping the pedestrian choice behavior and movement dynamics. The transition from laboratory and VR experiments to real-life scenarios rise two important questions. Firstly, can one accurately pinpoint the underlying cause driving the observed pedestrian behavior within an environment? In other words, can one determine which factors have the most significant impact on pedestrian behavior in that particular environment? This information can help crowd operators manage crowds efficiently within their environment. Secondly, which profiling factors influence the effectiveness of different steering mechanisms? In other words, which steering mechanisms are effective for one specific crowd but ineffective, or less effective, for another? This is essential information for crowd operators to ensure that they do not employ unsuitable crowd management strategies.

These questions are challenging to answer, yet, they are crucial to fully understanding the relationships between the profile of the crowd, the profile of the environment, and the steering mechanisms. Although laboratory and VR experiments show interesting results regarding the effects of crowd management strategies on pedestrian choice behavior and movement dynamics, they often reduce the variables that might influence pedestrian behavior to maintain control. That is, they often exclude the complex interaction between different profiling factors and steering mechanisms. These complex interactions are only present within case studies, which are defined as a research method to study the influence of crowd management strategies on pedestrian behavior within real-world environments. Thus, studies that implement crowd management strategies in existing pedestrian infrastructures, and analyze the effects of these strategies on the pedestrian choice behavior and movement dynamics.

It would be interesting to conduct more of these case studies in future crowd management research. Also, a database of different case studies featuring crowd managements is highly recommended, including the implemented crowd management measure (e.g., implementation of signage to influence exit choice), details of that implementation (e.g., the signs feature flashing lights), the profile of the crowd (e.g., mostly young adults), profile of the environment (e.g., temperature is 10 °C), and a description of the built environment (e.g., a station hall). This way, crowd operators can directly learn from case studies with similar environments, and maybe even employ similar crowd management strategies as in these studies.

7. Summary

This chapter provides a literature review aiming to inform crowd operators with respect to the effects of crowd management strategies on different types of pedestrian choice behavior and movement dynamics. Crowd management strategies are defined as the deployment of steering mechanisms to manage and control the crowd within a given environment. As it is essential to know the characteristics of the crowd and the environment before employing any steering mechanism, the literature review also includes how the profile of the crowd and the environment features influence pedestrian choice behavior and movement dynamics. Specifically, this chapter presents the effects of the profiling factors and the steering mechanisms on pedestrian walking speed, crowd flow rate, pedestrian route choice behavior and pedestrian wayfinding performance. In order to collectively assess the reviewed literature, this chapter includes an overview of the factor-behavior pairs, namely relationships between the profiling factors, steering mechanisms and pedestrian choice behavior and movement dynamics. This overview aims to identify the existence of a factor-behavior pair, characterize the nature of that relationship, and reference the studies that examine them.

The overview demonstrates the opportunity to use particular steering mechanisms to manage crowds within a given environment. Built environment features are a highly effective measure to affect pedestrian choice behavior and movement dynamics, highlighting the importance of profiling the environment for crowd management. Additionally, existing studies have established that lighting conditions (i.e., light intensity and light color) can affect pedestrian route choice. Lastly, the state-of-the-art

includes studies showing that information provision (e.g., signage) has a consistently positive impact on pedestrian route choice and pedestrian wayfinding performance in evacuation, indicating that information provision can serve as a crowd management strategy.

Next to the effects of steering mechanisms, research has shown the importance of identifying the profile of the crowd and its given environment. The overview includes the impact of different profiling factors on pedestrian choice behavior and movement dynamics, including the effects of individual characteristics of pedestrians, group size, and the climate in a given environment. These effects highlight that pedestrian choice behavior and movement dynamics strongly depend on the crowd and the environment they navigate. For example, a crowd of young and healthy adults at a music festival behaves differently from an elderly crowd navigating a city center.

Nonetheless, the overview also highlights some limitations in the state-of-the-art regarding the effects of the profiling factors and steering mechanisms on pedestrian choice behavior and movement dynamics. Specifically, the overview identifies the factor-behavior pairs that are missing, scarcely studied, or have inconclusive findings in the state-of-the-art. Three challenges for future crowd management are identified, including examining the effects of particular crowd management strategies, studying different types of crowds (e.g., crowds including pedestrians with disabilities), and addressing the effects of crowd management strategies on flow rate.

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Contributions

Arco van Beek: Conceptualization, Methodology, Formal analysis, Writing - Original Draft, Writing - Review & Editing. **Yan Feng**: Writing - Review & Editing, Supervision. **Dorine C. Duives**: Writing - Review & Editing, Supervision, Funding Acquisition.

Declaration of competing interest

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

Appendix A. Studies provided in review framework

1. Cabrera et al. (2016)
2. Gorrini et al. (2015)
3. Pinna and Murrau (2018)
4. Subaih et al. (2020)
5. Montufar et al. (2007)
6. O'Flaherty and Parkinson (1972)
7. Polus et al. (1983)
8. Zanlungo et al. (2020)
9. Chattaraj et al. (2009)
10. Rastogi et al. (2013)
11. Tanaboriboon et al. (1986)
12. Feng et al. (2022)
13. Daamen and Hoogendoorn (2012)
14. Yang et al. (2012)
15. Dachner and Kinateder (2016)
16. Moussaid et al. (2010)
17. Zhao et al. (2016)
18. Hu et al. (2020)
19. Rotton et al. (1990)
20. Kimura et al. (2015)
21. Dong et al. (2022)
22. Weidmann (1993)
23. Fridolf et al. (2014)
24. Jeon et al. (2011)
25. Ronchi et al. (2018)
26. Xie et al. (2020)
27. Dias et al. (2013)
28. Hoogendoorn and Daamen (2005)
29. Köster et al. (2019)
30. Seyfried et al. (2005)
31. Donker et al. (2011)
32. Duives et al. (2024)
33. Pedersen and Johansson (2018)
34. Kesler et al. (2005)
35. Styns et al. (2007)
36. Franek et al. (2014)
37. Meng et al. (2018)
38. Zeng et al. (2019)
39. Alhajyaseen et al. (2011)
40. Bode (2016)
41. Crociani et al. (2019)
42. Burghardt et al. (2013)
43. Dias and Sarvi (2016)
44. Shahhoseini and Sarvi (2019)
45. Tian et al. (2012)

46. Ikeda et al. (2017)
47. Yanagisawa et al. (2012)
48. Zeng et al. (2022)
49. Bernhoft and Carstensen (2008)
50. Brookfield and Tilley (2016)
51. Künzer et al. (2020)
52. Hill (1982)
53. Chen et al. (2018)
54. Lawton and Kallai (2002)
55. Liu et al. (2020)
56. Brscić et al. (2014)
57. Corbetta et al. (2016)
58. van Beek et al. (2024b)
59. Taylor and Socov (1974)
60. Benthorn and Frantzich (1999)
61. Kinateder et al. (2018)
62. Fang et al. (2010)
63. Fang et al. (2020)
64. Shiwakoti et al. (2017)
65. Kobes et al. (2010b)
66. Fu et al. (2021b)
67. Fu et al. (2021c)
68. Fridolf et al. (2013)
69. Jin (2002)
70. Bosina et al. (2020)
71. Hölscher et al. (2006a)
72. Vilar et al. (2013)
73. Moussaid et al. (2009)
74. Vilar et al. (2014)
75. Feliciani et al. (2024)
76. Nilsson et al. (2008)
77. Duarte et al. (2014)
78. Filippidis et al. (2009)
79. Galea et al. (2014)
80. Rousek and Hallbeck (2011)
81. Xia et al. (2021)
82. Zomer et al. (2015)
83. Head and Isom (2010)
84. Lee and Kline (2011)
85. Taillade et al. (2013)
86. Wang et al. (2018)
87. Chen et al. (2009)
88. Harrell et al. (2000)
89. Malinowski and Gillespie (2001)
90. Chebat et al. (2005)
91. Ewart and Johnson (2021)
92. O'Neill (1992)

93. Lin et al. (2019)
94. Cao et al. (2019)
95. Meng and Zhang (2014)
96. Bode et al. (2015)
97. Köster et al. (2011)
98. Hölscher et al. (2006b)
99. Lee (2010)
100. Natapov et al. (2022)
101. Suzer et al. (2018)
102. O'Neill (1991)
103. Vanumu et al. (2020)
104. Lin et al. (2020b)
105. Lin et al. (2020a)
106. Haghani et al. (2019)
107. Lu et al. (2017)
108. Cuesta et al. (2021)
109. Von Krüchten and Schadschneider (2017)
110. Sun (2009)
111. Kinkel et al. (2017)
112. Tang et al. (2009)
113. Tucker et al. (2018)
114. Feliciani et al. (2020)

References

Adrian, J., Boltes, M., Holl, S., Sieben, A., Seyfried, A., 2018. Crowding and queuing in entrance scenarios: influence of corridor width in front of bottlenecks. Proceedings of the 2018 Pedestrian and Evacuation Dynamics Conference.

Adrian, J., Boltes, M., Sieben, A., Seyfried, A., 2020. Influence of corridor width and motivation on pedestrians in front of bottlenecks. Traffic and Granular Flow 2019. Springer, pp. 3–9.

Aghabayk, K., Radmehr, K., Shiwakoti, N., 2020. Effect of intersecting angle on pedestrian crowd flow under normal and evacuation conditions. Sustainability 12 (4), 1301.

Alhajyaseen, W.K., Nakamura, H., Asano, M., 2011. Effects of bi-directional pedestrian flow characteristics upon the capacity of signalized crosswalks. Procedia-Soc. Behav. Sci. 16, 526–535.

Allen, M.J., Hogeland, R., 1978. Spatial problem-solving strategies as functions of sex. Percept. Mot. Skills 47 (2), 348–350.

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

Aultman-Hall, L., Lane, D., Lambert, R.R., 2009. Assessing impact of weather and season on pedestrian traffic volumes. Transp. Res. Rec. 2140 (1), 35–43.

Bao, Y., 2021. Room evacuation in the presence of obstacles using an agent-based model with turning behavior. Simul. Model. Pract. Theory 113, 102385.

Benthorn, L., Frantzich, H., 1999. Fire alarm in a public building: how do people evaluate information and choose an evacuation exit? Fire Mater. 23 (6), 311–315.

Bernhoft, I.M., Carstensen, G., 2008. Preferences and behaviour of pedestrians and cyclists by age and gender. Transp. Res. Part F: Traffic Psychol. Behav. 11 (2), 83–95.

Biassoni, F., Bina, M., Confalonieri, F., Ciceri, R., 2018. Visual exploration of pedestrian crossings by adults and children: comparison of strategies. Transp. Res. Part F: Traffic Psychol. Behav. 56, 227–235.
Blue, V.J., Adler, J.L., 2001. Cellular automata microsimulation for modeling bi-directional pedestrian walkways. Transp. Res. Part B: Methodol. 35 (3), 293–312.
Bode, N., 2016. The effect of social groups and gender on pedestrian behaviour immediately in front of bottlenecks. In: Proceedings of the 8th International Conference on Pedestrian and Evacuation Dynamics, University of Science and Technology of China Press, pp. 92–99.
Bode, N.W., Holl, S., Mehner, W., Seyfried, A., 2015. Disentangling the impact of social groups on response times and movement dynamics in evacuations. PloS ONE 10 (3), e0121227.
Bosina, E., Meeder, M., Büchel, B., Weidmann, U., 2016. Avoiding walls: what distance do pedestrians keep from walls and obstacles? Traffic and Granular Flow. Springer.
Bosina, E., Thurau, J., Oberholzer, T., Heule, S., 2020. Influence of small-scale obstacles on passenger flows in railway stations. Traffic and Granular Flow. Springer, pp. 31–37.
Brookfield, K., Tilley, S., 2016. Using virtual street audits to understand the walkability of older adults' route choices by gender and age. Int. J. Environ. Res. Public Health 13 (11), 1061.
Brščić, D., Zanlungo, F., Kanda, T., 2014. Density and velocity patterns during one year of pedestrian tracking. Transp. Res. Procedia 2, 77–86.
Buchmueller, S., Weidmann, U., 2006. Parameters of pedestrians, pedestrian traffic and walking facilities. IVT Schriftenreihe 132.
Büchner, S., Hölscher, C., Strube, G., Vosniadou, S., Kayser, D., Protopapas, A., 2007. Path choice heuristics for navigation related to mental representations of a building. Proceedings of the European Cognitive Science Conference. Taylor and Francis, Delphi, Greece, pp. 504–509.
Buikstra, N.J., 2021. Off the beaten track: the effectiveness of illuminance difference-based nudges on route choices of pedestrians in a crowd. PhD thesis, Master's thesis, Eindhoven University of Technology.
Burghardt, S., Seyfried, A., Klingsch, W., 2013. Performance of stairs-fundamental diagram and topographical measurements. Transp. Res. Part C: Emerg. Technol. 37, 268–278.
Cabrera, F., Munoz, F., Perez, C., 2016. Walking patterns of elderly in a peruvian public space. In: Proceedings of the 8th International Conference on Pedestrian and Evacuation Dynamics, pp. 12–17.
Cao, L., Lin, J., Li, N., 2019. A virtual reality based study of indoor fire evacuation after active or passive spatial exploration. Comput. Hum. Behav. 90, 37–45.
Cao, S., Lian, L., Chen, M., Yao, M., Song, W., Fang, Z., 2018. Investigation of difference of fundamental diagrams in pedestrian flow. Physica A: Stat. Mech. Appl. 506, 661–670.
Chattaraj, U., Seyfried, A., Chakroborty, P., 2009. Comparison of pedestrian fundamental diagram across cultures. Adv. Complex Syst. 12 (3), 393–405.
Chebat, J.-C., Gélinas-Chebat, C., Therrien, K., 2005. Lost in a mall, the effects of gender, familiarity with the shopping mall and the shopping values on shoppers' wayfinding processes. J. Bus. Res. 58 (11), 1590–1598.
Chen, C.-H., Chang, W.-C., Chang, W.-T., 2009. Gender differences in relation to wayfinding strategies, navigational support design, and wayfinding task difficulty. J. Environ. Psychol. 29 (2), 220–226.
Chen, L., Tang, T.-Q., Huang, H.-J., Song, Z., 2018. Elementary students' evacuation route choice in a classroom: a questionnaire-based method. Physica A: Stat. Mech Appl. 492, 1066–1074.

Chen, S., Fu, L., Fang, J., Yang, P., 2019. The effect of obstacle layouts on pedestrian flow in corridors: an experimental study. Physica A: Stat. Mech. Appl. 534, 122333.
Chen, X., Ye, J., Jian, N., 2010. Relationships and characteristics of pedestrian traffic flow in confined passageways. Transp. Res. Rec. 2198 (1), 32–40.
Choi, J.-S., Kang, D.-W., Shin, Y.-H., Tack, G.-R., 2014. Differences in gait pattern between the elderly and the young during level walking under low illumination. Acta Bioeng. Biomech. 16, 1.
Chowdhury, D., Santen, L., Schadschneider, A., 2000. Statistical physics of vehicular traffic and some related systems. Phys. Rep. 329 (4-6), 199–329.
Chraibi, M., Kemloh, U., Schadschneider, A., Seyfried, A., 2011. Force-based models of pedestrian dynamics. Netw. Heterog. Media 6 (3), 425–442.
Corbetta, A., Lee, C.-M., Muntean, A., Toschi, F., 2016. Asymmetric pedestrian dynamics on a staircase landing from continuous measurements. Traffic and Granular Flow'15. Springer, pp. 49–56.
Crociani, L., Gorrini, A., Feliciani, C., Vizzari, G., Nishinari, K., Bandini, S., 2019. Micro and macro pedestrian dynamics in counterflow: the impact of social group. Traffic and Granular Flow'17 12. Springer,, pp. 151–158.
Cuesta, A., Abreu, O., Balboa, A., Alvear, D., 2021. Alone or with others: experiments on evacuation decision making. Fire Safety J. 120, 103018.
Daamen, W., 2002. Modelling passenger flows in public transport facilities (ph.d. thesis). Delft University of Technology, Delft, Netherlands.
Daamen, W., Hoogendoorn, S., 2012. Emergency door capacity: influence of door width, population composition and stress level. Fire Technol. 48 (1), 55–71.
Dachner, G.C., Kinateder, M., 2016. Effects of visual information on decision making during way-finding in emergency and non-emergency situations. Collect. Dyn. 1, 185.
Dalton, R.C., Hölscher, C., Montello, D.R., 2019. Wayfinding as a social activity. Front. Psychol. 10, 433127.
Dias, C., Sarvi, M., 2016. Exploring the effect of turning manoeuvres on macroscopic properties of pedestrian flow. In: 38th Australasian transport research forum. Melbourne, Australia.
Dias, C., Sarvi, M., Shiwakoti, N., Ejtemai, O., 2013. Experimental study on pedestrian walking characteristics through angled corridors. In: Proceedings of 36th Australasian Transport Research Forum, pp. 1–11.
Dias, C., Sarvi, M., Shiwakoti, N., Ejtemai, O., Burd, M., 2014. Examining the impact of different turning angles on the collective egress of crowds. J. Transp. Saf. Secur. 6 (2), 167–181.
Dong, F., Li, X., Xie, Q., Ye, R., Cao, S., 2022. The influence of weather and temperature on pedestrian walking characteristics on the zigzag bridge. Int. J. Biometeorol. 66 (12), 2541–2552.
Donker, S.F., Kruisheer, J., Kooi, F., 2011. Pedestrian walking speed as a tool to study environment-behavior. In: Proceedings of the 9th Biennial Conference on Environmental Psychology.
Drury, J., 2020. Recent developments in the psychology of crowds and collective behaviour. Curr. Opin. Psychol. 35, 12–16.
Duarte, E., Rebelo, F., Teles, J., Wogalter, M.S., 2014. Behavioral compliance for dynamic versus static signs in an immersive virtual environment. Appl. Ergon. 45 (5), 1367–1375.
Duives, D.C., van Beek, A., Feng, Y., 2024. Nudging pedestrian walking dynamics using light intensity and color: a virtual reality study. Manuscript under revision.
Ewart, I.J., Johnson, H., 2021. Virtual reality as a tool to investigate and predict occupant behaviour in the real world: the example of wayfinding. ITcon 26, 286–302.

Fang, Z., Gao, H., Jiang, L., Li, X., Lv, W., 2020. Human movement characteristics during emergency evacuations in a virtual environment. Fire Saf. J. 115, 103147.
Fang, Z., Song, W., Zhang, J., Wu, H., 2010. Experiment and modeling of exit-selecting behaviors during a building evacuation. Physica A: Stat. Mech. Appl. 389 (4), 815–824.
Feliciani, C., Murakami, H., Shimura, K., Nishinari, K., 2020. Efficiently informing crowds-experiments and simulations on route choice and decision making in pedestrian crowds with wheelchair users. Transp. Res. Part C: Emerging Technol. 114, 484–503.
Feliciani, C., Nishinari, K., 2016. Empirical analysis of the lane formation process in bidirectional pedestrian flow. Phys. Rev. E 94 (3), 032304.
Feliciani, C., Tanida, S., Jia, X., Nishinari, K., 2024. Influencing pedestrian route choice through environmental stimuli: a long-term ecological experiment. J. Dis. Res. 19 (2), 325–335.
Feng, Y., Duives, D., Daamen, W., Hoogendoorn, S., 2019. Pedestrian exit choice behavior during an evacuation-a comparison study between field and vr experiment. In: Transportation Research Board 98th Annual Meeting Transporation Research Board.
Feng, Y., Duives, D.C., Hoogendoorn, S.P., 2021. Using virtual reality to study pedestrian exit choice behaviour during evacuations. Saf. Sci. 137, 105158.
Feng, Y., Duives, D.C., Hoogendoorn, S.P., 2022. Development and evaluation of a vr research tool to study wayfinding behaviour in a multi-story building. Saf. Sci. 147, 105573.
Filippidis, L., Galea, E.R., Blackshields, D., Lawrence, P., 2009. Experimental study of the effectiveness of emergency signage.
Fishman, E., Böcker, L., Helbich, M., 2015. Adult active transport in the netherlands: an analysis of its contribution to physical activity requirements. PloS ONE 10 (4), e0121871.
Franěk, M., 2013. Environmental factors influencing pedestrian walking speed. Percept. Mot. Skills 116 (3), 992–1019.
Franěk, M., Režny`, L., Šefara, D., Cabal, J., 2018. Effect of traffic noise and relaxations sounds on pedestrian walking speed. Int. J. Environ. Res. Public Health 15 (4), 752.
Franěk, M., van Noorden, L., Režny`, L., 2014. Tempo and walking speed with music in the urban context. Front. Psychol. 5, 1361.
Frankenstein, J., Brüssow, S., Ruzzoli, F., Hölscher, C., 2012. The language of landmarks: the role of background knowledge in indoor wayfinding. Cogn. Process. 13, 165–170.
Frantzich, H., 1996. Study of movement on stairs during evacuation using video analysing techniques.
Frantzich, H., Nilsson, D., 2004. Evacuation experiments in a smoke filled tunnel. In: 3rd international symposium on human behaviour in fire. Interscience Communications Ltd, pp. 229–238.
Fridolf, K., Andrée, K., Nilsson, D., Frantzich, H., 2014. The impact of smoke on walking speed. Fire Materi. 38 (7), 744–759.
Fridolf, K., Ronchi, E., Nilsson, D., Frantzich, H., 2013. Movement speed and exit choice in smoke-filled rail tunnels. Fire Saf. J. 59, 8–21.
Fruin, J.J., 1971. Designing for pedestrians a level of service concept. Highw. Res. Rec. 355, 1–15.
Fu, L., Liu, Y., Shi, Y., Zhao, Y., 2021a. Dynamics of bidirectional pedestrian flow in a corridor including individuals with disabilities. Physica A: Stat. Mech. Appl. 580, 126140.
Fu, M., Liu, R., Zhang, Y., 2021b. Do people follow neighbors? An immersive virtual reality experimental study of social influence on individual risky decisions during evacuations. Autom. Constr. 126, 103644.

Fu, M., Liu, R., Zhang, Y., 2021c. Why do people make risky decisions during a fire evacuation? study on the effect of smoke level, individual risk preference, and neighbor behavior. Saf. Sci. 140, 105245.
Galea, E.R., Xie, H., Lawrence, P.J., 2014. Experimental and survey studies on the effectiveness of dynamic signage systems. Fire Saf. Sci. 11, 1129–1143.
Gipps, P.G., Marksjö, B., 1985. A micro-simulation model for pedestrian flows. Math. Comput. Simul. 27 (2-3), 95–105.
Goldiez, B.F., Ahmad, A.M., Hancock, P.A., 2007. Effects of augmented reality display settings on human wayfinding performance. IEEE Trans. Syst. Man, Cybern. Part C (Applications and Reviews) 37 (5), 839–845.
Gorrini, A., Bandini, S., Vizzari, G., 2015. Empirical investigation on pedestrian crowd dynamics and grouping. Traffic and Granular Flow. Springer.
Gorrini, A., Vizzari, G., Bandini, S., 2016. Granulometric distribution and crowds of groups: focusing on dyads. Traffic and Granular Flow. Springer.
Graat, E., Midden, C., Bockholts, P., 1999. Complex evacuation; effects of motivation level and slope of stairs on emergency egress time in a sports stadium. Saf. Sci. 31 (2), 127–141.
Guo, R.-Y., Huang, H.-J., Wong, S., 2012. Route choice in pedestrian evacuation under conditions of good and zero visibility: experimental and simulation results. Transp. Res. Part B: Methodol. 46 (6), 669–686.
Gwynne, S., Galea, E.R., Owen, M., Lawrence, P.J., Filippidis, L., 1999. A review of the methodologies used in the computer simulation of evacuation from the built environment. Build. Environ. 34 (6), 741–749.
Gwynne, S., Kuligowski, E., Kratchman, J., Milke, J.A., 2009. Questioning the linear relationship between doorway width and achievable flow rate. Fire Saf. J. 44 (1), 80–87.
Habicht, A.T., Braaksma, J.P., 1984. Effective width of pedestrian corridors. J. Transp. Eng. 110 (1), 80–93.
Haghani, M., 2021. The knowledge domain of crowd dynamics: anatomy of the field, pioneering studies, temporal trends, influential entities and outside-domain impact. Physica A: Stat. Mech. Appl. 580, 126145.
Haghani, M., Sarvi, M., 2018. Crowd behaviour and motion: empirical methods. Transp. Res. Part B: Methodol. 107, 253–294.
Haghani, M., Sarvi, M., 2019. herding'in direction choice-making during collective escape of crowds: how likely is it and what moderates it? Saf. Sci. 115, 362–375.
Haghani, M., Sarvi, M., Shahhoseini, Z., Boltes, M., 2019. Dynamics of social groups' decision-making in evacuations. Transp. Res. Part C: Emer. Technol. 104, 135–157.
Hannun, J., Dias, C., Taha, A.H., Almutairi, A., Alhajyaseen, W., Sarvi, M., Al-Bosta, S., 2022. Pedestrian flow characteristics through different angled bends: exploring the spatial variation of velocity. PLoS ONE 17 (3), e0264635.
Harrell, W.A., Bowlby, J.W., Hall-Hoffarth, D., 2000. Directing wayfinders with maps: the effects of gender, age, route complexity, and familiarity with the environment. J. Soc. Psychol. 140 (2), 169–178.
Head, D., Isom, M., 2010. Age effects on wayfinding and route learning skills. Behav. Brain Res. 209 (1), 49–58.
Helbing, D., 1991. A mathematical model for the behavior of pedestrians. Behav. Sci. 36 (4), 298–310.
Helbing, D., 2001. Traffic and related self-driven many-particle systems. Rev. Mod. Phys. 73 (4), 1067.
Helbing, D., Molnar, P., 1995. Social force model for pedestrian dynamics. Phys. Rev. E 51 (5), 4282.
Hill, M.R., 1982. Spatial Structure and Decision-Making Aspects of Pedestrian Route Selection Through an Urban Environment. The University of Nebraska-Lincoln.

Hölscher, C., Büchner, S.J., Meilinger, T., Strube, G., 2006a. Map use and wayfinding strategies in a multi-building ensemble. International Conference on Spatial Cognition. Springer.
Hölscher, C., Büchner, S.J., Meilinger, T., Strube, G., 2009. Adaptivity of wayfinding strategies in a multi-building ensemble: The effects of spatial structure, task requirements, and metric information. J. Environ. Psychol. 29, 208–219.
Hölscher, C., Meilinger, T., Vrachliotis, G., Brösamle, M., Knauff, M., 2006b. Up the down staircase: wayfinding strategies in multi-level buildings. J. Environ. Psychol. 26 (4), 284–299.
Hoogendoorn, S.P., Bovy, P.H., 2004. Pedestrian route-choice and activity scheduling theory and models. Transp. Res. Part B: Methodol. 38 (2), 169–190.
Hoogendoorn, S.P., Daamen, W., 2005. Pedestrian behavior at bottlenecks. Transp. Sci. 39 (2), 147–159.
Hu, Y., Bode, N.W., 2023. A systematic review and meta-analysis on the effect social groups have on the egress times of pedestrian crowds. Transp. A: Transp. Sci. 19 (1), 1998243.
Hu, Y., Zhang, J., Song, W., 2020. The difference between individuals and social groups in multidirectional movement. Collect. Dyn. 5, 332–339.
Huo, F., Song, W., Chen, L., Liu, C., Liew, K., 2016. Experimental study on characteristics of pedestrian evacuation on stairs in a high-rise building. Saf. Sci. 86, 165–173.
Iachini, T., Ruotolo, F., Ruggiero, G., 2009. The effects of familiarity and gender on spatial representation. J. Environ. Psychol. 29 (2), 227–234.
Ikeda, S., Nozawa, T., Yokoyama, R., Miyazaki, A., Sasaki, Y., Sakaki, K., Kawashima, R., 2017. Steady beat sound facilitates both coordinated group walking and inter-subject neural synchrony. Front. Neurosci. 11, 147.
Irnich, J., Wal, N.v., Duives, D., Auping, W., 2022. Impact of leader-follower behavior on evacuation performance: an exploratory modeling approach. Conference of the European Social Simulation Association. Springer.
Jeon, G.-Y., Kim, J.-Y., Hong, W.-H., Augenbroe, G., 2011. Evacuation performance of individuals in different visibility conditions. Build. Environ. 46 (5), 1094–1103.
Jia, X., Feliciani, C., Yanagisawa, D., Nishinari, K., 2020. Experimental study on the evading behaviour of single pedestrians encountering an obstacle. Collect. Dyn. 5, 77–84.
Jin, C.-J., Jiang, R., Liu, T., Li, D., Wang, H., Liu, X., 2021. Pedestrian dynamics with different corridor widths: Investigation on a series of uni-directional and bi-directional experiments. Physica A: Stat. Mech. Appl. 581, 126229.
Jin, C.-J., Jiang, R., Yin, J.-L., Dong, L.-Y., Li, D., 2017. Simulating bi-directional pedestrian flow in a cellular automaton model considering the body-turning behavior. Physica A: Stat. Mech. Appl. 482, 666–681.
Jin, T., 2002. Visibility and human behavior in fire smoke. SFPE Handbook of Fire Protection Engineering. Springer Nature, pp. 3.
Jones, B., Hewitt, J.A., 1986. Leadership and group formation in high-rise buidling evacuations. Fire Saf. Sci. 1, 513–522.
Kalantari, S., Tripathi, V., Kan, J., Rounds, J.D., Mostafavi, A., Snell, R., Cruz-Garza, J.G., 2022. Evaluating the impacts of color, graphics, and architectural features on wayfinding in healthcare settings using eeg data and virtual response testing. J. Environ. Psychol. 79, 101744.
Kesler, A., Leibovich, G., Herman, T., Gruendlinger, L., Giladi, N., Hausdorff, J.M., 2005. Shedding light on walking in the dark: the effects of reduced lighting on the gait of older adults with a higher-level gait disorder and controls. J. NeuroEng. Rehabil. 2 (1), 1–8.
Kimura, T., Kobayashi, H., Nakayama, E., Kakihana, W., 2015. Seasonality in physical activity and walking of healthy older adults. J. Physiol. Anthropol. 34, 1–6.

Kinateder, M., Comunale, B., Warren, W.H., 2018. Exit choice in an emergency evacuation scenario is influenced by exit familiarity and neighbor behavior. Saf. Sci. 106, 170–175.
Kinateder, M., Müller, M., Jost, M., Mühlberger, A., Pauli, P., 2014. Social influence in a virtual tunnel fire-influence of conflicting information on evacuation behavior. Appl. Ergon. 45 (6), 1649–1659.
Kinateder, M., Warren, W.H., 2021. Exit choice during evacuation is influenced by both the size and proportion of the egressing crowd. Physica A: Stat. Mech. Appl. 569, 125746.
Kinkel, E., Daamen, W., Hoogendoorn, S., 2017. The effect of stressful circumstances on planning and problem-solving abilities and egress time. Technical report.
Kirchner, A., Schadschneider, A., 2002. Simulation of evacuation processes using a bionics-inspired cellular automaton model for pedestrian dynamics. Physica A: Stat. Mech. Appl. 312 (1-2), 260–276.
Kobes, M., Helsloot, I., de Vries, B., Post, J., 2010a. 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. Proc. Eng. 3, 37–51.
Kobes, M., Helsloot, I., De Vries, B., Post, J.G., 2010b. Building safety and human behaviour in fire: a literature review. Fire Saf. J. 45 (1), 1–11.
Kobes, M., Oberijé, N., Groenewegen, K., Helsloot, I., De Vries, B., 2009. Hotel evacuation at night: an analysis of unannounced fire drills under various conditions. In: Proc. of Human Behavior in Fire Symp, vol. 13, p. 15.
Köster, G., Lehmberg, D., Kneidl, A., 2019. Walking on stairs: experiment and model. Phys. Rev. E 100 (2), 022310.
Köster, G., Seitz, M., Treml, F., Hartmann, D., Klein, W., 2011. On modelling the influence of group formations in a crowd. Contemp. Soc. Sci. 6 (3), 397–414.
Kretz, T., Grünebohm, A., Schreckenberg, M., 2006. Experimental study of pedestrian flow through a bottleneck. J. Stat. Mech.: Theory Exper. 2006 (10), P10014.
Kuliga, S.F., Nelligan, B., Dalton, R.C., Marchette, S., Shelton, A.L., Carlson, L., Hölscher, C., 2019. Exploring individual differences and building complexity in wayfinding: the case of the seattle central library. Environ. Behav. 51 (5), 622–665.
Künzer, L., Zinke, R., Hofinger, G., 2020. Dynamic guidance by colored running lights and affordance: route choices of adults and older children. Collect. Dyn. 5, 214–221.
Lawton, C.A., 1994. Gender differences in way-finding strategies: relationship to spatial ability and spatial anxiety. Sex Roles 30, 765–779.
Lawton, C.A., Kallai, J., 2002. Gender differences in wayfinding strategies and anxiety about wayfinding: a cross-cultural comparison. Sex Roles 47, 389–401.
Laxman, K.K., Rastogi, R., Chandra, S., 2010. Pedestrian flow characteristics in mixed traffic conditions. J. Urban Plan. Dev. 136 (1), 23–33.
Lee, S., 2010. Understanding wayfinding for the elderly using vr. In: Proceedings of the 9th ACM SIGGRAPH Conference on Virtual-Reality Continuum and its Applications in Industry, pp. 285–288.
Lee, S., Kline, R., 2011. Wayfinding study in virtual environments: the elderly vs. the younger-aged groups. ArchNet-IJAR: Int. J. Arch. Res. 5 (2), 63.
Lian, L., Mai, X., Song, W., Richard, Y.K.K., Rui, Y., Jin, S., 2017. Pedestrian merging behavior analysis: an experimental study. Fire Saf. J. 91, 918–925.
Liang, S., Leng, H., Yuan, Q., Wang, B., Yuan, C., 2020. How does weather and climate affect pedestrian walking speed during cool and cold seasons in severely cold areas? Build. Environ. 175, 106811.
Lin, J., Cao, L., Li, N., 2019. Assessing the influence of repeated exposures and mental stress on human wayfinding performance in indoor environments using virtual reality technology. Adv. Eng. Inform. 39, 53–61.

Lin, J., Cao, L., Li, N., 2020a. How the completeness of spatial knowledge influences the evacuation behavior of passengers in metro stations: a vr-based experimental study. Autom. Constr. 113, 103136.
Lin, J., Zhu, R., Li, N., Becerik-Gerber, B., 2020b. Do people follow the crowd in building emergency evacuation? A cross-cultural immersive virtual reality-based study. Adv. Eng. Inform. 43, 101040.
Liu, Y., Yang, D., de Vries, B., Timmermans, H.J., 2020. Analysis of built environment influence on pedestrian route choice behavior in dutch design week using gps data. Collect. Dyn. 5, 262–270.
Lovreglio, R., Fonzone, A., Dell'Olio, L., 2016a. A mixed logit model for predicting exit choice during building evacuations. Transp. Res. Part A: Policy Pract. 92, 59–75.
Lovreglio, R., Fonzone, A., Dell'Olio, L., Borri, D., 2016b. A study of herding behaviour in exit choice during emergencies based on random utility theory. Saf. Sci. 82, 421–431.
Lu, L., Chan, C.-Y., Wang, J., Wang, W., 2017. A study of pedestrian group behaviors in crowd evacuation based on an extended floor field cellular automaton model. Transp. Res. Part C: Emer. Technol. 81, 317–329.
Ma, J., Song, W.-g., Fang, Z.-m., Lo, S.-m., Liao, G.-x., 2010. Experimental study on microscopic moving characteristics of pedestrians in built corridor based on digital image processing. Build. Environ. 45 (10), 2160–2169.
Malinowski, J.C., Gillespie, W.T., 2001. Individual differences in performance on a large-scale, real-world wayfinding task. J. Environ. Psychol. 21 (1), 73–82.
Meng, F., Zhang, W., 2014. Way-finding during a fire emergency: an experimental study in a virtual environment. Ergonomics 57 (6), 816–827.
Meng, Q., Zhao, T., Kang, J., 2018. Influence of music on the behaviors of crowd in urban open public spaces. Front. Psychol. 9, 329274.
Miller, L.K., Santoni, V., 1986. Sex differences in spatial abilities: strategic and experiential correlates. Acta Psychol. 62 (3), 225–235.
Miranda-Moreno, L.F., Lahti, A.C., 2013. Temporal trends and the effect of weather on pedestrian volumes: a case study of Montreal, Canada. Transp. Res. Part D: Transp. Environ. 22, 54–59.
Montufar, J., Arango, J., Porter, M., Nakagawa, S., 2007. Pedestrians' normal walking speed and speed when crossing a street. Transp. Res. Rec. 2002 (1), 90–97.
Moussaïd, M., Helbing, D., Garnier, S., Johansson, A., Combe, M., Theraulaz, G., 2009. Experimental study of the behavioural mechanisms underlying self-organization in human crowds. Proc. R. Soc. B: Biol. Sci. 276 (1668), 2755–2762.
Moussaïd, M., Kapadia, M., Thrash, T., Sumner, R.W., Gross, M., Helbing, D., Hölscher, C., 2016. Crowd behaviour during high-stress evacuations in an immersive virtual environment. J. R. Soc. Interface 13 (122), 20160414.
Moussaïd, M., Perozo, N., Garnier, S., Helbing, D., Theraulaz, G., 2010. The walking behaviour of pedestrian social groups and its impact on crowd dynamics. PloS ONE 5 (4), e10047.
Natapov, A., Parush, A., Laufer, L., Fisher-Gewirtzman, D., 2022. Architectural features and indoor evacuation wayfinding: the starting point matters. Saf. Sci. 145, 105483.
Nilsson, D., Frantzich, H., Saunders, W., 2008. Influencing exit choice in the event of a fire evacuation. Fire Saf. Sci. 9, 341–352.
Nilsson, D., Johansson, A., 2009. Social influence during the initial phase of a fire evacuation—analysis of evacuation experiments in a cinema theatre. Fire Saf. J. 44 (1), 71–79.
Older, S., 1968. Movement of pedestrians on footways in shopping streets. Traffic Eng. Control 10 (4), 160.

O'Neill, M.J., 1991. Effects of signage and floor plan configuration on wayfinding accuracy. Environ. Behav. 23 (5), 553–574.
O'Neill, M.J., 1992. Effects of familiarity and plan complexity on wayfinding in simulated buildings. J. Environ. Psychol. 12 (4), 319–327.
O'Flaherty, C., Parkinson, M., 1972. Movement on a city centre footway. Traffic Eng. Control 13 (10), 434–438.
Pedersen, E., Johansson, M., 2018. Dynamic pedestrian lighting: effects on walking speed, legibility and environmental perception. Light. Res. Technol. 50 (4), 522–536.
Pinna, F., Murrau, R., 2018. Age factor and pedestrian speed on sidewalks. Sustainability 10 (11), 4084.
Polus, A., Schofer, J.L., Ushpiz, A., 1983. Pedestrian flow and level of service. J. Transp. Eng. 109 (1), 46–56.
Pouyan, A.E., Ghanbaran, A., Shakibamanesh, A., 2021. Impact of circulation complexity on hospital wayfinding behavior (case study: milad 1000-bed hospital, tehran, iran). J. Build. Eng. 44, 102931.
Rastogi, R., Ilango, T., Chandra, S., 2013. Pedestrian flow characteristics for different pedestrian facilities and situations. Eur. Transp. - Trasp. Eur. 53, 1–21.
Ren, X., Zhang, J., Song, W., 2021. Flows of walking and running pedestrians in a corridor through exits of different widths. Saf. Sci. 133, 105040.
Ren, X., Zhang, J., Song, W., Cao, S., 2019. The fundamental diagrams of elderly pedestrian flow in straight corridors under different densities. J. Stat. Mech.: Theory Exper. 2019 (2), 023403.
Ronchi, E., Fridolf, K., Frantzich, H., Nilsson, D., Walter, A.L., Modig, H., 2018. A tunnel evacuation experiment on movement speed and exit choice in smoke. Fire Saf. J. 97, 126–136.
Rotton, J., Shats, M., Standers, R., 1990. Temperature and pedestrian tempo: walking without awareness. Environ. Behav. 22 (5), 650–674.
Rousek, J., Hallbeck, M., 2011. Improving and analyzing signage within a healthcare setting. Appl. Ergon. 42 (6), 771–784.
Sarkar, A., Janardhan, K., 2001. Pedestrian flow characteristics at an intermodal transfer terminal in calcutta. World Transp. Policy Pract. 7 (1), 32–38.
Schreckenberg, M., Sharma, S.D., 2002. Pedestrian and Evacuation Dynamics. vol.1 Springer.
Seneviratne, P.N., Morrall, J.F., 1985. Analysis of factors affecting the choice of route of pedestrians. Transp. Plan. Technol. 10 (2), 147–159.
Seyfried, A., Passon, O., Steffen, B., Boltes, M., Rupprecht, T., Klingsch, W., 2009. New insights into pedestrian flow through bottlenecks. Transp. Sci. 43 (3), 395–406.
Seyfried, A., Steffen, B., Klingsch, W., Boltes, M., 2005. The fundamental diagram of pedestrian movement revisited. J. Stat. Mech.: Theory Exper. 2005 (10), P10002.
Shahhoseini, Z., Sarvi, M., 2019. Pedestrian crowd flows in shared spaces: investigating the impact of geometry based on micro and macro scale measures. Transp. Res. Part B: Methodol. 122, 57–87.
Sharifi, M.S., Christensen, K., Chen, A., Stuart, D., Kim, Y.S., Chen, Y., 2017. A large-scale controlled experiment on pedestrian walking behavior involving individuals with disabilities. Travel Behav. Soc. 8, 14–25.
Shi, X., Ye, Z., Shiwakoti, N., Tang, D., Wang, C., Wang, W., 2016. Empirical investigation on safety constraints of merging pedestrian crowd through macroscopic and microscopic analysis. Accid. Anal. Prev. 95, 405–416.
Shi, Y., Kang, J., Xia, P., Tyagi, O., Mehta, R.K., Du, J., 2021. Spatial knowledge and firefighters' wayfinding performance: A virtual reality search and rescue experiment. Saf. Sci. 139, 105231.

Shiwakoti, N., Gong, Y., Shi, X., Ye, Z., 2015. Examining influence of merging architectural features on pedestrian crowd movement. Saf. Sci. 75, 15–22.
Shiwakoti, N., Sarvi, M., Rose, G., Burd, M., 2011. Consequence of turning movements in pedestrian crowds during emergency egress. Transp. Res. Rec. 2234 (1), 97–104.
Shiwakoti, N., Tay, R., Stasinopoulos, P., Woolley, P.J., 2017. Likely behaviours of passengers under emergency evacuation in train station. Safety Sci. 91, 40–48.
Sieben, A., Schumann, J., Seyfried, A., 2017. Collective phenomena in crowds–where pedestrian dynamics need social psychology. PLoS ONE 12 (6), e0177328.
Still, G.K., 2014. Introduction to Crowd Science. CRC Press.
Stoker, P., Garfinkel-Castro, A., Khayesi, M., Odero, W., Mwangi, M.N., Peden, M., Ewing, R., 2015. Pedestrian safety and the built environment: a review of the risk factors. J. Plan. Lit. 30 (4), 377–392.
Styns, F., van Noorden, L., Moelants, D., Leman, M., 2007. Walking on music. Hum. Mov. Sci. 26 (5), 769–785.
Subaih, R., Maree, M., Chraibi, M., Awad, S., Zanoon, T., 2020. Experimental investigation on the alleged gender-differences in pedestrian dynamics: a study reveals no gender differences in pedestrian movement behavior. IEEE Access 8, 33748–33757.
Sun, C., 2009. Architectural cue model in evacuation simulation for underground space design. Faculteit bouwkunde of Technische Universiteit Eindhoven.
Sun, S., Sun, C., Duives, D.C., Hoogendoorn, S.P., 2021. Deviation of pedestrian path due to the presence of building entrances. J. Adv. Transp. 2021, 1–12.
Suzer, O.K., Olgunturk, N., Guvenc, D., 2018. The effects of correlated colour temperature on wayfinding: a study in a virtual airport environment. Displays 51, 9–19.
Taillade, M., Sauzéon, H., ArvindPala, P., Déjos, M., Larrue, F., Gross, C., N'Kaoua, B., 2013. Age-related wayfinding differences in real large-scale environments: detrimental motor control effects during spatial learning are mediated by executive decline? PloS ONE 8 (7), e67193.
Tanaboriboon, Y., Hwa, S.S., Chor, C.H., 1986. Pedestrian characteristics study in singapore. J. Transp. Eng. 112 (3), 229–235.
Tang, C.-H., Wu, W.-T., Lin, C.-Y., 2009. Using virtual reality to determine how emergency signs facilitate way-finding. Appl. Ergon. 40 (4), 722–730.
Taylor, L.H., Socov, E.W., 1974. The movement of people toward lights. J. Illum. Eng. Soc. 3 (3), 237–241.
Templeton, A., Drury, J., Philippides, A., 2018. Walking together: behavioural signatures of psychological crowds. R. Soc. Open Sci. 5 (7), 180172.
Thompson, P.A., Marchant, E.W., 1995. A computer model for the evacuation of large building populations. Fire saf. J. 24 (2), 131–148.
Tian, W., Song, W., Ma, J., Fang, Z., Seyfried, A., Liddle, J., 2012. Experimental study of pedestrian behaviors in a corridor based on digital image processing. Fire Saf. J. 47, 8–15.
Tucker, A., Marsh, K., Gifford, T., Lu, X., Luh, P., Astur, R., 2018. The effects of information and hazard on evacuee behavior in virtual reality. Fire Saf. J. 99, 1–11.
van Beek, A., Duives, D.C., Feng, Y., Hoogendoorn, S.P., 2024a. Comparison of pedestrian wayfinding behavior between a real and a virtual multi-story building-a validation study. Transp. Res. Part C: Emer. Technol. 163, 104650.
van Beek, A., Feng, Y., Duives, D.C., Hoogendoorn, S.P., 2024b. Studying the impact of lighting on the pedestrian route choice using virtual reality. Saf. Sci. 174, 106467.
van der Wal, C.N., Robinson, M.A., de Bruin, W.B., Gwynne, S., 2021. Evacuation behaviors and emergency communications: an analysis of real-world incident videos. Saf. Sci. 136, 105121.
Vanumu, L.D., Arya, A., Gaddam, H.K., Rao, K.R., 2020. Modelling emergency evacuation of classroom with different age profiles. Collect. Dyn. 5, 374–381.

Vilar, E., Rebelo, F., Noriega, P., Duarte, E., Mayhorn, C.B., 2014. Effects of competing environmental variables and signage on route-choices in simulated everyday and emergency wayfinding situations. Ergonomics 57 (4), 511–524.
Vilar, E., Rebelo, F., Noriega, P., Teles, J., Mayhorn, C., 2013. The influence of environmental features on route selection in an emergency situation. Appl. Ergon. 44 (4), 618–627.
VonKrüchten, C., Schadschneider, A., 2017. Empirical study on social groups in pedestrian evacuation dynamics. Physica A: Stat. Mech. Appl. 475, 129–141.
Wang, C., Chen, Y., Zheng, S., Liao, H., 2018. Gender and age differences in using indoor maps for wayfinding in real environments. ISPRS Int. J. Geo-Inform. 8 (1), 11.
Wang, J., Ma, J., Lin, P., 2020. Effect of architectural adjustments on pedestrian flow at bottleneck. Collect. Dyn. 5, 167–172.
Ward, S.L., Newcombe, N., Overton, W.F., 1986. Turn left at the church, or three miles north: a study of direction giving and sex differences. Environ. Behav. 18 (2), 192–213.
Weidmann, U., 1993. Transporttechnik der fußgänger: transporttechnische eigenschaften des fußgängerverkehrs, literaturauswertung. VT Schriftenreihe 90.
Wiener, J.M., Hölscher, C., Büchner, S., Konieczny, L., 2012. Gaze behaviour during space perception and spatial decision making. Psychol. Res. 76, 713–729.
Xia, X., Li, N., González, V.A., 2021. Exploring the influence of emergency broadcasts on human evacuation behavior during building emergencies using virtual reality technology. J. Comput. Civ. Eng. 35 (2), 04020065.
Xia, Y., Wong, S., Shu, C.-W., 2009. Dynamic continuum pedestrian flow model with memory effect. Phys. Rev. E—Stat. Nonlin. Soft Matter Phys. 79 (6), 066113.
Xie, W., Lee, E.W.M., Cheng, Y., Shi, M., Cao, R., Zhang, Y., 2020. Evacuation performance of individuals and social groups under different visibility conditions: experiments and surveys. Int. J. Disaster. Risk Reduct. 47, 101527.
Yamamoto, H., Yanagisawa, D., Feliciani, C., Nishinari, K., 2019. Body-rotation behavior of pedestrians for collision avoidance in passing and cross flow. Transp. Res. Part B: Methodol. 122, 486–510.
Yanagisawa, D., Tomoeda, A., Nishinari, K., 2012. Improvement of pedestrian flow by slow rhythm. Phys. Rev. E 85 (1), 016111.
Yang, L., Rao, P., Zhu, K., Liu, S., Zhan, X., 2012. Observation study of pedestrian flow on staircases with different dimensions under normal and emergency conditions. Saf. Sci. 50 (5), 1173–1179.
Ye, J., Chen, X., Yang, C., Wu, J., 2008. Walking behavior and pedestrian flow characteristics for different types of walking facilities. Transp. Res. Rec. 2048 (1), 43–51.
Zanlungo, F., Yücel, Z., Kanda, T., 2020. Social group behaviour of triads dependence on purpose and gender. Collect. Dyn. 5, 118–125.
Zeng, G., Schadschneider, A., Zhang, J., Song, W., 2020. Experimental study on the influence of background music on pedestrian movement in high densities. Collect. Dyn. 5, 126–133.
Zeng, G., Schadschneider, A., Zhang, J., Wei, S., Song, W., Ba, R., 2019. Experimental study on the effect of background music on pedestrian movement at high density. Phys. Lett. A 383 (10), 1011–1018.
Zeng, G., Zhang, J., Ye, R., Cao, S., Song, W., 2022. Pedestrian dynamics of single-file experiments with music considering different music and different instructions. Physica A: Stat. Mech. Appl. 594, 126825.
Zhang, J., Klingsch, W., Rupprecht, T., Schadschneider, A., Seyfried, A., 2011. Empirical study of turning and merging of pedestrian streams in t-junction. arXiv preprint arXiv:1112.5299.

Zhang, J., Klingsch, W., Schadschneider, A., Seyfried, A., 2012. Ordering in bidirectional pedestrian flows and its influence on the fundamental diagram. J. Stat. Mech.: Theory Exp. 2012 (02), P02002.

Zhang, J., Wang, Q., Hu, Y., Cao, S., Xia, L., Song, W., 2018. The effect of a directional split flow ratio on bidirectional pedestrian streams at signalized crosswalks. J. Stat. Mech.: Theory Exp. 2018 (7), 073408.

Zhang, M., Ke, J., Tong, L., Luo, X., 2021. Investigating the influence of route turning angle on compliance behaviors and evacuation performance in a virtual-reality-based experiment. Adv. Eng. Inform. 48, 101259.

Zhao, H., Thrash, T., Kapadia, M., Wolff, K., Hölscher, C., Helbing, D., Schinazi, V.R., 2020. Assessing crowd management strategies for the 2010 love parade disaster using computer simulations and virtual reality. J. R. Soc. Interface 17 (167), 20200116.

Zhao, P., Sun, L., Cui, L., Luo, W., Ding, Y., 2016. The walking behaviours of pedestrian social group in the corridor of subway station. In: Proceedings of the 2016 Pedestrian and Evacuation Dynamics Conference.

Zomer, L.B., Daamen, W., Meijer, S., Hoogendoorn, S.P., 2015. Managing crowds: the possibilities and limitations of crowd information during urban mass events. Planning Support Systems and Smart Cities 77–97.