Comprehensive Review and New Analysis Software for Single-file Pedestrian Experiments

Rudina Subaih[1,2,*] · Antoine Tordeux[2] · Mohcine Chraibi[1] ·

[1] Institute for Advanced Simulation, Forschungszentrum, Jülich, 52425, Germany.
E-mail: r.subaih@fz-juelich.de, m.chraibi@fz-juelich.de

[2] School for Mechanical Engineering and Safety Engineering, University of Wuppertal, Wuppertal, 42119, Germany.
E-mail: rudina.subaih@uni-wuppertal.de, tordeux@uni-wuppertal.de

Abstract This paper offers a comprehensive examination of single-file experiments within the field of pedestrian dynamics, providing a thorough review from both theoretical and analytical perspectives. It begins by tracing the historical context of single-file movement studies in pedestrian dynamics. Then, the significance of understanding the fundamental relationships among density, speed, and flow in pedestrian dynamics through the lens of simple single-file systems is explored in depth. Furthermore, we investigate various traffic systems involving human or non-human entities such as ants, mice, bicycles, and cars, and provide insights. We explore the types of experimental setups, data collection methods, and influential factors that affect pedestrian movement. We also define and explain the common concepts concerning single-file movement, particularly in experimental research. Finally, we present a Python tool named "SingleFileMovementAnalysis" designed for analyzing single-file experimental data, specifically head trajectories. This tool provides a cohesive approach to preparing and calculating movement metrics like speed, density, and headway. The article aims to stimulate further research and underscore the areas where future researchers can contribute to advancing and enhancing single-file studies.
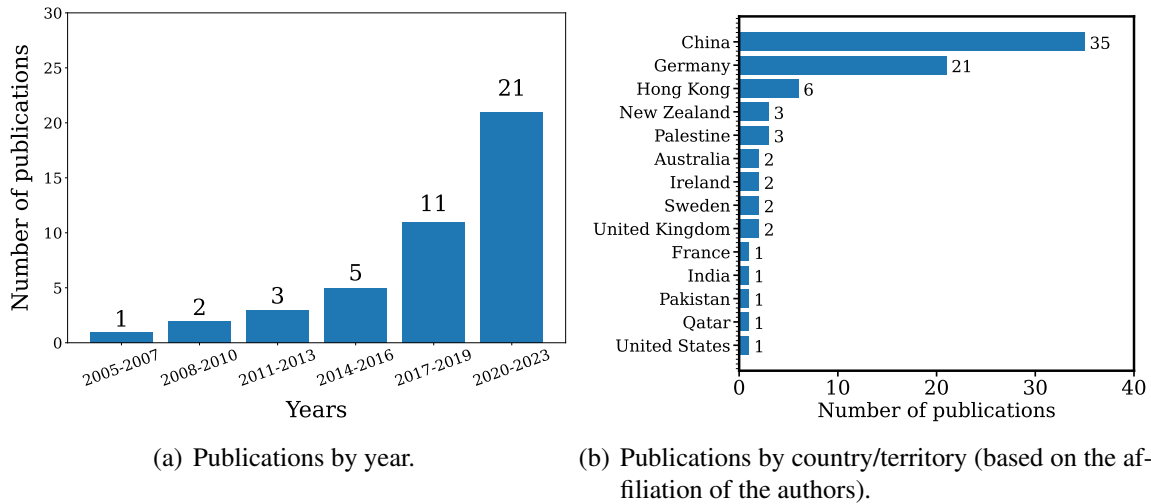
Keywords Single-file Movement · Single-file Motion · Single-File Flow · Pedestrian Dynamics · Fundamental Diagram · Experiment · Software

1. Introduction

In their seminal work, Seyfried et al. [1] presented the concept of single-file movement in pedestrian dynamics to explore the relationship between density-flow and density-velocity,

also known as the fundamental diagrams, within pedestrian traffic. The fundamental diagram quantifies the capacity of pedestrian facilities, allowing the assessment of escape routes and the evaluation of pedestrian models. To assess dependence on the fundamental diagram, Seyfried et al. investigated experiments of single-file movement, where the pedestrian walks in a unidirectional manner along a line with reduced degrees of freedom. This restricts the possible influential factors that affect the fundamental diagram. In 2009, Chattaraj et al. [2] replicated the same experiment in India [1], with the main aim of analyzing the cultural influence (social conventions) on pedestrians' movement. The motivation behind performing single-file experiments, as pointed out by Chattaraj et al., is that the density-speed relation is influenced by multiple factors that are still not completely understood. After reviewing the literature, we attribute the significance of studying single-file movement to the open questions: Which factors influence the fundamental relationships? What are the possible movement quantities that describe the walking characteristics of pedestrians?

Over the past decade, several experiments have been conducted to explore single-file movement. The objective of these experiments is to identify basic relationships within a system using a minimal number of variables and significant factors. In these experiments, researchers typically set up a controlled environment in which pedestrians are asked to walk through a narrow corridor without overtaking. Figures 1(a) and 1(b) show the publication trends over the years and countries/territories, respectively. The surge in publications over the past years

(a) Publications by year.

(b) Publications by country/territory (based on the affiliation of the authors).

Figure 1   The number of publications that mentions **single-file movement pedestrian dynamics** or **single-file motion pedestrian dynamics**, according to a Scopus search on 29 March 2024.

shows a rising interest in single-file movement in pedestrian dynamics. However, it is worth noting that the terminology **single-file movement pedestrian dynamics** or **single-file motion pedestrian dynamics** is a relatively recent concept that, until now, has not been well-established (see the number of publications in Figure 1(a)). We can divide the research focus of publications on single-file movement in pedestrian dynamics into four main subjects: experiments, data analysis, modeling, and experiments with models (see Figure 2). We note that the number of publications on the main four subjects is relatively sparse compared to other research areas in pedestrian dynamics.

Given the importance of single-file experimental research, conducting a comprehensive literature review is essential to identify the gaps in previous studies and outline directions

for future research. Xue et al. [3] have examined and compared pedestrian single-file experiments. They have collected existing experimental work and compared the basic characteristics of pedestrian movement. This analysis offers insights into experimental configurations, scenarios, and movement parameters. Their work also covers methods for measurement, data extraction, stepping behavior quantities, influential factors, and simulations of single-file pedestrian flow. Still, a more in-depth review, focusing on the details of the experiments from a data analytical viewpoint, is required. In this work, we aim to explore various traffic systems, including humans, mice, ants, bicycles, and cars, to identify similarities and differences that can improve pedestrian dynamics. Furthermore, we define pedestrian single-file systems and discuss their types. We provide more types of experimental setups and movement influential factors, along with discussion. Moreover, we propose a methodology for preparing trajectory data and calculating movement quantities using an open-source Python tool called "SingleFileMovementAnalysis" [4], which is significant for enabling future research to build on.

The subsequent sections of this paper are structured as follows. In Section 2, we explore the single-file traffic systems available in the literature and provide comparative insights. Additionally, we define the single-file pedestrian system. In Section 3, we review the single-file experiments in the literature focusing on the type of setups. In Sections 4, we explore the data collection methods adopted and the movement quantities investigated in the single-file experimental research. In Section 6, the influential factors affecting pedestrian movement are studied. In Section 7, we propose a methodology for preparing trajectory data and calculating movement quantities and present a Python software tool to analyze single-file movement data. Finally, in Section 8, we provide a summary of the findings, identify open issues, and suggest future research directions.
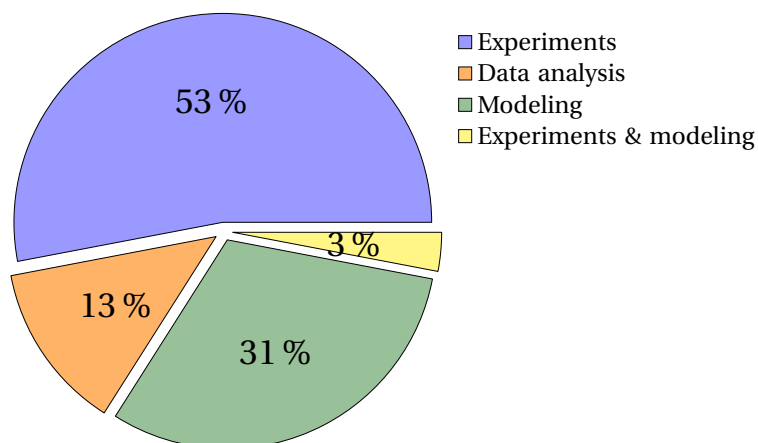
Figure 2   The percentage distribution of single-file movement publications in pedestrian dynamics across various subjects, from the literature reviewed for this paper.

2. Exploring Single-File Traffic Systems: Definition of the Pedestrian System and Comparative Insights

Several single-file experiments have been conducted to investigate human movement [1, 2, 5–41]. After reviewing the literature above, we define the **single-file pedestrian system**, following the general definition of a system as described by Backlund et al. [42], as a group of interacting pedestrians walking in a narrow path (physical or virtual path [22]), where individuals are unable to pass each other (rule: no overtaking). The order of the pedestrians remains constant throughout the duration of the experiment. In this context, the system aims to question the basic elements of pedestrian movement, including physical and psychological interactions.

The single-file system can be a **closed system** or an **open system**. In a closed system, pedestrian movement is influenced by elements within the system. Whereas in an open system, the surroundings influence pedestrian movement. The term "surroundings" refers to the systems adjacent to the area of interest. For example, this includes when pedestrians leave the predefined system boundaries and interact with the external environment. Further explanation of the open and closed single-file systems is described in Section 3. After defining the pedestrian single-file system, this section aims to identify similarities between human and non-human single-file systems. We investigate the fundamental principles of movement that govern these systems and identify possible movement similarities.

Exploring other single-file systems involving non-human entities offers valuable insights into understanding movement properties and relations in these systems. For example, studying the adaptive behaviors of ants and mice, and observing the movement of bicycles, and cars in response to movement stimuli (obstacles, other entities around, etc.) can inspire innovative modeling or crowd management approaches. Table 3 in Appendix A summarizes all single-file experiments reviewed in this article for various traffic systems.

Non-human single-file systems, such as those observed in insects and rodents within animal societies, have been explored in the literature [43, 44]. Both systems (mice and ants) demonstrate that speed decreases with increasing density and exhibit a piecewise linear relationship between headway distance and speed, similar to the human system. However, scattered data points have been observed in these relationships. The researchers attribute this primarily to random pauses. For example, Xiao et al. [43] found that at all densities, mice stop under various circumstances, including spontaneous pauses, space constraints, and tail effects. Similarly, Wang et al. [44] observed that ants exhibit random pauses during their experiments. Unlike in human systems, stopping occurs only when insufficient space is available to move forward at high densities [45]. Another difference is that mice and ants do not maintain personal space while walking, which results in increased speed and flow at high densities. For instance, in the experiment with mice, the flow remains almost constant at high densities (non-dimensional density above 0.4 m) because the mice tend to make contact and move on top of each other, a behavior we refer to as overlapping. Like in ant experiments, behaviors such as touching and moving backward were observed. Unlike the human system, where flow and speed decrease at high densities because pedestrians maintain some distance to avoid collisions and touching others. We recognize that differences in movement can be attributed to the dissimilar physical attributes (i.e., body size and shape), cognition, and decision-making processes of humans and non-human beings. However, we assume that touching and pausing behavior helps to gain insight into improving flow in high densities

(short headway distances less than personal space).

Another group of single-file systems explored in the literature is vehicular systems. Research on vehicular single-file movement shows good agreement on the relationship between certain movement quantities [46], such as the density-flow and density-speed. However, vehicles such as bicycles [14, 46, 47] and both human-driven and autonomous cars [48–51], are machines controlled by humans. This indicates that the movement of these vehicles is systematic and dominated by the physical restrictions on the car, such as limitations on possible acceleration. We assume that investigating vehicular systems helps us understand how humans make decisions to control vehicles, addressing three main concerns: following instructions, avoiding collisions, and ensuring safety. Thus, the advantages reflected in pedestrian dynamics from studying vehicular traffic can be linked to understanding cognitive processes. The differences and similarities in the movement characteristics among single-file traffic systems (such as pedestrians, mice, ants, bicycles, and cars) are summarized in Table 1.

Table 1 Comparison of movement characteristics among different single-file traffic systems.

Traffic system	Keep distance in front	Sensitivity to distance in front in controlling the speed	Overlap behavior	Pauses/stopping behavior	Backward movement
Human	Yes, respect personal space	Sensitive	Do not occur	Stop-and-go waves at high densities	Rarely (when someone unintentionally collides with the proceeding)
Mice	No	Not sensitive	Occur	At all densities (spontaneous pauses because of space constraints, and tail effects)	-
Ants	No	Not sensitive	Occur	Short pauses	Occur (despite the large distance available in front)
Bicycles	Yes, keep distance to avoid potential collisions	Sensitive	Do not occur	Stop-and-go-waves at high densities	Do not occur
Cars	Yes, keep distance to avoid potential collisions	Sensitive	Do not occur	Stop-and-go-waves at high densities	Do not occur

3. Types of Experimental Setups

In this section, we review the forms of the setup configurations and discuss their distinct features of available single-file experiments involving pedestrians. Then, we discuss aspects of the setup types that have already been investigated in the literature, presenting our insights in this regard.

Experimental studies on pedestrians' single-file movement have been performed in various shapes/types of setups (see Figure 3): oval [1, 2, 5, 6, 8, 11–13, 17, 19, 21, 25, 26, 28, 29, 32–34, 38, 39, 41], circle [7, 9, 10, 14, 16, 22, 24, 32], stairs [15, 35, 36], one-dimensional observation area [22, 27, 31], square with four straight corridors and four arcs [40], rectangle [30], rectangle with four straight corridors and four arcs [23], ship corridor [20], branched [37], seat aisle [18], flood [52].
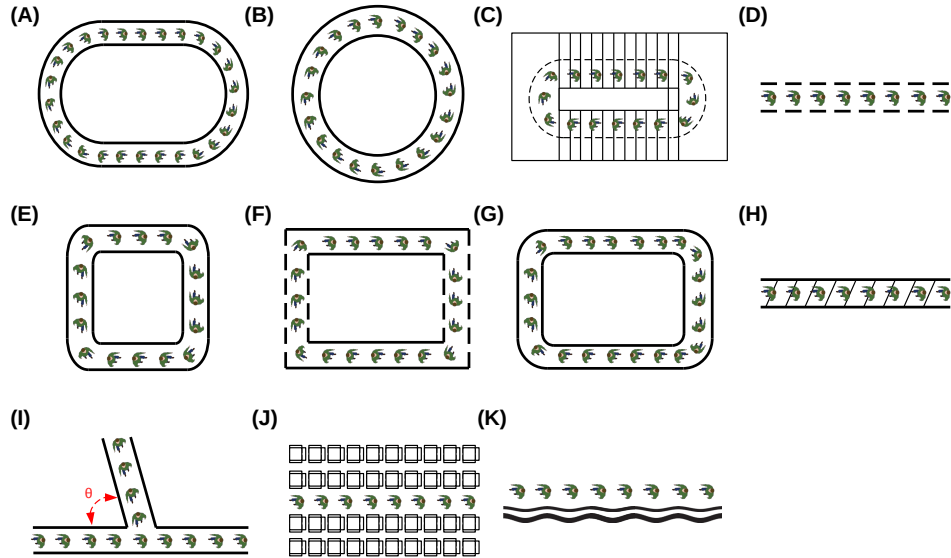
Figure 3   Illustrations of the experimental setups for different evacuation scenarios: (A) Oval (B) Circle (C) Stairs (D) One-dimensional observation area (E) Square with four straight corridors and four arcs (F) Rectangle (G) Rectangle with four straight corridors and four arcs (H) Ship corridor (I) Branched (J) Seat aisle (K) Flood.

We observe that the selection of the shape/type of the experimental setup is contingent upon the **evacuation scenario** the authors intend to investigate. After reviewing the literature, we can categorize single-file experiments into five evacuation scenarios based on the evacuation facility under study: flood (moving in water), stairs, ships, seat aisles, and ground level (in general).

Here, we provide a brief overview of the relevant literature on the evacuation scenario in flood, stairs, ship corridors, and seat aisles. Li et al. [52] investigate the effectiveness of different formations for evacuating pedestrians during a flood. They experimented with a pool, using a single-file system at two specific water depths (0.35 m and 0.60 m), and compared the efficiency of evacuations with and without a rescue rope. In the investigation of stair evacuations, Chen et al. [15] conducted experiments exploring the density-velocity and headway-velocity relations for pedestrians ascending and descending stairways. Wang et al. [35] further investigate the impact of stair configuration (ascent or descent) and explore the influence of stair dimensions on pedestrian movement characteristics. Ye et al. [36] focus

on analyzing pedestrian movement under motivation, specifically fast walking, and compare it with normal walking. Shifting the focus to evacuation in ship corridors, Sun et al. [20] designed a simulator for ship corridors and conducted experiments on single-file movement to explore the impact of trim and heeling on walking characteristics. Lastly, for seat aisle evacuations, Huang et al. [18] explore aspects such as headway distances, walking speed, effects of inactive pedestrians (non-moving), aisle width's impact, and density-speed relations in pedestrian dynamics. While these studies offer valuable perspectives on single-file movement, our research aims to narrow the focus to ground-level experiments.

In ground-level experiments, various shapes/types of setups were explored and can be divided into two groups depending on the boundary conditions under which the experiment was conducted: **open (open system) or closed boundary conditions (closed system)**. Experiments under open boundary conditions include setups with open entrances so that pedestrians can enter and leave during the experiment. Examples include branched and one-dimensional observation areas. Lian et al. [37] employs a branched setup in which pedestrian streams from two entrances converge into a single main channel to reach the exit. The authors aim to explore pedestrian movement properties through single-file merging experiments, varying merging angles, and inflow rates. In the one-dimensional observation area, Appert-Rolland et al. [22] conducted unidirectional experiments to investigate collective and individual decisions in walking. In other words, they study how pedestrians adapt their trajectories and velocities while walking freely in a group of people, rather than moving within a fixed density of pedestrians. During the experiments, pedestrians moved along a fixed straight line across the facility, one after the other, following a leader who walked at either their free velocity or a prescribed low velocity. Huang et al. [27] performed a one-dimensional observation area experiment to analyze the impact of luggage on pedestrian flow at traffic terminals. Participants were instructed to imitate walking in a terminal by following the queue while passing through the observation area. Wang et al. [31] also conducted a one-dimensional observation area experiment to study knee and hand crawling evacuations in fire accidents. Participants passed through a narrow channel divided into two parts: an upright walking area and a knee and crawling area, allowing the investigation of the sole movement characteristics of pedestrians and their movement properties under an increasing inflow at the channel's entrance. In the aforementioned studies, we observe that the authors opted for an open-boundary setup because they are interested in monitoring inflow and outflow, to and from, the experimental setup.

In experiments under closed boundary conditions, the configuration is enclosed, enabling pedestrians to move within the setup without exiting during the experiment. Examples include an oval, circle, rectangle, a rectangle with four straight corridors and four arcs, and a square with four straight corridors and four arcs. The most commonly explored shape/type is the oval; approximately 52% oval from the total single-file experiments reviewed for this article (for all evacuation scenarios). Seyfried et al. [1] are the first researchers who introduced the oval setup for pedestrian's single-file experiments. The authors explain that the oval setup, similar to the one in [53], limits the number of test objects in the experimental setup and achieves high density without boundary effects. Besides, implementing circular guiding of the passageway gives periodic boundary conditions.

Experiments involving single-file movement in a circle shape or type constitute approximately 19% of the total single-file experiments. The initial research adopting the circle shape in single-file experiments was done by Jezbera et al. [7]. Subsequent studies have continued to perform circle experiments [9, 10, 14, 16, 22, 24, 32]. None of the researchers explicitly

stated the rationale behind choosing the circle over the oval configuration. Jezbera et al. [7] merely state that they chose a geometry allowing pedestrians to walk in a single line without overtaking, to perform experiments at various pedestrian densities, and to operate in closed boundary conditions. After reviewing the single-file experiments, we summarize the purposes of experimenting as follows:

1. **Investigate movement characteristics or behavior** such as distances between pedestrians who are prevented from avoiding each other [7], the relationship between density and speed [1], the relationship between instantaneous velocity and spatial headway (the distance to the predecessor) [10], microscopic movement characteristics (density-speed, lateral sway, step frequency, headway distances, and speed-headway distances) [11], stepping behavior (step length, step duration, stepping synchronization, step extent and contact buffer) [19,34,54], the movement in high-density conditions [24], and influence of bottlenecks on pedestrian flow [55].

2. **Validate the newly developed methods for extracting** trajectories of pedestrians' heads [6].

3. **Assess the effects of several influential factors** on movement properties, such as pedestrian flow conditions [9], walking and stepping without a steady beat [16], adapting trajectories and velocities in crowds [22], social conventions and location (the place where pedestrians live) [2, 41], age groups/compositions [12, 25], gender [26, 39, 56], background music [28], height constraints [29], and social distancing measures [33].

4. **Compare different traffic systems**: cars, bicycles, and pedestrians. Zhao et al. [14] conducted comparative research on the three traffic systems, employing space-time, flow-density, and space-velocity phase diagrams for analysis.

5. **Compare the data extracted from** both experiments and field studies [17].

6. **Compare the influence of different shapes of experimental setups** on pedestrian walking characteristics: oval vs. circle [32].

In ground-level experiments under closed boundary conditions, few researchers have studied single-file movement using the following setup shapes/types: a rectangle, a rectangle with four straight corridors and four arcs, and a square with four straight corridors and four arcs. Wang et al. [30] investigate the movement characteristics of pedestrians during the deceleration phase. The experimental setup employed a rectangular configuration; the rationale behind using a rectangular shape is not explicitly stated. This configuration consisted of two horizontal and longitudinal paths. The authors emphasize the significance of understanding the deceleration phase in real-life scenarios, where pedestrians slow down to avoid collisions when their predecessors suddenly come to a stop. The focus of Wang et al.'s article is on examining different stop-distance commands: normal stop and close stop, for two types of walking speeds, namely normal and fast walking. Cao et al. [23] investigate the influence of the pedestrian's visibility on the movement properties in a rectangle with four straight corridors and four arcs setup. The authors performed three types of experiments under limited visibility: 0.3% (partial visibility), 0.1% (partial visibility), and 0.0% (no visibility) light transmissions. The shape of the setup has four straight corridors with three arcs built with longitudinal walls. These long walls serve as boundaries to ensure that participants remained within the experimental setup while walking with limited visibility.

From reviewing the ground-level experiments, we observe that the selection of open or closed shapes/types depends on the goal of limiting the number of pedestrians inside the experimental setup and achieving high density without encountering boundary effects. Additionally, it depends primarily on the **purpose of the experiment**. For example, Lian et al. [37] aims to investigate the effect of complex structures (pedestrians merging on branching walking paths) on the properties of pedestrian movement. Another experiment by Seyfried et al. [1], where they executed an oval setup to analyze the simple system of pedestrians walking at different densities and without boundary effect. However, some researchers do not explicitly state the reason for choosing the shape/type of the experimental setup, but we deduce it based on the experimental information and details provided.

In conclusion, we offer valuable insights and recommendations derived from a comprehensive review of the literature on the shapes of setups and experimental settings. We recommend having fewer variables in the experimental settings. That emphasizes isolating unwanted effects from the surrounding environment, including external sounds, weather changes, and light changes. Any variation in the experiments can impact the way pedestrians walk. Some research has already examined the potential effect of the setup configuration (oval and circle) on pedestrian movement [1, 8, 32]. The oval setup consists of two straight parts and two curvatures, whereas the circular setup is entirely composed of a continuous curve. Seyfried et al. [1] consider the possible influence of the curve part of the oval setup. To avoid this effect, they widened the width of the corridor in the curves, and a measurement section was selected in the center of the straight part of the passageway. However, we assume that limiting the investigation only to the straight part will neglect the characteristics that could be explored in the entire walking path. To avoid the previous issue, Ziemer et al. [13] proposes the transformation of the oval trajectories to straight trajectories using a transformation equation. In this case, the investigation of all trajectories is applicable. From observing some oval experimental videos, we notice that the navigation between the two parts (straight and curved) could be possible for a change in the walking behavior because the pedestrian turns at the beginning of the curve. The study of [13] already assumes the potential influence and compares the fundamental diagram relationship (density-speed) of the straight and curved parts. They use the Kolmogorov-Smirnov test to determine whether two data sets in the density-speed relationship have the same distribution. The results found that the difference between the straight and curved parts can be neglected. Fu et al. [32] have another opinion about the possible influence of the curve. The authors conducted a comparative analysis of two experiments: the oval and circle experiment, and kept the other experimental setting identical including the central circumference of the movement path, the number of participants in each run, trajectory extraction methods, movement direction, and measurement methodologies for movement quantities. The results show discrepancies in pedestrians' flow characteristics. The flow in the straight part of the oval setup is 20% higher than in the curved part, both in the oval and in the circular passage. The authors relate this observation to the spatial distribution of pedestrians. The distribution on the straight part is more heterogeneous, allowing for a more efficient use of available space and leading to a longer flow. In contrast, curvature influences a more homogeneous distribution of pedestrians than that observed on the straight part. Additionally, the probability density function of the instantaneous density for both setups is compared. It is found that the mean instantaneous density in the oval passage is higher than in the circular passage at a high global density. The curvature effect causes differences in pedestrian distribution and decreases density. The findings indicate notable discrepancies in the movement characteristics between the oval and circle setups. Thus, we advise researchers

planning to analyze experiments involving curves to either smooth the turns using the same turning angles as the experiments they intend to compare with or compare the results with experiments of similar shapes.

4. Data Collection

This section provides an overview of the data collection processes for pedestrians' single-file experiments conducted under closed-boundary conditions (for more details, refer to Table 4 in Appendix B). This section does not explore the devices suitable for data collection in achieving the experiment objectives. However, we provide an overview of the data collection processes in the literature, the data types, and the devices used to collect data from single-file experiments.

We define **data collection** in single-file experiments as a systematic process for collecting and processing data to investigate the characteristics of pedestrian motion. Several data collection processes are followed depending on the **data type, devices, and methods** used for data collection. The process mainly includes the following steps: installing the devices to collect data (i.e., capturing videos and detecting brain signals) and processing the data (e.g., extracting head positions by detecting pedestrians' heads and tracking them throughout the experiment duration). Based on the experiments we review, the data collection processes can be categorized into two groups:

1. **Semi-automatic data collection**: combines both manual and automatic processes. In other words, some tasks or functions in the data collection processes are automated, while others require human intervention. For instance, Chattaraj et al. [2] use a digital camera to capture the experiments and manually extract the data frames of participants entering/exiting from the measurement area by observing the videos. This category includes the following researches [1, 2, 5, 16, 17, 26, 41].

2. **Automatic data collection**: all processes are fully automated. The only involvement of humans is to verify and manually adjust the results from the system. For example, Paetzke et al. [39] capture the whole experiment using a digital camera and then detect and extract pedestrians' heads using PeTrack [57] software. This category includes the following studies [1, 6, 7, 11–14, 16, 19, 21–25, 28–30, 32–34, 37–40, 54, 58].

The first step in the data collection process involves employing the **appropriate devices** to collect data required for the investigation. In single-file experiments, various devices are installed to collect data and differ in the type of data they measure (see Figure 4).

The primary focus of most experiments is to capture pedestrians' positions over time through **head trajectories** [5, 6, 11–14, 19, 21–26, 28–30, 32, 33, 39, 40, 58], which is significant for calculating movement quantities such as speed, density, and headway distances. **Cameras** are the predominant devices used to collect head trajectories. The cameras capture video footage, enabling the extraction of head trajectories; or other data of interest; by detecting and tracking pedestrians' heads throughout the experiment execution. This process results in 2D or 3D positions of pedestrians over time, referred to as pedestrian head trajectories. Various types of cameras are utilized for this purpose. For instance, **digital cameras** are used to capture the experiment from a side-view [1, 5, 38] or bird's-eye view [6, 11–14, 19, 21, 23, 25, 28–30, 32, 33, 37, 39, 58]. The former condition (side-view) is
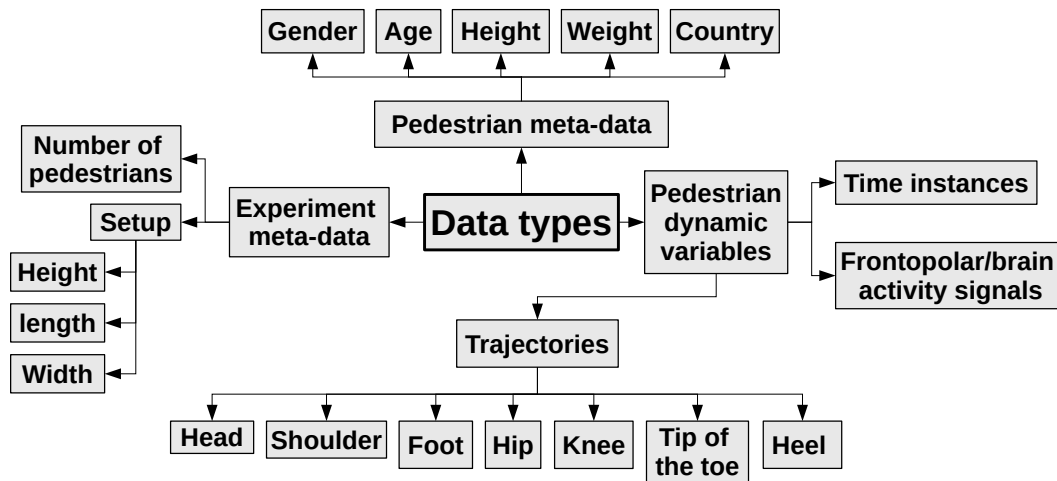
Figure 4   The data types presented in the single-file movement articles (under closed-boundary conditions)
from the literature in this article.

recommended when the roof of the experimental hall is not high enough to locate the camera
perpendicular to the setup, or if the researchers are interested in observing the movement
characteristics from the side view. Whereas, the latter condition (bird's-eye view) provides
the data of the overall periodic movement of all pedestrians inside the entire setup. Also, the
foot trajectories extracted by Ma et al. [19] from the videos. Another type of camera used
by Seyfried et al. [1] is the **Stereo Vision camera**, which is connected directly to a software
package for detecting and tracking pedestrians. Jin et al. [24] used a **UAV drone camera**
to capture the entire experiment from the sky during a not-windy day. The experiment took
place away from buildings, where the camera could not be fixed to a stable surface. A differ-
ent type of used by [10, 22] is the **infrared camera**, where they installed the VICON motion
capture system, which contains an **infrared camera** to collect head trajectories and **shoulder
trajectories** [10]. Ma et al. [34] used the **Camcorders device**; a portable combined video
camera and recorder; to collect head and **foot trajectories**.

More data types are extracted from video footage, as demonstrated in the Thompson et
al. [38] experiment. They use a digital camera to capture video and track white sticker mark-
ers that pinpoint specific points of interest on participants' bodies: shoulders, **hips**, **knees**,
tips of the toes, and **heels**. This video footage is processed, and markers are detected to
extract trajectories of the hip, knee, tip of the toe, and heel. Furthermore, **time instances** are
extracted or recorded from videos. For example, time frames of entry/exit to/from a specified
measurement area are recorded to calculate the density in [1, 2, 5, 17, 41].

Other devices are less commonly used in the literature for extracting movement data, such
as the **light gate** [7], which detects the time each pedestrian crosses a designated spatial
point, and the ultra-small near-infrared spectroscopy **(NIRS)** device [16] to measure **fron-
topolar/brain activity signals** for investigating cognitive processes while pedestrians are
walking or stepping. Furthermore, an **Ultra-Wideband (UWB)** positioning and sensors are
used to collect pedestrians' trajectories by utilizing tag signals combined with the location co-
ordinates of the base station [40]. As a result of a comprehensive review of the data collection
processes in the literature, we deduce that the selection of data collection devices depends on
the types of data one aims to measure or record to investigate quantities related to move-
ment. Besides, this choice is influenced by the researchers' preferences, which are shaped

by the availability of both experience and financial resources to explore and implement new, specialized devices.

The second step of data collection involves the **processing of the collected data**. We define the processing of collected data step as extracting the data of interest from collected data and preparing the data for usage. Processing steps vary depending on the requirements of the collected data and their utilization in the investigation (i.e., calculating movement quantities using pedestrian positions). One of the most common processing steps for video footage is the extraction of pedestrians' head trajectories over the experimental duration. To achieve this, the process begins by detecting persons' heads or head markers in the initial frame. Then, track the head/marker positions of individuals in the subsequent frames. Other data types can be extracted from the videos, such as pedestrians' properties stored in an ID marker used in the Paetzke et al. experiment [39]. Several methods have been employed in the literature to process the data, such as **manual observation** of the videos [1, 17, 41], applying image processing techniques based on the **mean-shift algorithm** [19, 23, 33, 37], **Tracker software** [24], and **PeTrack software** [5, 12, 21, 25, 26, 28–30, 32, 39]. PeTrack is the most commonly used software in the literature because it is specialized software for calibrating, recognizing, and tracking pedestrians [57]. Besides, it is free and open-source software.

5. Movement Quantities

After collecting the movement data, the next step in conducting analysis is to use this data to calculate movement quantities that describe the motion behavior of pedestrians. In this section, we narrow the focus on the research of ground-level experiments conducted under closed boundary conditions. We discuss the movement quantities of pedestrians and the methodologies employed to calculate these quantities. We also summarize some artifacts that influence the analysis results in single-file movement.

The most common movement quantities described in the literature to characterize pedestrian dynamics are pedestrians' walking speed, density, and headway. There are other movement quantities to describe the pedestrian movement. We can categorize them into four groups based on **their focus on different aspects of human behavior**: quantities to describe **head movement** (to represent pedestrian movement) [1, 2, 6–8, 10, 12–14, 17, 22–26, 29, 30, 32, 33, 39, 41, 55, 56, 58], and quantities related to **stepping locomotion** [9, 19, 21, 34, 38, 54], **both** (head movement, stepping locomotion) [11, 28], and **cognitive behavior** (using brain signals) [16]. Here, we focus our review on the head movement research.

Different methodologies are employed to calculate movement quantities based on several aspects. The first aspect is the **level of movement they describe**, including **microscopic** [12, 13, 26, 30, 31, 33, 37, 39] and **macroscopic** levels [1, 2, 28, 41]. At the microscopic level, the movement properties of each pedestrian are investigated over the experiment's duration. At the macroscopic level, the movement properties of a group of pedestrians are studied over the experiment's duration, either averaged by time or space (refer to Xue et al. [3] review, Section 3, for the equations for calculating movement quantities). Jelic et al. [10] qualitatively analyzed the influence of different measurement procedures: macroscopic and microscopic; which they named as global and local measurements, respectively. The finding of comparing the density-speed diagram of both measurements show a quite similar result when the density is low (approximately density less than 1.2 m^{-1}). While, for larger densities (when stop-and-go waves appear), the results of both measurements differ. Similarly, Ren et al. [25]

observed that the density-speed relation for both macroscopic and microscopic measurements have no significant differences. We notice that using macroscopic measurements, where the movement quantities are averaged for multiple pedestrians, ignores the individual movement characteristics. To better understand the underlying causes of the observed disparities in results, it is significant to conduct further quantitative research. The research should aim to compare the outcomes of various measurement procedures for single-file experiments in the future. It has already been reported that differences in measurement procedures yield varying results in terms of density-speed relation [59]. However, these results are validated for crowds in straight corridor and T-junction experiments, not for a single-file movement experiment.

The second aspect is the **setup area that the measurements cover**. In the literature, investigations conducted in the **measurement area** (a predefined part of the experimental setup) [2, 23, 26, 28, 29, 32, 33, 39, 41], or the **entire setup path** (after applying a linear transformation or using 2D calculations) [12, 13, 25, 28]. Upon reviewing the literature, we notice that the calculations of the movement quantities covering a specific part of the setup are simpler. This is because there is no need to perform any transformation (we further discuss this in Section 7) on the trajectory data - if the aim is to investigate the longitudinal movement (along the x-axis trajectories)-, and the equations for calculating movement quantities apply solely to that area. However, investigating the movement of pedestrians throughout the entire setup offers the advantage of observing phenomena that become visible only when including complete trajectories of pedestrians. Examples of such phenomena include stop-and-go waves [13].

The third aspect concerns the **dimension upon which movement quantities are calculated**: **one dimension (1D)**, or **two dimensions (2D)**. Most single-file movement literature focuses on the one-dimensional movement characteristics. The researchers are interested in the longitudinal interactions among pedestrians walking in single-file experiments. Only Fu et al. [32] calculated the speed and density in 2D in the circle experiment. Yet, no research has compared the differences in the analysis results using measurements over 1D and 2D. We plot, using data from Paetzke et al. [39] experiment, the speed-density relation utilizing our analysis tool (more details in the next Section 7) to see the differences between 1D or 2D measurements. We calculate the pedestrian displacement in the 2D for speed calculation. The density in 2D is the reciprocal of the half horizontal distances with the follower and predecessor plus the vertical distances with the wall, which is a constant value equal to the corridor width. By disregarding the constant term, the density equation remains consistent between 1D and 2D analyses (the density values in 2D increase by a constant). Thus, we discarded the analysis of density in 2D. As we see in Figure 5, the volume of speed in 2D is larger than 1D, because naturally, the magnitude of the speed in 2D is larger than 1D. The significance of this difference can be further investigated, depending on quantitative analysis and the objective of the experimental study (is the lateral displacement of the head important for the research?). The fourth aspect under consideration pertains to the **phase of movement during which the analysis is conducted**. In single-file experiments, Chattaraj et al. [2] identified three distinct phases of movement: acceleration, in which pedestrians start walking and the speed increases gradually; a steady state; and deceleration, where individuals gradually reduce speed until they leave the setup or stop. Most studies have been focusing on investigating movement characteristics during the steady state, except Wang et al. [30]. Wang et al. [30] specifically examined stop distances during the deceleration phase, which corresponds to the period wherein individuals progressively slow down until halting their movement. In our opinion, analyzing the data from a steady state allows gaining valuable
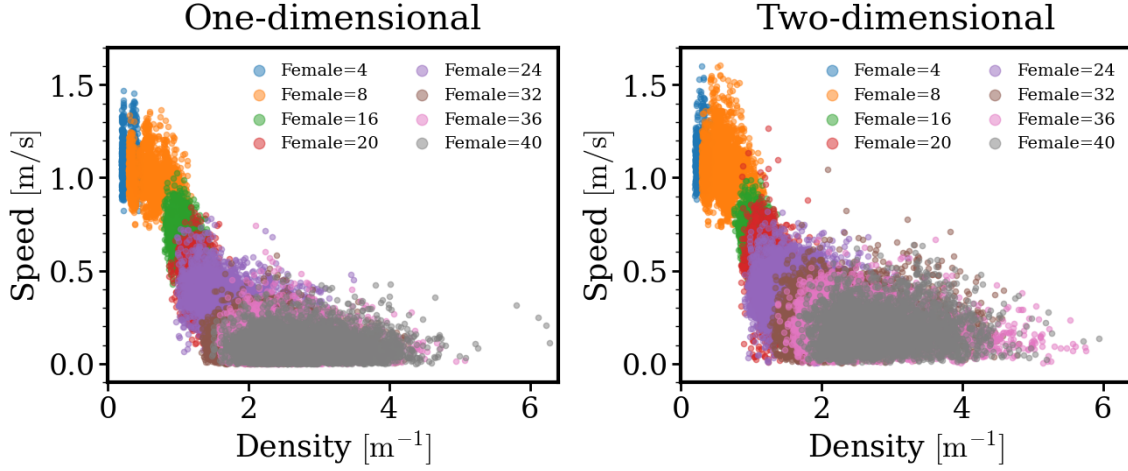
Figure 5   Speed-density relation using 1D and 2D measurements of the speed.

insights into system behavior while simplifying the analysis process. However, we assume it is essential to recognize the limitations of steady-state analysis and consider transient effects when necessary for a comprehensive understanding of pedestrian dynamic systems.

Finally, we summarize some artifacts, concerning the movement quantities calculation, that influence the results of analysis in single-file movement as reported in the literature. Jelic et al. [10] demonstrate how the number of detected markers (during the data extraction step) influences the analysis results. In the experimental videos, some pedestrians' head markers are occluded. This leads to a loss of some pedestrians' head trajectory data within a specific time interval during data extraction. Jelic et al. compared the density-speed relation using different numbers of detected markers to examine their impact on pedestrian movement analysis. In the density-speed relation, the data points for all marker quantities mostly overlap. Calculated density values are larger with fewer marker detections than with a higher number of markers detected. The reason is that in the density calculations, we include the distance between the pedestrians and their predecessors and followers. Thus, the hidden predecessor or follower (not included in the trajectory data) increases the distance value included in the calculations. We recommend that the position and number of markers detected should be as precise as in the real experiment to avoid any inaccurate findings. Another artifact is that the differences in the analysis findings depend on the density ranges covered by the experimental analysis. In Chattaraj et al.'s study [2], it is found that a linear fit can be applied to the speed-headway relation for the data points within the oval global density ranges of 0.86 m^{-1} to 1.96 m^{-1}. While, in Jelic et al.'s study, it is found that the instantaneous speed-headway relation follows a piecewise linear pattern with three regimes for investigation over an inner circle with a global density ranging from 1.06 m^{-1} to 1.85 m^{-1} and an outer circle with a global density ranging from 0.31 m^{-1} to 1.08 m^{-1}. We emphasize the importance of defining the density ranges included in the research (in general). Finally, we present in Table 2, the minimum and maximum values of global densities investigated in single-file experiments. Global density is the number of pedestrians divided by the length of the overall walking path. The lowest density investigated in the literature is equal to 0.1 m^{-1} [14, 28] and the highest value is equal to 4.03 m^{-1} [24].

Table 2   The minimum and maximum values of global densities for ground-level experiments under closed
boundary conditions (based on the literature reviewed for this article).

| Setup shape	Minimum global density (m^{-1})	Maximum global density (m^{-1})
Oval	0.1	3.5
Circle	0.1	4.03
Rectangle	0.12	0.32
Rectangle with four straight corridors and four arcs	0.21	1.30
Square with four straight corridors and four arcs	0.18	1.9

6. Movement Influential Factors

Various influential factors were investigated in pedestrians' single-file experiments (see Figure 7). In this section, we focus on discussing the influential factors of the ground-level evacuation scenario under closed-boundary conditions. We categorize these factors and discuss their influence on the characteristics of pedestrian movement.

Investigating and analyzing the potential impact of various influential factors is crucial for modelers aiming to simulate pedestrian movement and crowd event organizers to employ safety procedures. To comprehend the walking behavior of pedestrians, we need to thoroughly explore potential factors and understand their impact on movement quantities (i.e., increasing or decreasing speed, changing in flow, etc.). Additionally, understanding the movement's influential factors using experimental analysis assists in uncovering correlations and causal relationships between different variables, which is essential for defining the quantities that represent movement, such as speed, density, flow, etc. Some influential factors have already been investigated in the literature include social conventions [2], location [41], motivation-haste [5], age [12, 25], height constrains [29], setup shape [32], motivation-social distancing measures [33], gender [26, 39, 56], location [41], visibility [23], motivation-music [28], motivation-rhythm (Metronome) [9, 16, 28, 40], motivation-walking decisions [22], global density groups [1, 24], headway distance [7], walking path [10], and motivation-stop distance [30].

Upon observing various experimental videos for single-file movement, participating in experiments, reviewing relevant literature, and conducting research on diverse aspects of single-file movement, we can categorize these influential factors into three main groups based on their sources (see Figure 6):

- **Pedestrian characteristics or properties**, such as age, gender, etc.

- **Cognitive factors** involve mental processes and knowledge acquisition through thoughts, experience, and the senses, i.e., route choice, and motivation.

- **Social factors** including interactions with nearby pedestrians, etc.

- **Environmental factors**: location, weather, lighting conditions, etc.

We define **social conventions** as a set of agreed-upon or generally accepted standards and social norms that a group of people follows. These conventions influence walking behavior,
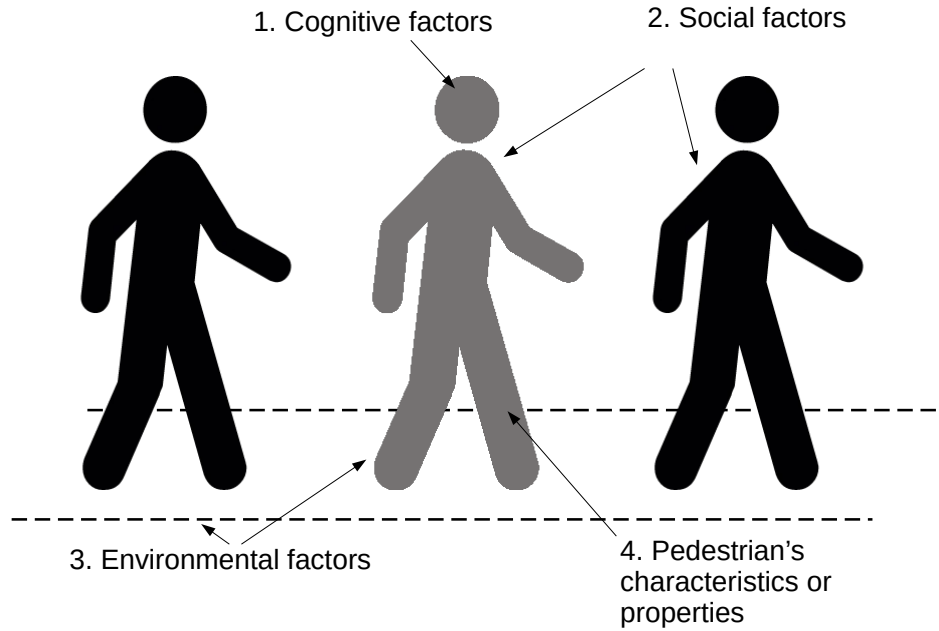
Figure 6 Main groups of the single-file movement influential factors proposed by the authors.

as observed by Chattaraj et al. [2] in their experimental research comparing the movement of German and Indian young participants. They conducted quantitative and qualitative statistical analyses by comparing the free-flow speed, density-speed, and speed-headway relations of Indian and German experiments. The results indicate that the speed of Germans is more dependent on density than the speed of Indians, and there are unordered movement characteristics in the Indian data, with more fluctuation in speed and density values than in the German data. Additionally, similar free-flow speeds were found for both Germans and Indians, indicating that when walking alone, both groups move at approximately the same speed. Another finding shows that Germans maintain more personal space (headway distance between pedestrians and those in front of them) than Indians. Bilintoh et al. [41] also study the effect of social conventions by examining the **locations** of compatriots. They performed single-file experiments in Ghana and China for African students and compared their movement characteristics (density, speed, flow, headway). The findings of statistical analysis by comparing the density-speed relation show that Ghanaian pedestrians (speed interval equal 0.74 ± 0.01 m/s and 0.32 ± 0.02 m/s) walk slower than the African students living in China (speed interval equal 1.11 ± 0.01 m/s and 0.31 ± 0.03 m/s) with the same global density of 0.62 m^{-1} and 0.95 m^{-1}, respectively. Besides, Ghanaians maintain a smaller personal space than African students living in China by comparing the headway distances.

The influential factors concerning the **properties of pedestrians**, such as age and gender, are investigated. Ren et al. [25] and Cao et al. [12] research the **age** effect on pedestrian movement. Cao et al. perform a comparative analysis between homogeneous and heterogeneous age groups, including youth (age range 16-18 with an average mean age of 17 years old), old adults (age range 45-73 with an average mean age of 52 years old), and mixed random (youth and elders together ordered randomly in the setup). Whereas, Ren et al. focused on the elders' movement of age range between 50-85 years old, with an average age of 70. Cao et al. found from the analysis of the speed-density relation at the microscopic level that

young students move faster than old adults. At the same density situations, the speed of the young group is higher than that of a mixed group. The speed of the mixed group is a little lower than that of the old adult's group for the density between $0.5\,\mathrm{m}^{-1}$ and $1.2\,\mathrm{m}^{-1}$, whereas it is higher for density less than $0.5\,\mathrm{m}^{-1}$. Besides, the flow increases monotonically with the increase in density for all groups but reaches different peak flows -1.3 s^{-1}, 0.9 s^{-1}, and 0.7 s^{-1} for youth, old adults, and mixed, respectively- around a density of $0.9\,\mathrm{m}^{-1}$. Ren et al. compare the speeds of elders and old adults. The elders walk slower than the adults in the low-density group but at approximately the same speed as those in the mixed group. Furthermore, from observing the time-space diagram, the stop-and-go waves occur more frequently and last for a longer duration in the elderly group compared with the old adult group. Moreover, the authors observe from the experiment videos, time-space diagrams, and headway values that some elders wait several seconds until they have a certain amount of distance in front to move again. The elders do not walk again synchronously with the proceeding pedestrian after stopping. They call this phenomenon the "active cease". We ascribe the difference in movement to the physical mobility capabilities of pedestrians. In **gender** investigations, two experiments were conducted by Subaih et al. [56] and Paetzke et al. [39] to explore the impact of gender composition on pedestrian dynamics. While their objective is similar, their contributions and findings have some differences. Both studies utilize statistical analyses to determine the significance of their findings with different testing methods. The authors aim to understand whether variations in pedestrian dynamics are attributed to gender differences. In both research studies, the results show that pedestrian groups with homogeneous gender compositions (either all female or all male) exhibit similar density-speed relationships. When comparing the homogeneous and heterogeneous (male-mixed alternating with female) gender groups, Subaih et al. found differences in the density-speed diagram. It means there is an effect of the gender of neighboring pedestrians on the pedestrian movement under investigation. However, the analysis by Paetzke et al. extends to different group compositions (homogeneous male, homogeneous female, mixed alternating, and mixed random gender order), and compares Subaih et al.'s experiments' fundamental relations using a Tukey HSD test. In contrast to Subaih et al. results, the analysis demonstrates that any effects of gender composition on pedestrian speed-density relations are either nonexistent or only observable within a narrow density interval. Paetzke et al. state that the reason for these discrepancies depends on the verification of the results (statistical testing method applied), as well as on the data preparation. Furthermore, Paetzke et al. investigate whether including additional human factors such as **weight**, **height**, and the gender of the preceding pedestrian would improve the predictability of pedestrian dynamics represented by speed. They conclude that these factors do not significantly enhance the speed model. This reinforces the idea that both, gender composition and these additional factors, have a minimal impact on pedestrian dynamics in single-file movement.
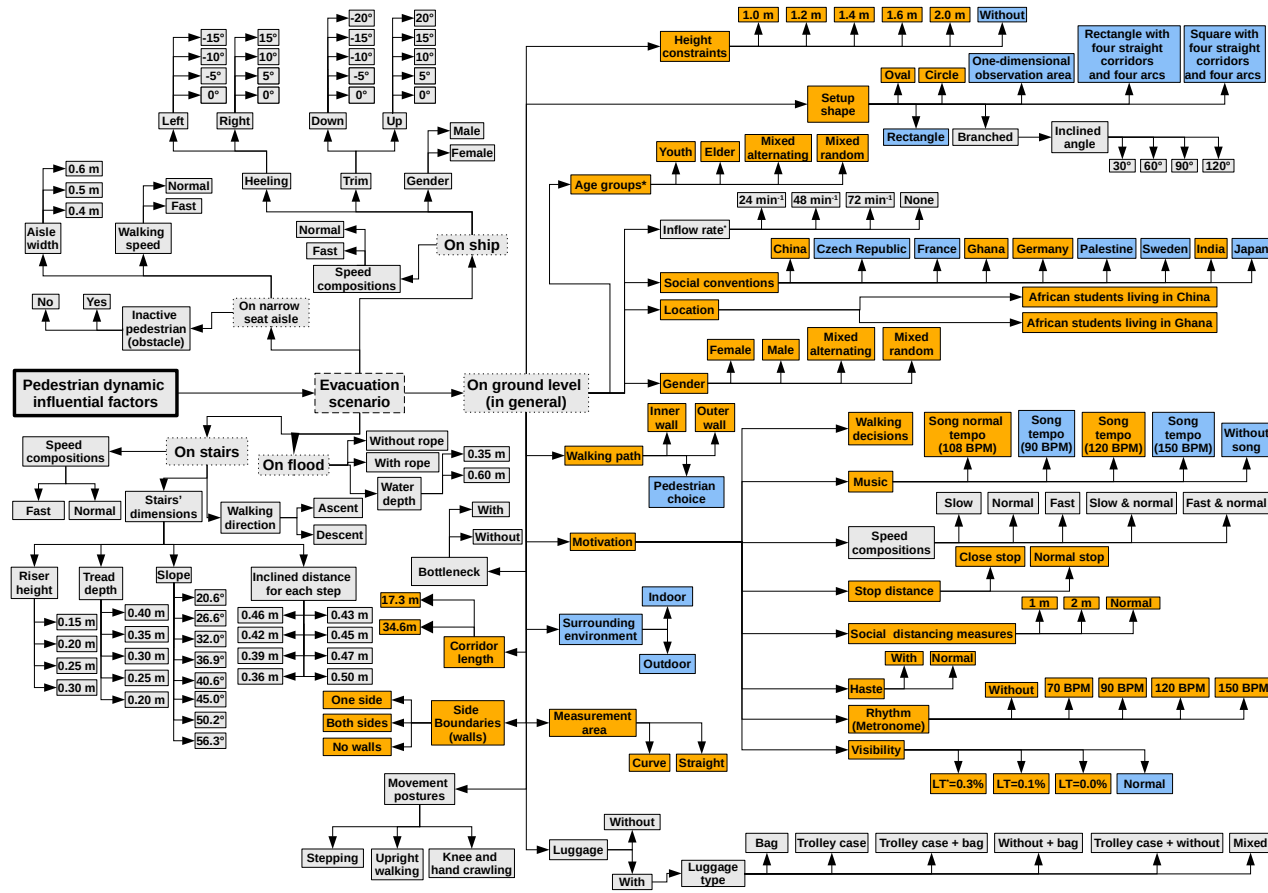
Figure 7 Categories of influential factors investigated in single-file experiments from the literature. The arrows point to, at the first level, categories of influential factors concerning the evacuation scenario, and at the subsequent levels, influential factors along with lists of quantitative and categorical variables for comparison. Orange denotes influential factors studied in single-file experiments under closed boundary conditions at ground level, while blue represents influential factors assumed in the literature to potentially affect movement or suggested by the authors.

Some influential factors are controlled or manipulated to observe their effects on the experiment's results. For example, experiment organizers motivate the participants with instructions, music, and changes in the environment to observe how their behavior and walking patterns are affected. In the research of Lu et al. [33], the authors investigate the movement characteristics of pedestrians under different **social distancing measures** similar to those followed during the time of COVID-19 in China: 1 m, 2 m, and normal conditions (before COVID-19). The analysis results indicate that with social distancing measures, participants keep a greater distance when proceeding than under normal conditions, but some violations occur. Stop-and-go waves under social distancing measures are observed not only at high densities but also at low-density ranges. We suppose the reason is that pedestrians prefer to stay alert and maintain the predefined distance to follow the instructions. Thus, they stop to estimate and adjust the distance headway before proceeding. Wang et al. [30] investigate the effect of **stop distances**. They ask the experimental participants in the deceleration phase to either stop close to the predecessor or stop normally. The authors found that the close-stop experiment resulted in a shorter average stop distance (0.34 m), in comparison to the normal stop (0.63 m). Furthermore, the slope of the speed-distance headway relationship is larger in the close-stop experiment than in the normal stop, indicating that participants in the close-stop condition decelerated more abruptly as they came closer to the person in front of them. Another example is a study by Appert-Rolland et al. [22], which focuses on the **cognitive processes** of pedestrians. They investigate how pedestrians adapt when they have more freedom of movement. The aim is to understand pattern formation, the interaction between participants, and decision-making in crowds using a simple system (single-file system). A group of participants in the experiments (18 pedestrians) were instructed to walk in a circle (a virtual circle the participant chooses without any predefined boundaries or specifications) and choose their trajectories. As a result, participants decided to form a circular path by following the predecessor and interacting with them (following behavior).

Another group of researchers focuses on the influence of **music, songs, and metronome** rhythm on pedestrian motion. They assume that music and rhythm improve the flow of pedestrians in congested situations, where there are too many pedestrians in a restricted space, without any danger. Zeng et al. [28] performed an oval experiment to understand the impact of background music on human movement (head movement and stepping behavior). Seven experiments were performed: three with music of different tempos, three with rhythm from a metronome device, and one with normal conditions (without music). The authors include, in their paper, only the analysis of the results comparing movement under normal conditions and music at 120 BPM. From the analysis of density-speed and density-flow, the results show that at medium and high-density ranges investigated, the speed and flow in the background music experiment are lower than those under normal conditions. Furthermore, from observing the space-time diagrams, stop-and-go waves in both cases (with background music and without music) start to appear at the global density $\rho_{\text{glob}} = 1.82 \text{ m}^{-1}$. However, participants stop more frequently with background music. Moreover, the stopping duration decreases with background music compared to that under normal conditions when the stopping duration is below 1.4 s, but increases when it exceeds 4.6 s. In studying the impact of metronome rhythm, Yanagisawa et al. [9], Ikeda et al. [16], and Li et al. [40] conducted experiments, each with different setup type. They all compare the movement of pedestrians in experiments with rhythm (70 BPM), and without rhythm. Yanagisawa et al. focus on step size and pace (number of steps per unit of time). Ikeda et al. study the impact of steady beats on the cognitive processes of pedestrians, measuring the participants' frontopolar activities

(brain activity) in walking and stepping groups. We recognize that the results of music and metronome rhythm research show how flow increases in congestion situations as a reason for the change in stepping behavior and cognitive processes of pedestrians.

Cao et al. [23] investigate the movement characteristics of pedestrians under various **visibility conditions**. Three levels of light transmission (0.3%, 0.1%, and 0.0%) were tested to observe how visibility impacts pedestrian dynamics. The study found that pedestrian speed and flow change significantly under different visibility conditions. Specifically, the following behavior (proceeding pedestrian or the walls) is observed under light transmissions of 0.1% and 0.0%. Moreover, stop-and-go waves appear at low densities and increase gradually with decreasing visibility. Furthermore, the maximum specific flow rates vary with visibility, being 1.3 s^{-1}, 1.15 s^{-1}, and 0.9 s^{-1} for light transmissions of 0.3%, 0.1%, and 0.0%, respectively. Furthermore, the maximum specific flow rates vary with visibility, being 1.3 s^{-1}, 1.15 s^{-1}, and 0.9 s^{-1} for light transmissions of 0.3%, 0.1%, and 0.0%, respectively. Additionally, pedestrians exhibit different sensitivities to density changes based on visibility.

Environmental factors are the physical characteristics and layout of the experiment where individuals move and interact. These factors impact the experiments' results and pedestrians' movement characteristics. Several studies have delved into environmental factors. For example, Chattaraj et al. [2] investigate the influence of **corridor length**, which reveals no significant impact on speed-density and speed-headway distance relations. Jelic et al. [10] analyze how the **walking path**: walk along the inner wall (radius equal to 2 m, length 15.08 m) or the outer wall (radius equal to 4.5 m, length 25.76 m) of the circle setup influences the pedestrian movement. The authors note that pedestrians typically maintain a slightly greater distance from the wall when walking along the outer path than the inner path. Furthermore, they found no significant variation in density-speed relations between the outer and inner paths. Ren et al. [25] explore the effects of **vertical walls** in different experimental setups, observing varying pedestrian behaviors in response to wall presence or absence. Several cases of walls exist on the setup: case one (straight part with a wall from one side), case two (straight part with a wall from both sides), and case three (curved parts without walls). The authors observe that the pedestrians in area one tend to walk away from the wall and inclined to the side without the wall. Whereas in case two, the movements of pedestrians are less fluctuated and concentrated than in the cases without the walls from one side or both (cases one and three). In case three, the fluctuations appear more frequently, and pedestrians cross the boundaries, especially in high density, which produces overlapping pedestrians. We conclude that the type of boundaries, whether vertical walls or tape on the ground, affects the movement characteristics of pedestrians. Ren et al. [25] also observe the influence of the **setup shape** on the speed of pedestrians (straight and curved). This influence was further analyzed by Fu et al. [32], where they found that pedestrian flow increases in the straight part (oval experiments) than the flow in the curve part (discussed before in Section 3). Ma et al. [29] perform experiments to understand how **height constraints** (1.0 m, 1.2 m, 1.4 m, 1.6 m, and 2.0 m) impact pedestrian movement. Key findings reveal that the speed distributions across different heights follow a Gaussian distribution, and pedestrian speeds show two distinct trends at high densities, varying significantly with the height constraint. Moreover, the results show that lower height constraints significantly reduce pedestrian speeds and affect the dynamics of pedestrian flow. In conclusion, certain experimental settings, including instructions, setup shape, and boundaries, can influence the analysis of pedestrian movement based on head trajectories, of which one should be aware.

7. Methodology for Preparing Trajectory Data and Calculating Movement Quantities

In this section, we introduce a Python tool for analyzing single-file experiments. We also propose a methodology for preparing experimental data (head trajectories), calculating movement quantities, and analyzing the common relations investigated in the single-file literature: density-speed and density-headway.

To qualitatively and quantitatively analyze the single-file movement by using head trajectories, we propose the methodology outlined in the flowchart presented in Figure 8 to prepare the raw data and calculate movement quantities.
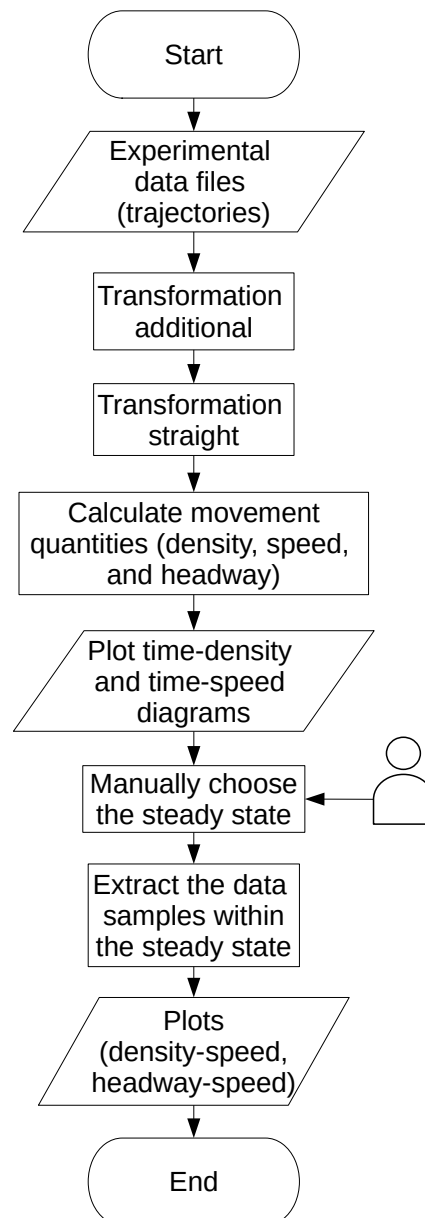
Figure 8 Flowchart for calculating movement quantities using head trajectories.

The first two steps in the methodology for preparing the raw trajectory data are **transformation additional** and **transformation straight**. Upon observing the plots of raw trajec-

tories in the literature, we noticed that the (x, y) values are centered around different points, depending on the trajectory extraction process (location of the coordination system). To convert oval trajectories into straight - a process we refer to as the "transformation straight" step, following the method of Ziemer et al. [13] - we adjust the trajectories to a new, unified Cartesian coordinate system, $T : \mathbb{R}^2 \to \mathbb{R}^2$, $\begin{pmatrix} x \\ y \end{pmatrix} \mapsto \begin{pmatrix} x' \\ y' \end{pmatrix}$.

In this system, trajectories represent a person starting her/his walk from the beginning of the bottom straight corridor $(x = 0)$, along the corridor's central line $(y = 0)$ (Sub-figure 9(b) show the new coordination system). **Additional transformation** is achieved by applying appropriate transformations in geometry, such as rotation, shifting, etc (see Sub-figures 9(a) transform to 9(c)).

Some common cases for additional transformation are summarized as follows:

1. In some experiments, the (x, y) coordinates are given in centimeters. We convert them to meters by setting the unit conversion factor u as follows: if the original units are in centimeters, then $u = 100$ to convert to meters; otherwise, $u = 1$.

2. To ensure the straight segments of the oval setup are parallel to the x-axis, rotate the trajectories by $90°$ clockwise, transforming $(x, y) \to (y, -x)$, or $90°$ anticlockwise, transforming $(x, y) \to (-y, x)$. For experiments, pedestrians walk either clockwise or anticlockwise. In clockwise experiments, apply horizontal reflection to calculate distances, setting constraints $i = -1$ and $j = -1$ for axis reflections; otherwise, set $i = 1$ and $j = 1$.

3. To align the origin with the middle line of the corridor, as shown in Sub-figure 9(b), we need to shift the trajectories horizontally or vertically. For vertical and horizontal translations, we use the constants c and d, respectively, with the value of shifting defined as $\{k, d\} \in \mathbb{R}^2$.
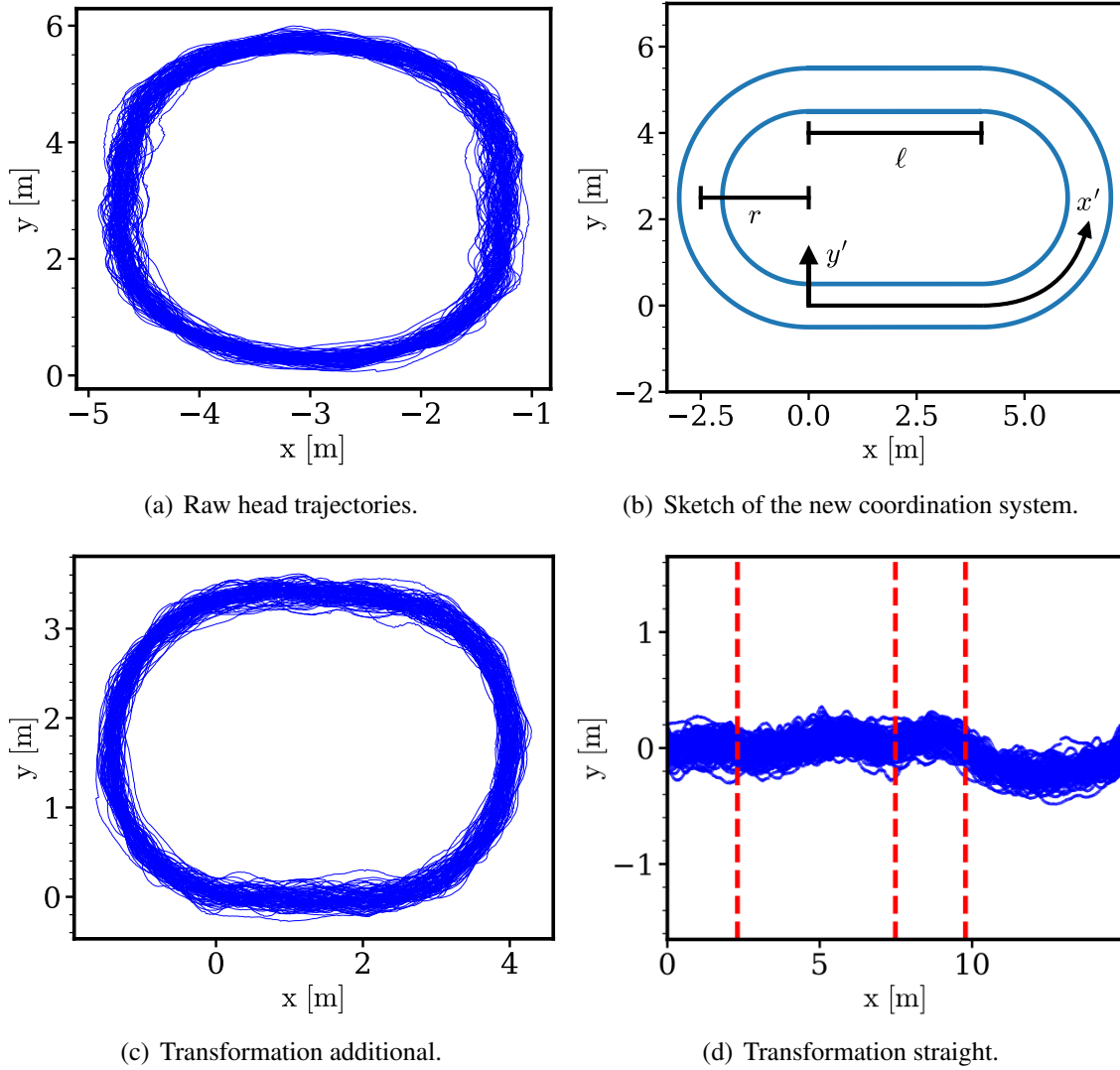
The additional transformation equations T are:

$$x' = \frac{i.x}{u} + k. \tag{1}$$

$$y' = \frac{j.y}{u} + d. \tag{2}$$

In case we want to calculate the movement quantities for pedestrians walking inside a specific area (the straight part), we need to extract (x, y) values from within the space interval of the measurement area, $(x, y) \in [a, b]$, where a and b represent the minimum and maximum x-axis values, respectively, with $\{a, b\} \in \mathbb{R}$.

To apply **transformation straight**, $T' : \mathbb{R}^2 \to \mathbb{R}^2$, $\begin{pmatrix} x' \\ y' \end{pmatrix} \mapsto \begin{pmatrix} x'' \\ y'' \end{pmatrix}$, the equations are defined as follows:

$$x'' = \begin{cases} \ell + r \arccos\left(\frac{r-y}{\sqrt{(x-\ell)^2+(y-r)^2}}\right) & x > \ell, \\ x & 0 \le x \le \ell, \ y < r, \\ 2\ell + r\pi - x & 0 \le x \le \ell, \ y \ge r, \\ 2\ell + r\pi + r \arccos\left(\frac{-r+y}{\sqrt{x^2+(y-r)^2}}\right) & x < 0. \end{cases} \tag{3}$$

(a) Raw head trajectories.

(b) Sketch of the new coordination system.

(c) Transformation additional.

(d) Transformation straight.

Figure 9   The steps of the transformation applied to the trajectory data extracted from the single-file experiment.

$$y'' = \begin{cases} \sqrt{(y-r)^2} - r & 0 \le x \le \ell, \\ \sqrt{(x-\ell)^2 + (y-r)^2} - r & x > \ell, \\ \sqrt{x^2 + (y-r)^2} - r & x < 0. \end{cases} \tag{4}$$

Where ℓ represents the length of the straight segment of the oval corridor, and r denotes the radius of the curved part (see Figure 9(b)).

The third step of the methodology involves calculating the movement quantities. In our paper, we calculate **Voronoi 1D density**, **individual instantaneous speed**, and **headway distance**. To calculate the **headway distance**, we apply the following equation:

$$h_i(x) = \begin{cases} x_{i+1}(t) - x_i(t) & i = 1, \dots, n-1, \\ (c - x_n(t)) + x_1(t) & i = n. \end{cases} \tag{5}$$

where n is the number of pedestrians in the experiment and c is the setup circumference.

Voronoi 1D density is defined as:

$$\rho_i(x) = \begin{cases} \frac{2}{h_{i-1}(x)+h_i(x)} & x \in [\frac{h_{i-1}(x)}{2}, \ \frac{h_i(x)}{2}[, \\ 0 & \text{Otherwise.} \end{cases} \tag{6}$$

Finally, we calculate the **individual instantaneous speeds** of pedestrians using the following equation for **side-view experiments** or analysis within a specific measurement area:

$$v_i(t) = \begin{cases} \frac{x_i(t+\Delta t/2)-x_i(t-\Delta t/2)}{\Delta t} & t+\Delta t/2 \leq t_{\text{end}}, \ t-\Delta t/2 \geq t_{\text{start}}, \\ \frac{x_i(t_{\text{start}})-x_i(t-\Delta t/2)}{t-t_{\text{start}}+\Delta t/2} & t+\Delta t/2 > t_{\text{end}}, \ t-\Delta t/2 \geq t_{\text{start}}, \\ \frac{x_i(t+\Delta t/2)-x_i(t_{\text{end}})}{t_{\text{end}}-t+\Delta t/2} & t+\Delta t/2 \leq t_{\text{end}}, \ t-\Delta t/2 < t_{\text{start}}, \\ 0 & \text{Otherwise.} \end{cases} \tag{7}$$

where t_{start} and t_{end} are the time when the pedestrian i enters and leaves the measurement area, respectively. The short time constant of $\Delta t = 0.4$ s (10 frames) is used to smooth trajectories and avoid fluctuations in the stepping behavior of pedestrians. For the **top-view experiments**, Equation 7 (case one) is used to calculate the **1D** individual instantaneous speeds. in **2D**, the speed is calculated by dividing the displacement in 2D by Δt as follows:

$$v_i(t) = \frac{\sqrt{(x_i(t+\Delta t/2)-x_i(t-\Delta t/2))^2 + (y_i(t+\Delta t/2)-y_i(t-\Delta t/2))^2}}{\Delta t}. \tag{8}$$

For more details regarding the proposed analysis tool, check the GitHub project **Single-FileMovementAnalysis** [4]. Our proposed tool is tested across 10 experiments involving 28 datasets, as detailed in Appendix C, Table 5.

8. Conclusion

This article comprehensively reviews the literature on single-file pedestrian movement, with a focus on experiments and data analysis. We provide a scientific background and discuss the significance of single-file experiments in pedestrian dynamics. Then, we compare different traffic systems - including humans, mice, rats, bicycles, and cars - to highlight their similarities and differences. From this comparison, we derive insights that contribute to our understanding of pedestrian dynamics. Furthermore, we present a detailed discussion and categorization of the types of experimental setups, data collection methods, movement quantities, and influential factors of the movement, and provide our discussion. Finally, we propose a methodology and introduce the "SingleFileMovementAnalysis" tool for analyzing single-file pedestrian dynamics. After the comprehensive review, we recognize the ongoing need for further research in single-file movement. Specifically, experimental research focuses on the cognition processes of moving pedestrians to understand the related influential factors. We also suggest performing research concerning defining and automating the steady-state in pedestrian single-file movement. Moreover, we encourage further experiments to investigate new influential factors and validate new data collection devices. There is room for improvement in research on pedestrian single-file movement. We hope that our review article opens a new perspective for researchers. It should enable them to compare their experimental data against existing research objectively and easily, thereby improving the quality of analysis.

Author Contributions Rudina Subaih: Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Data curation, Visualization, Writing –original draft, Writing – review & editing. Antoine Tordeux: Conceptualization, Writing – review & editing, Supervision. Mohcine Chraibi: Conceptualization, Writing – review & editing, Supervision.

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A. Single-file Experiments

Table 3 Overview of the experimental publications reviewed by the authors that focus on single-file experiments for various traffic systems.
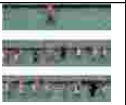
	Experiment (AuthorYear [cite])	Snapshot	Objects	Country/territory (where the experiment performed)	Environment	Setup shape/type
1	Seyfried2005 [1]		Pedestrians	Germany	Indoor	Oval
2	Sugiyama2008 [48]		Cars (human-driven)	Japan	Outdoor	Circle
3	Chattaraj2009 [2]		Pedestrians	India	Outdoor	Oval
4	Lukowski2009 [5]		Pedestrians	Germany	Indoor	Oval
5	Liu2009 [6]		Pedestrians	China	Outdoor	Oval
6	Jezbera2010 [7]		Pedestrians	Czech Republic	Outdoor	Circle
7	Seyfried2010 [8, 58]		Pedestrians	Germany	Indoor	Oval
8	Yanagisawa2012 [9]		Pedestrians	Japan	Indoor	Circle
9	Jelic2012 [10, 54]		Pedestrians	France	Indoor	Circle
10	Song2013 [11]		Pedestrians	China	Outdoor	Oval

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11	Tadaki2013 [49]		Cars (human-driven)	Japan	Indoor	Circle
12	Zhang2014 [46]		Bicycles	Germany	Outdoor	Oval
13	Cao2016 [12]		Pedestrians	China	Outdoor	Oval
14	Ziemer2016 [13]		Pedestrians	Germany	Indoor	Oval
15	Zhao2017 [14]		Pedestrians, Bicycles	China	Outdoor	Circle
16	Jiang2017 [47]		Bicycles	China	Outdoor	Oval
17	Chen2017 [15]		Pedestrians	China	Indoor	Stairs
18	Ikeda2017 [16]		Pedestrians	Japan	Indoor	Circle
19	Gulhare2018 [17]		Pedestrians	India	Outdoor	Oval
20	Huang2018 [18]		Pedestrians	China	Indoor	Seat aisle
21	Ma2018 [19]		Pedestrians	China	Outdoor	Oval

22	Sun2018 [20]		Pedestrians	China	Indoor	Ship corridor
23	Wang2018 [21]		Pedestrians	Germany	Indoor	Oval
24	Stern2018 [50]		Cars (autonomous vehicle)	USA	Outdoor	Circle
25	Appert-Rolland2018 [22]		Pedestrians	France	Indoor	Circle (virtual, without pre-defined path), one-dimensional observation area
26	Cao2019 [23]		Pedestrians	China	Outdoor	Rectangle with four straight corridors and four arcs
27	Jin2019 [24, 55]		Pedestrian	China	Outdoor	Circle
28	Ren2019 [25]		Pedestrian	China	Outdoor	Oval
29	Subaih2019 [26, 56]		Pedestrians	Palestine	Indoor	Oval
30	Xiao2019 [43]		Mices	China	Indoor	One-dimensional observation area
31	Huang2019 [27]		Pedestrians	China	Indoor	One-dimensional observation area

32	Zeng2019 [28,60,61]		Pedestrians	China	Outdoor	Oval
33	Ma2020 [29]		Pedestrians	China	Outdoor	Oval
34	Wang2020 [44]		Ants	China	Indoor	One-dimensional observation area
35	Wang2020a [30]		Pedestrians	China	Indoor	Rectangle
36	Wang2020b [31]		Pedestrians	China	Outdoor	One-dimensional observation area
37	Fu2021 [32]		Pedestrians	China	Outdoor	Oval, circle
38	Lu2021 [33]		Pedestrians	China	Outdoor	Oval
39	Ma2021 [34]		Pedestrians	China	Outdoor	Oval
40	Wang2021 [35]		Pedestrians	China	Indoor	Stairs
41	Ye2021 [36]		Pedestrians	China	Outdoor	Stairs
42	Ciuffo2021 [51]		Cars (autonomous vehicle)	Hungary	Outdoor	Motorway with random shape
43	Lian2022 [37]		Pedestrians	China	Outdoor	Branched
44	Thompson2022 [38]		Pedestrians	Sweden	Indoor	Oval

45	Paetzke2023 [39]		Pedestrians	Germany	Indoor	Oval
46	Li2023 [40]		Pedestrians	China	Indoor	Square with four straight corridors and four arcs
47	Bilintoh2023 [41]		Pedestrians	African students living in China	Outdoor	Oval
48	Li2024 [52]		Pedestrians	China	Indoor	One-dimensional observation area

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B. Data Collection

Table 4 Overview of data collection from experiments on single-file pedestrian movement during ground-level evacuation scenarios with closed boundaries, as reviewed by the authors.

	Experiment (AuthorYear [cite])	Country/territory (where the experiment performed)	Surrounding environment	Setup shape/type	Data type	Data collection device	Data collection process
1	Seyfried2005 [1]	Germany	Indoor	Oval	Time instances	Digital camera (side-view, video recordings)	Semi-automatic
					Head trajectories	Stereo vision camera (bird's-eye view)	Automatic
2	Chattaraj2009 [2]	India	Outdoor	Oval	Time instances	Digital camera (side-view, video recordings)	Semi-automatic
3	Lukowski2009 [5]	Germany	Indoor	Oval	Time instances	Digital camera (side-view, video recordings)	Semi-automatic
					Head trajectories		
4	Liu2009 [6]	China	Outdoor	Oval	Head trajectories	Digital camera (bird's-eye view, video recording)	Automatic
5	Jezbera2010 [7]	Czech Republic	Outdoor	Circle	Time instances	Light gate	Automatic
6	Seyfried2010 [8, 58]	Germany	Indoor	Oval	Head trajectories	Digital camera (bird's-eye view, video recording)	Automatic
7	Yanagisawa2012 [9]	Japan	Indoor	Circle	Time instances	No details	No details

8	Jelic2012 [10, 54]	France	Indoor	Circle	Head and shoulders trajectories	Infrared camera (VICON motion capture system)	Automatic
9	Song2013 [11]	China	Outdoor	Oval	Head trajectories	Digital camera (bird's-eye view, video recording)	Automatic
10	Cao2016 [12]	China	Outdoor	Oval	Head trajectories	Digital camera (bird's-eye view, video recording)	Automatic
11	Ziemer2016 [13]	Germany	Indoor	Oval	Head trajectories	Digital camera (bird's-eye view, video recording)	Automatic
12	Zhao2017 [14]	China	Outdoor	Circle	Head trajectories	Digital camera (bird's-eye view, video recording)	Automatic
13	Ikeda2017 [16]	Japan	Indoor	Circle	Frontopolar/brain activity signals	NIRS	Automatic
					Number of pedestrians	Digital camera (side-view around the circle, video recording)	Semi-automatic
14	Gulhare2018 [17]	India	Outdoor	Oval	Time instances	Digital camera (side-view, video recordings)	Semi-automatic
15	Ma2018 [19]	China	Outdoor	Oval	Head and foot trajectories	Digital camera (bird's-eye view, video recordings)	Automatic (mean-shift algorithm)
16	Wang2018 [21]	Germany	Indoor	Oval	Head trajectories	Digital camera (bird's-eye view, video recordings)	Automatic

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17	Appert-Rolland2018 [22]	France	Indoor	Circle (virtual, without predefined path)	Head trajectories	Infrared camera (VICON motion capture system)	Automatic
18	Cao2019 [23]	China	Outdoor	Rectangle with four straight corridors and four arcs	Head trajectories	Digital camera (bird's-eye view, video recordings)	Automatic
19	Jin2019 [24, 55]	China	Outdoor	Circle	Head trajectories	UAV drone camera (bird's-eye view, video recordings)	Automatic
20	Ren2019 [25]	China	Outdoor	Oval	Head trajectories	Digital camera (bird's-eye view, video recordings)	Automatic
21	Subaih2019 [26, 56]	Palestine	Indoor	Oval	Head trajectories	Digital camera (side-view, video recordings)	Semi-automatic
22	Zeng2019 [28,60,61]	China	Outdoor	Oval	Head trajectories	Digital camera (bird's-eye view, video recordings)	Automatic
23	Ma2020 [29]	China	Outdoor	Oval	Head trajectories	Digital camera (bird's-eye view, video recordings)	Automatic
24	Wang2020a [30]	China	Indoor	Rectangle	Head trajectories	Digital camera (bird's-eye view, video recordings)	Automatic
25	Fu2021 [32]	China	Outdoor	Oval, circle	Head trajectories	Digital camera (bird's-eye view, video recordings)	Automatic
26	Lu2021 [33]	China	Outdoor	Oval	Head trajectories	Digital camera (bird's-eye view, video recordings)	Automatic
27	Ma2021 [34]	China	Outdoor	Oval	Head and foot trajectories	Camcorders	Automatic

28	Lian2022 [37]	China	Outdoor	Branched	Head trajectories	Digital camera (bird's-eye view, video recordings)	Automatic
29	Thompson2022 [38]	Sweden	Indoor	Oval	Right shoulder, hip, knee, the tip of the toe, and heel trajectories	Digital camera (side-view, video recordings)	Automatic
30	Paetzke2023 [39]	Germany	Indoor	Oval	Head trajectories	Digital camera (bird's-eye view, video recordings)	Automatic
31	Li2023 [40]	China	Indoor	Square with four straight corridors and four arcs	Head trajectories	UWB	Automatic
					No details	DJI camera (side-view, video recordings, entire setup)	No details
32	Bilintoh2023 [41]	African students living in China	Outdoor	Oval	Time instances	Digital camera (bird's-eye view, video recordings)	Semi-automatic

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C. Collected experimental data for testing the proposed analysis tool

Table 5 The details of the experiments, which were used to test our proposed analysis tool, comprise 28 datasets.

	Experiment (AuthorYear [cite])	Investigates	Dimensions of the experimental setup					Radius [m]	Trajectory extraction	Camera top/side view	Frame-rate (fps)
			Setup Central circumference [m]	Straight part length [m]	Measurement area length [m])	Corridor width (straight, curved) [m]					
1	Lukowski2009 [5]	Motivation - haste	17.30	4	2	0.8, 1.2		2.20	Manually	Side view	25
2	Seyfried2010 [58]	Stop-and-go waves	26.80	4	4	0.7, 0.7		3.00	PeTrack	Top view	25
3	Cao2016 [12]	Age	25.70	5	-	0.8, 0.8		2.90	PeTrack	Top view	25
4	Ziemer2016 [13]	Congestion Dynamics	26.84	4	-	1.0, 1.0		3.00	PeTrack	Top view	16
5	Wang2018 [21]	Step style	16.6	2.5	-	0.8, 0.8		2.25	PeTrack	Top view	25
6	Subaih2019 [26]	Gender	17.27	3.14	3.14	0.6, 0.6		2.05	PeTrack	Side view	25
7	Ren2019 [25]	Age	25.70	5	-	0.8, 0.8		2.50	PeTrack	Side view	25
8	Zeng2019 [28]	Motivation - music	21.93	5	-	0.8, 0.8		1.90	PeTrack	Top view	25
9	Ma2020 [29]	Height constraints	28.08	4	3	0.8, 0.8		2.4	PeTrack	Top view	25
10	Paetzke2023 [39]	Gender	14.97	2.3	-	0.8, 0.8		1.65	PeTrack	Top view	25