

# Understanding the Characteristics of Pedestrians when Passing Obstacles of Different Sizes: An Experimental Study

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**Abstract** The aim of this study is to understand the collective movements of individuals and to observe how individuals interact within a physical environment in a crowd dynamic, which has drawn the attention of many researchers. We conducted an experimental study to observe interactions in the collective motions of people and to identify characteristics of pedestrians when passing obstacles of different sizes (bar-shaped, 1.2 m, 2.4 m, 3.6 m and 4.8 m), going through one narrow exit and employing three different flow rates in walking and running conditions. According to the results of our study, there were no differences in collision-avoidance behavior of pedestrians when walking or running. The pedestrians reacted early to the obstacles and changed the direction in which they were walking by quickly turning to the left or to the right. In terms of the speed of the pedestrians, the average velocity was significantly affected while performing these tasks, decreasing as the size of the obstacle increased; therefore, the size of obstacles will affect flow and speed levels. Travel time was shorter when participants were in the medium-flow rate experiments. In terms of the distance of each individuals travel, our data showed that there was no significant difference in all the flow rate experiments for both speed levels. Our results also show that when the pedestrians crossed an obstacle, the lateral distance averaged from 0.3 m to 0.7 m, depending on the flow rate and speed level. We then explored how the body sways behaved while avoiding obstacles. It is observed that the average sway of the body was less in the high-speed conditions compared to the low-speed conditions except for the HF & 4.8 m experiment. These results are expected to

provide an insight into the characteristics of the behavior of pedestrians when avoiding objects, and this could help enhance agent-based models.

**Keywords** Obstacles evading behaviour · pedestrian sway · walking behaviour · pedestrian dynamic

## 1 Introduction

Investigating pedestrian behavior has attracted the attention of many researchers in recent decades [1–6]. To investigate the behaviors involved in the movements of pedestrians, various experiments have been conducted concerning the avoidance of obstacles [7–11]. However, obstructions are commonly used in outdoor and indoor environments, such as sidewalks or various corridors in public facilities like subway and railway stations and airports. Obstacles that can be of various shapes, such as walls, pillars, or barriers, could affect many aspects of the movements of pedestrians when walking in these environments; they could delay pedestrian movement in built-up environments. Therefore, knowing how obstacles influence human behavior is critical to enhancing the architecture of these environments.

Also, the effects of these obstacles have direct relevance to crowd modelling and simulations [12–16]. This concept is validated based on the simulation in [17]. Due to the difficulty involved in conducting experiments with humans and also regarding data collection, many researchers have used mice [18], sheep [19] and ants [20] to validate their models. These studies are intended to determine commonalities among different obstacles and the fundamental characteristics of pedestrian movements in various forms of interaction between flows. They are also used to determine whether placing an obstruction in front of an exit is beneficial to control the flow of crowds and pedestrian evacuation. Some studies have discussed the effects of architectural changes on pedestrians [21], using different obstacle sizes to discover that corner exits are more efficient than those in the middle of an area following an obstacle of the same size [22]. Other scholars have found that there are differences in the speed of pedestrians. When comparing their speeds in different layouts (parallel and non-parallel), the difference in speed was 19% less than the others; they also found that there was a difference of 17% in the average passing time when compared to that in a different layout, according to [23]. Therefore, to achieve an optimal improvement in evacuation time, we should adjust the size of an obstacle and its distance from an exit [24]. This could be true for both self-driven and gravity-driven components. Some studies have suggested that this could increase pedestrian outflow by up to 30% or even double the normal levels of flow that would occur without any obstacles. However, these studies are still limited and do not explore all pedestrians behaviors under different arrangements.

A small number of studies have focused on the avoidance-based behavior of people when encountering different obstacles. Jia et al. [25] explored the impacts of various obstructions and revealed that when pedestrians encountered an obstacle, they would walk a certain distance and then change direction. Due to differing experiment setups, including

the shape and location of the obstacles, the results vary. In addition, the positioning of an obstruction might also increase its influence on pedestrian behavior. These factors may be one reason for the growing interest in the aspects that affect how pedestrians respond to environments in walking facilities or to different obstacles, but this is in the early stages and is not yet fully understood. Chen et al. [23] also examined this point, and they investigated the effects of how obstacles are laid out on pedestrian flow in the corridors mentioned; they saw that pedestrians changed their direction of walking to avoid collision with different objects, such as obstacles. According to them, determining the actual avoidance distance of the pedestrian is related to the various characteristics, such as the distance from a pedestrian to the obstacle, the walking distance, the deviation angles or direction and the moment the pedestrian evades the obstruction. Thus far, therefore, there is ambiguity regarding the expected distance, time or location pedestrians take when deciding to avoid objects. Also, other related studies found that the average walking distance before a pedestrian deviates varies from 0.8 m to 1.5 m [26] and from 2.0 m to 2.64 m [25], and one aspect of collision-avoiding behavior is the consideration of how to evade the obstacle. They mentioned that pedestrians begin to evade obstacles when they are 4.40 m away from it and stop evading it when they are 4.85 m beyond the obstacle. However, an accurate method to finding the exact locations for deviation was not yet understood, research was carried out on a small number of participants, experiments were only performed under walking scenarios and each experiment represented different cultures. Therefore, more studies are needed to explore pedestrian movement when passing various obstacles. Another problem is the lateral distance, defined in Ref [25], which is the distance between the edges of an obstruction and a pedestrian when passing different obstacles. This can also be described as the space between the edges and walls. This distance has been seen as static values [25], and it was only 0.4 m after considering the average shoulder width for all participants, but this value needs further investigation, which we have achieved in this study.

Besides, 'pedestrian trajectories, according to some studies, involve two forms of information: body sway and walking direction. For example, Hoogendoorn and Daamen [27] held the view that pedestrians require space in both the longitudinal line and in the lateral direction. The latter encompasses the shoulder width of the pedestrian, the shy-away distance from obstructions and other pedestrians directly beside him or her, but also the distance taken up by swaying. The body swaying amplitude for a crowd of pedestrians when heading to a bottleneck ranged from 0.04 m to 0.06 m and showed a negative correlation when associated with velocity ranging from 0.5 m/s to 1.5 m/s [28]. The amplitude ranged from 0.024 m to 0.034 m, and body sway ranged from 0.28 m to 1.6 m [29]. Another study [30] measured the length of the steps and sways to determine how much space was required for each pedestrian when walking, and that measurement was critical to determining the level of service and was thus a factor for the design of walking facilities. Therefore, there is again ambiguity in relation to body sway, regarding how the body's movements respond to other objects.

Understanding the characteristics of pedestrians walking and their behavior when avoiding objects might support the calibration of parameter rules for microscopic pedestrian simulation models in which individual agents are treated as separate entities and have

their own characteristics. This understanding is especially important regarding how individuals interact with their physical surroundings, such as avoiding obstacles, engaging in turning maneuvers and choosing between a stairway or an escalator in indoor environments. These examples could involve different levels of speed, varying levels of density and other contextual elements. Several simulation models that describe the characteristics of collision avoidance [31] or collective behavior [32] are technologically advanced in how they can describe the interactions of pedestrians movements or collective behavior and how people respond to different obstacles such as agent-based models [33], social force models [34] and cellular automata models [35]. Several researchers have used these models because of their promising results, and they are well accepted. However, these models have produced some unrealistic results concerning interaction forces or environmental geometries relating to the relative positions of individuals in built-up environments and how pedestrians evade objects.

To deal with the concerns raised and to understand the avoidance-based behavior of crowds of pedestrians within different geometrical settings, this paper proposes an analytical study to investigate pedestrian behavior while passing various obstacles. Several characteristics are studied to explore behavior, such as examining the actions of pedestrians when avoiding obstacles (collision avoidance behavior), comparing the travel time and the individual travel time to discover how obstructions influence pedestrian movements, observing the impact of speed on pedestrian movement, finding the lateral distances at the edges of obstacles and exploring the effects of obstructions on body sway (slope) by using different flow rates in walking and running conditions. In this way, we hope to improve the database related to pedestrian avoidance behavior and contribute to a better understanding of the collective movements of pedestrians under different obstacle sizes and flow rates.

## 2 Experiment Setup

On 6 March 2017, 20 trials were performed to gain an understanding of the characteristics of collective motion when passing by obstacles of different sizes in the basketball court at the Melbourne University sports center. Ethical approval was granted by the Engineering Human Research Ethics Advisory Group. We involved over 110 students of both sexes who moved in a special zone (the x axis was 12 m, and the y axis was free). The participants who attended were all university students aged 21-25 years. The participants had to self-register their information through a website designed for these tasks. To avoid participants becoming tired during the day of the experiments, we purchased snacks, meals, and bottles of water for each participant during the experiments. Also, we provided them with a lunch meal at the end of the day, and each participant was paid around 80 AUD per day in the form of a purchase voucher that they could use at a later date.

To determine the specific characteristics involved in collective motion regarding a pedestrians behavior when avoiding obstacles, we asked the participants to pass the different obstacles (1.2 m, 2.4 m, 3.6 m and 4.8 m) at two different speeds (here represented as low speed [LS] and high speed [HS] and also identified as walking and running) and at three

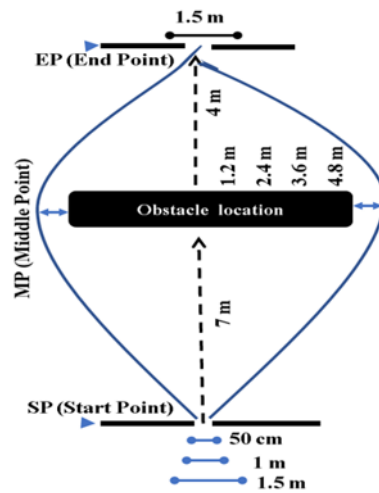
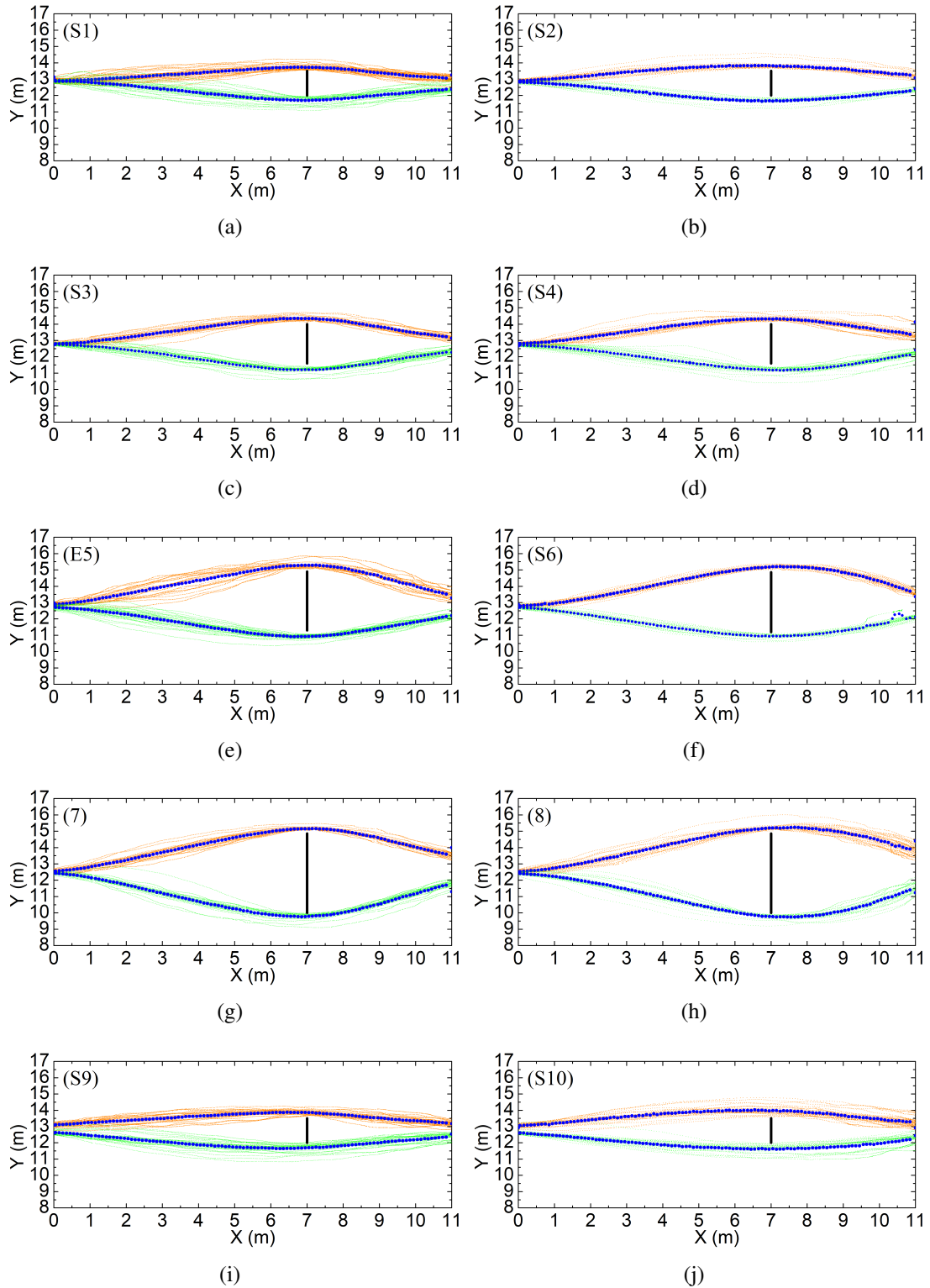


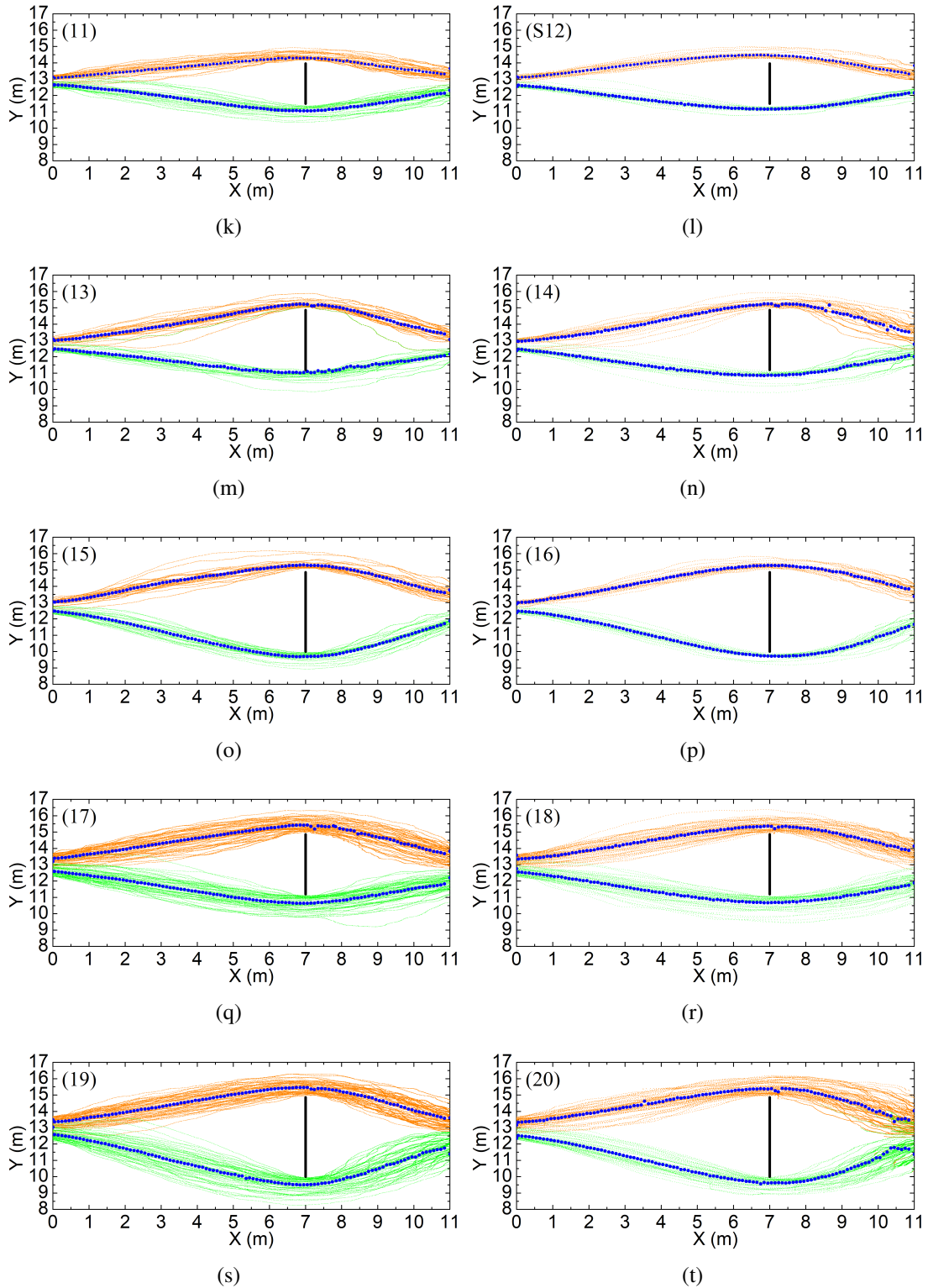
Figure 1 Layout of the experiments

Scenarios	Condition	Entrance Width(m)	Speed Level	Size of Obstacles (m)	Number of Participants (Ped)
E1	LF	0.5	Low	1.2	55
E2	LF	0.5	High	1.2	55
E3	LF	0.5	Low	2.4	55
E4	LF	0.5	High	2.4	55
E5	LF	0.5	Low	3.6	55
E6	LF	0.5	High	3.6	55
E7	LF	0.5	Low	4.8	55
E8	LF	0.5	High	4.8	55
E9	MF	1.0	Low	1.2	55
E10	MF	1.0	High	1.2	55
E11	MF	1.0	Low	2.4	55
E12	MF	1.0	High	2.4	55
E13	MF	1.0	Low	3.6	55
E14	MF	1.0	High	3.6	55
E15	MF	1.0	Low	4.8	55
E16	MF	1.0	High	4.8	55
E17	HF	1.5	Low	3.6	110
E18	HF	1.5	High	3.6	110
E19	HF	1.5	Low	4.8	110
E20	HF	1.5	High	4.8	110

Table 1 Details of the experiment trails



**Figure 2** Trajectories for all the participants while passing 1.2 m, 2.4 m, 3.6 m and 4.8 m obstacles; these show the average trajectory in each experiment, indicating the locations where the decision was made to evade the obstacles in LF, MF and HF for LS and HS experiments.



**Figure 2** Trajectories for all the participants while passing 1.2 m, 2.4 m, 3.6 m and 4.8 m obstacles; these show the average trajectory in each experiment, indicating the locations where the decision was made to evade the obstacles in LF, MF and HF for LS and HS experiments.

different entrance sizes (50 cm [low flow (LF)], 1.0 m [medium flow (MF)] and 1.5 m [high flow (HF)]), which were designed to control the pedestrian inflow rate. We used a high-definition video camera to process and record the trajectories of the participants to gain a better understanding of individual behavior. We used the PeTrack software system [36] to track the pedestrians positions. The program parameters were calibrated according to the experimental environments in the field. The movement of the participants was recorded at 50 frames per seconds by a video camera straddled at the experiment site.

Fig. 1 shows a schema of the measurements. The start points (SP) were used to control the different entrance sizes (50 cm, 1.0 m and 1.5 m). The middle point (MP), 7.0 m, was used as the location of the obstacles position. The endpoint (EP) was the end of the measured region. Tab. 1, provides the details of these trials and assigns a number to each scenario for further references to this work. Snapshots of the experiments settings, from the interface of the tracking program, that show the pedestrians passing obstacles of different sizes for each scenario are depicted in Fig. 2.

### 3 Results and Analysis

Results are based on the PeTrack software system [37], which provided a mass of the trajectory files for each experiment as the raw output data. With these data, we first quantified the differences in the speed regimes as LS and HS and the inflow rate as LF, MF and HF conditions.

We calculated the average velocity for each individual (indi velocity, in m/s) in both experiments under LS and HS conditions with a color-coded method based on the subjects movements, as presented in Fig. 3. According to this figure, the average individual velocity in the LFLS scenarios ranged from 1.1 m/s to 1.3 m/s, and that of the LFHS experiments ranged from 2.1 m/s to 2.5 m/s. For MF conditions, the individual average speed in the LS system was around 1.2 m/s and was 2.2 m/s to 2.4 m/s in the HS system. For the HF conditions, individual average speed in the LS and HS speed systems was around 1.0 m/s and 1.9 m/s/2.2 m/s, respectively. The estimated individual average speed from LF, MF and HF conditions all indicate a significance at a 99% confidence level between the LS and HS approach.

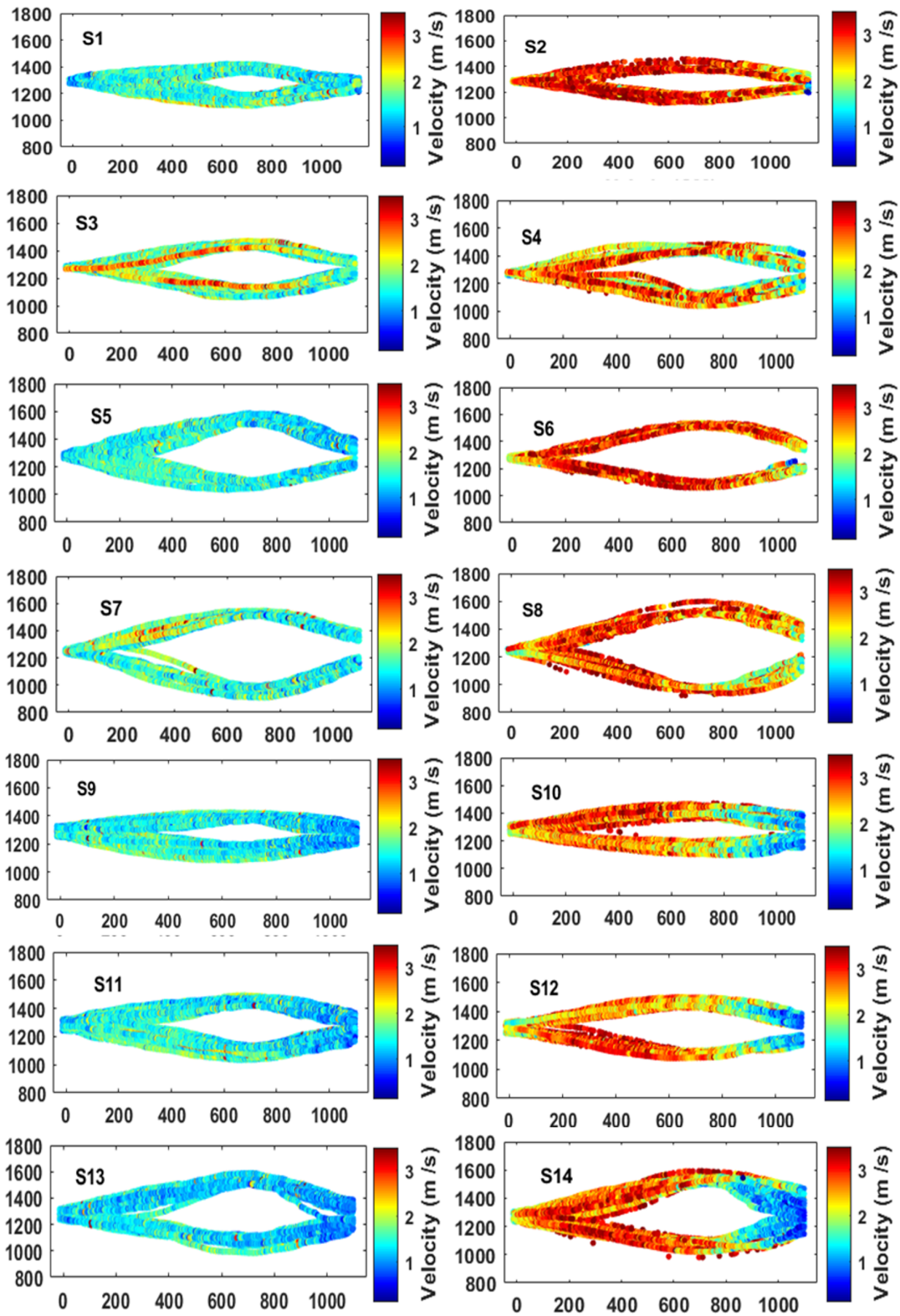
We estimated the average flow rate of each experiment by determining the number of individuals (N) passing the SP (Fig. 3) within a certain time (T), as presented in Eq. 1. The obtained average flow rate for each experiment is shown in Tab. 2. As clearly indicated by Tab. 2, pedestrians showed extensive ingress under HF conditions, then follows by MF conditions and LF conditions.

$$Flowrate = N/t \quad (1)$$

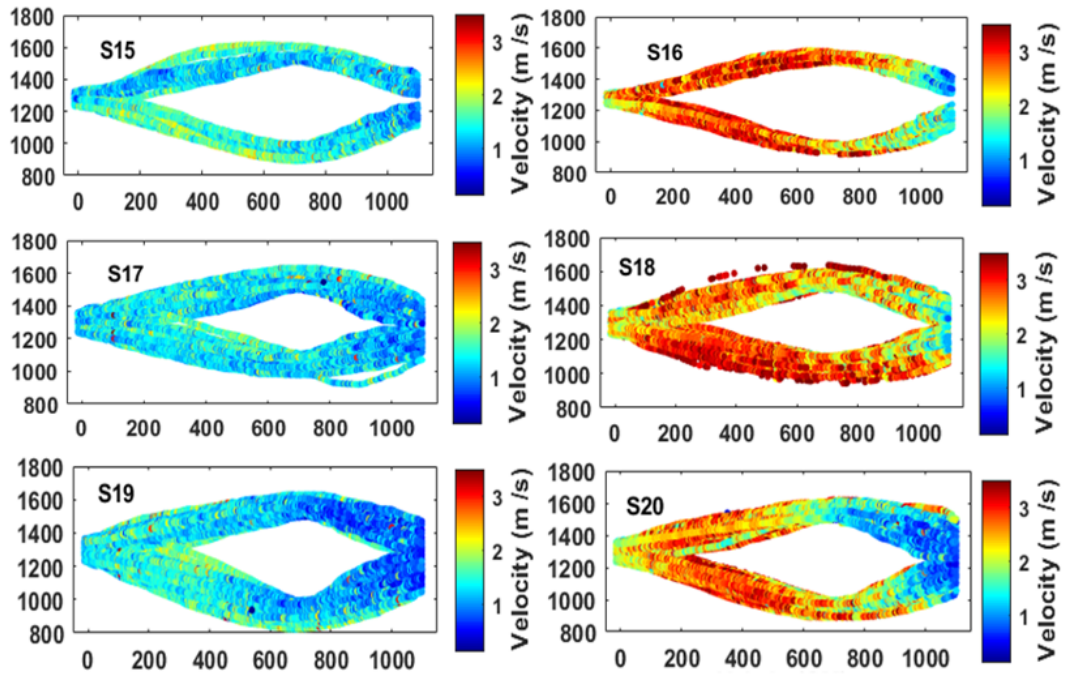
#### 3.1 Collision Avoidance Behavior

To analyze obstacle-avoiding behavior, we assumed that the participants follow the experiment trajectories, as showing the participant movements in the experiment field. Based





**Figure 3** Comparison of the velocity of the participants in 120 experiments, in LS and HS, color-coded based on the participant's movements in the LF, MF and HF experiments (unit: cm).



**Figure 3** Comparison of the velocity of the participants in 120 experiments, in LS and HS, color-coded based on the participant's movements in the LF, MF and HF experiments (unit: cm).

Speed Levels	LS Experiments	-	-	HS Experiments	-	-
Obstacle Size	LF(Ped/s)	MF(Ped/s)	HF(Ped/s)	LF(Ped/s)	MF(Ped/s)	HF(Ped/s)
1.2 m	1.17±0.02	2.17±0.04	-	1.69±0.01	3.21±0.19	-
2.4 m	1.26±0.01	2.37±0.10	-	1.52±0.06	3.19±0.33	-
3.6 m	1.05±0.01	2.46±0.13	3.42±0.54	1.68±0.07	2.94±0.14	4.78±0.67
4.8 m	1.27±0.03	2.13±0.10	3.54±0.23	1.48±0.03	3.27±0.08	4.84±1.10

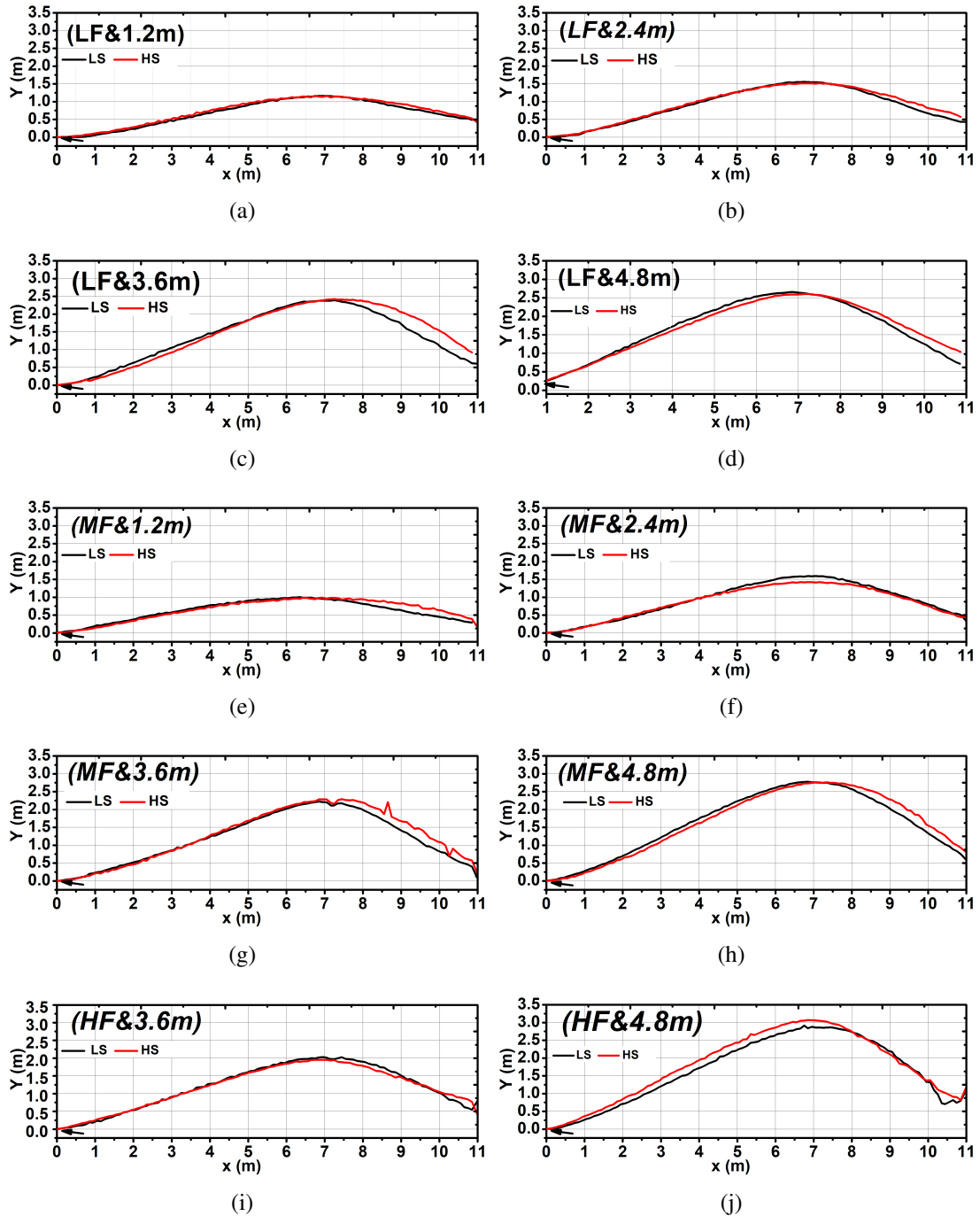
**Table 2** Comparison of the flow rates for all scenarios

on this, we calculated the average trajectory for each path (left and right) by using the binning method [38] to gain a better understanding of the routes in each LS and HS experiment, which helps us explore the behaviors involved in evading obstacles. This assumption could be represented as a linear path that increases following an increase in the size of the obstacle. This linear path could be used as the SP (see Fig. 1 and Fig. 2), where the participants enter the experiment field, and the MP, where the edges of the obstacles are, which can be seen in the following figures as indicating the average trajectories for each experiment. By doing so, we can observe the general features of the participants and see the obstacle-avoiding behavior from the SP to the EP for each studied scenario. Then, we calculated the average trajectory of each scenario by reversing all the trajectories from the right or the lowercase by the y-axis and y coordinate of the EP, and then we applied the binning method. This method is used to calculate the average values of the x and y coordinates on all the trajectories extracted from each experiment scenario. To do so, we set an interval of 0.2 m on the x coordinate (for example, the x coordinate ranges from 0 m to 0.2 m), selected all the x coordinate data in this range and then calculated the average values of the selected x coordinate and corresponding y coordinate. The x coordinate ranged from 0.2 m to 0.4 m, and we calculated the average values of the x coordinate in this range and the corresponding y coordinate. Finally, when the x coordinate was larger than 11.0 m, the procedure was halted. Fig. 4, presents a contrast of the average trajectory between the LS and the HS conditions for all the studied experiments. The participants responded to different obstacles in the early stages and tried to avoid a collision from the entry point, where the SP was.

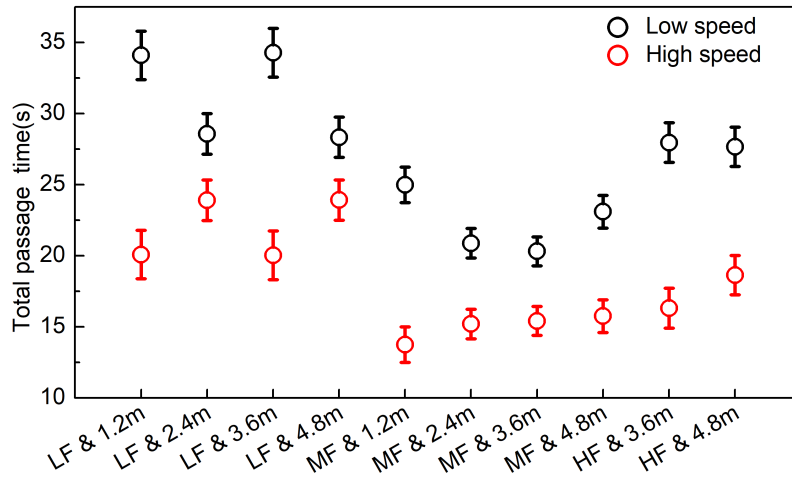
### 3.2 Travel Time

To ascertain the influence of obstacles on architecture, we then investigated the average passage time from the SP to the EP (see Fig. 1 and Fig. 2) in each experiment under two different speeds while the pedestrians avoided the different obstacles. Based on the trajectory data, as presented in Fig. 2, we see the average passage times under various pedestrian speeds and obstacle setups, which are presented in Fig. 5.

The first observation regarding the data in Fig. 5, is that pedestrian speeds have a significant effect on the total travel time from the SP to the EP. It is apparent that a shorter total passing time was observed under HS conditions than under LS conditions for all the test experiments. The effect of the obstacles size on the pedestrians average travel time seems unclear; the average travel time does not show a constant upward or downward trend with different obstacle sizes. For example, the average travel time in LF experiments fluctuates when using with a 1.2 m obstacle compared to 4.8 m and under both speed conditions. The MF experiment shows an inverted U shape with LS conditions, but continuously increases under HS conditions. The third observation from Fig. 5, is that the pedestrian inflow rate impacts the average time. A faster travel time is observed for the MF rate experiments, followed by the HF and LF rate experiments. The reason for this may be related to the pedestrians choice when moving direction, choosing to turn left or right when an obstacle is located in front of them.



**Figure 4** Comparison of the average trajectories of LS vs HS in LF (LF & 1.2 m, LF & 2.4 m, LF & 3.6 m and LF & 4.8 m), MF (MF & 1.2 m, MF & 2.4 m, MF & 3.6 m and MF & 4.8 m) and HF (HF & 3.6 m and HF & 4.8 m) experiments.



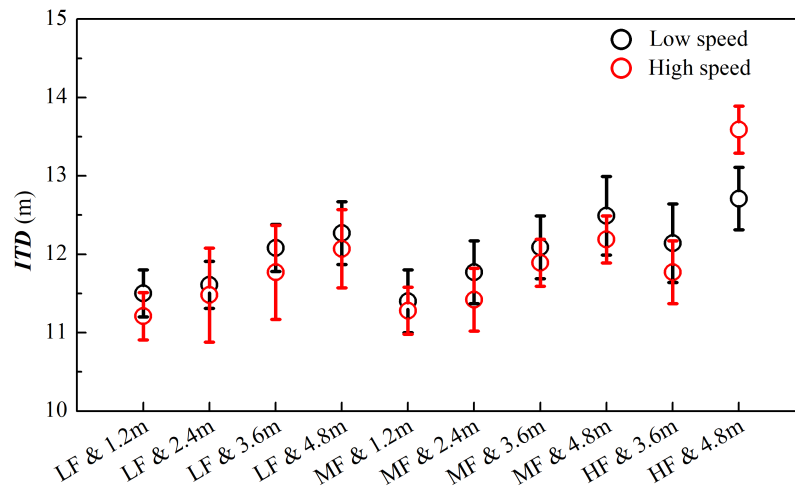
**Figure 5** A comparison of the passage time under the three flow levels: LS vs HS in LF, (LF & 1.2 m, LF & 2.4 m, LF & 3.6 m and LF & 4.8 m), MF (MF & 1.2 m, MF & 2.4 m, MF & 3.6 m and MF & 4.8 m) and HF (HF & 3.6 m, and HF & 4.8 m) experiments. The error bar means the standard deviation.

### 3.3 Individual Travel Distance

We will now contrast the average individual travel distance (*ITD*) for each experiment under LS and HS conditions, as presented in Fig. 6. According to our data, the first observation in the HS experiments is that the average *ITD* was shorter than that of the LS experiment. The second observation is that there was a small increase in the *ITD* whenever the size of the obstacle was increased in each experiment except for the HF & 4.8 m experiment, and that was because of the different size of the obstacles. The third observation is that the *ITD* was affected by the different inflow rates, which led to a decrease in the *ITD* whenever the inflow rate increased. We then made a quantitative comparison between the average *ITD* for each experiment under LS and HS experiments. Our quantitative results indicate that there were no significant differences between the average *ITD* in each experiment under the LS and HS conditions.

### 3.4 Overall Speed

In Fig. 7, we look at another pedestrian behavior, as the effect of the speed on pedestrians when pedestrian evades obstacles. To determine the effects, we calculated the average velocity before and after the positioning of the obstacle, and the results of our data are presented in Fig. 8. From this figure, we can immediately observe that a higher inflow rate can lead to a lower pedestrian movement speed under both speed conditions. For example, in the LS experiment, the average velocity in the LF experiments was a little higher than in the MF experiments, and the average velocity of the MF experiments was slightly higher than that in the HF experiments. The average velocity in LS conditions, before and after the positioning of an obstacle, shows that the velocity was less affected compared to the HS experiments, which saw a greater drop in the average velocity before



**Figure 6** Comparing the average ITD, under three flow levels: LS vs HS in LF, (LF & 1.2 m, LF & 2.4 m, LF & 3.6 m and LF & 4.8 m), MF (MF & 1.2 m, MF & 2.4 m, MF & 3.6 m and MF & 4.8 m) and HF (HF & 3.6 m, and HF & 4.8 m). The error bar means the standard deviation.

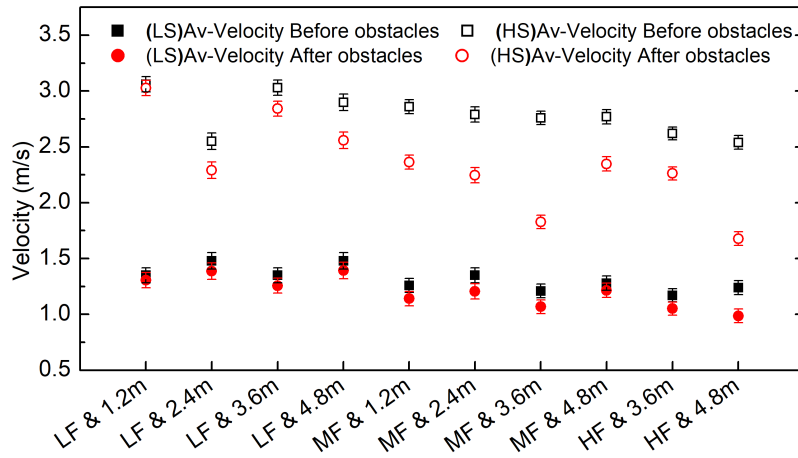
and after the placement of the obstacle. The second observation is that obstacles had more of an influence on velocity when the participants were in HS experiments; the average velocity decreased with an increase in the obstacle size at all three flow levels. However, the obstacles had a greater influence on the pedestrians when they were at HS compared to LS.

### 3.5 Speed and the Cumulative Numbers of Evacuee Relation

In this section, we explore other pedestrian behaviors while comparing the relationship between pedestrian velocity and the cumulative number of evacuees who entered the chamber for each scenario; our results are presented in Fig. 8. Our results indicate three things. First, in the LF experiment, the obstacles had more of an impact on the total number of an evacuee in the two speed conditions compared to the MF and HF rate experiments. Second, in the LF rate and MF rate experiments, the velocity increased whenever the number of evacuees increased in the HS conditions, and the best pattern for the evacuation efficacy was found in this layout, when participants passed obstacles of differing sizes (1.2 m, 2.4 m, 3.6 m and 4.8 m) compared to the other flow rate experiments. Third, the velocity decreased when the flow rate increased, as seen in the HF experiments. The pattern of velocity and the numbers of evacuees decreased when the flow rate increased. That means pedestrian speed was affected by other aspects, including obstacles, which led to an increase in speed and a decrease based on the different flow rates of each experiment.

### 3.6 Lateral Distance and Swaying

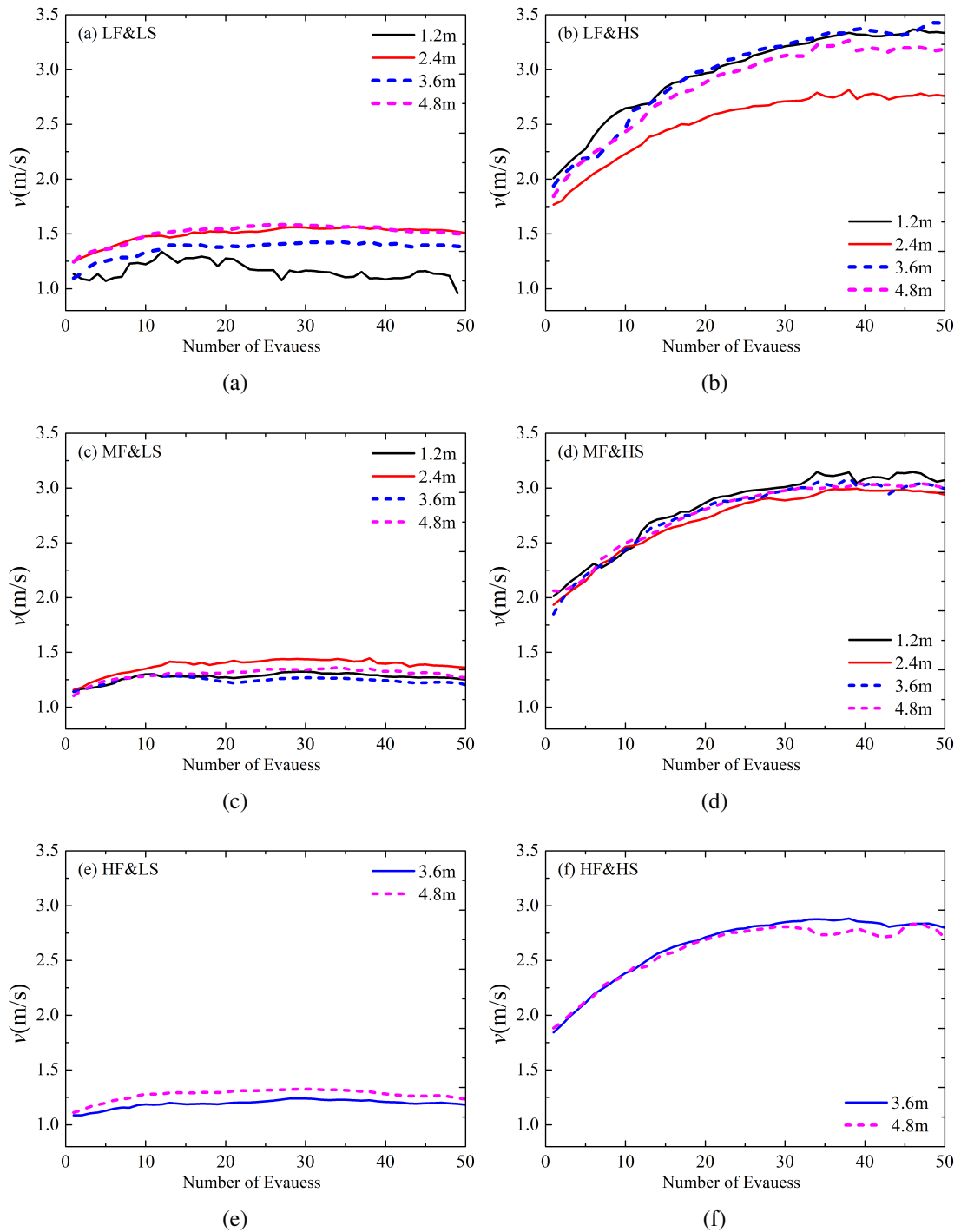
**Lateral Distance** For this section, we calculated the lateral distance, which can be defined as the average space between the edges of each obstacle and the average trajectories



**Figure 7** A comparison of the average velocity of the participants before and after obstacles under the three flow levels: LS vs HS in LF (LF & 1.2 m, LF & 2.4 m, LF & 3.6 m and LF & 4.8 m), in MF (MF & 1.2 m, MF & 2.4 m, MF & 3.6 m and MF & 4.8 m) and HF (HF & 3.6 m, and HF & 4.8 m). The error bar means the standard deviation.

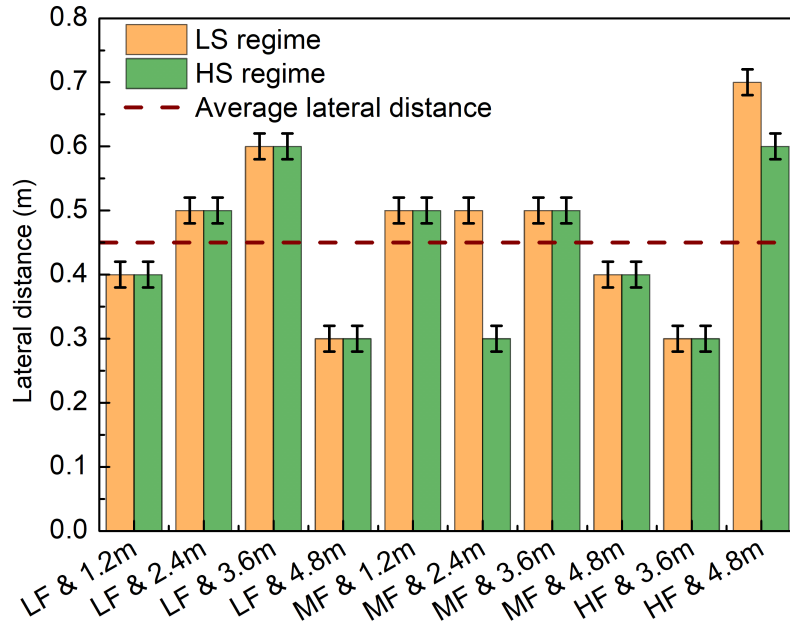
of each experiment. We looked at the lateral distance by exploring the actual locations under different obstacles (1.2 m, 2.4 m, 3.6 m and 4.8 m) on the y-axis after finding the  $|y|$  coordinate of the MP, where the MP is 7 m on the x-axis, for each obstacle (see Fig. 2). Also, in Fig. 9, we calculated the average lateral distance at the edges of the obstacles, where MP is  $|x| = 7$  m and  $|y| =$  a coordinate value of each participant at the edges of the obstacles. We then compared the average trajectory values and the obstacle locations in the y coordinate MP to determine the difference between the edges and average trajectory values. We then compared the average lateral distance in the MP for each experiment with the actual locations of the edges of the obstacles in both speed conditions (LS vs HS).

Our results indicate that the different speed conditions, including LS and HS, seem to have little impact on the average pedestrian lateral distance. In most experiments, the average lateral distance from the LS experiment was equal to that of the HS experiment. The only differences were found in the MF & 3.6 m and HF & 4.8 m scenarios, where the average lateral distance from the LS experiment were about 0.3 m and 0.1 m shorter, respectively, than that of the HS experiment. Moreover, the average distance also varied with different obstacle sizes. For the LF experiments, the average lateral distance was about 0.3 m with a 1.2 m obstacle size (LF & 1.2 m) and continuously increased up to 0.5 m with a 3.6 m obstacle size (LF & 3.6 m) but dropped to 0.4 m with a 4.8 m obstacle size (LF & 4.8 m). For the MF experiments, the average lateral distance fluctuated around 0.4 m with the four different sizes of obstacle scenarios. And for the HF scenarios, the lateral distance was just 0.3 m with a 3.6 m-wide obstacle (HF & 3.6 m), which increased to 0.6 m to 0.7 m with the HF & 4.8 m experiment. The average lateral distance for all the experiments was also presented and was 0.45 m, which will be used for the calibration parameter for our future work.



**Figure 8** A comparison of the relation between the velocity and the number of evacuees under three flow levels: obstacles in LS and HS in LFLS (1.2 m, 2.4 m, 3.6 m and 4.8 m), obstacles in LFHS (1.2 m, 2.4 m, 3.6 m and 4.8 m), obstacles in MFLS (1.2 m, 2.4 m, 3.6 m and 4.8 m), obstacles in MFLS (1.2 m, 2.4 m, 3.6 m and 4.8 m), obstacles in HFLS (3.6 m and 4.8 m) and obstacles in HFHS (3.6 m and 4.8 m).





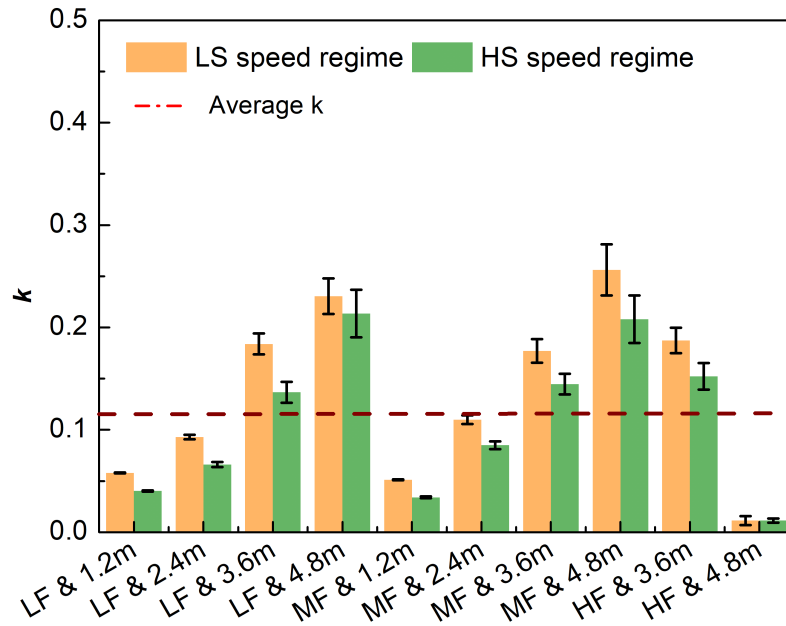
**Figure 9** Comparisons of lateral distance at the edges of obstacles while turning, at three flow levels: LF, MF and HF, where orange is low speed and green is high speed. The error bar means the standard deviation.

**Swaying** For a final analysis, we applied the same previous assumption that there was a variation trend in the pedestrian trajectories that would appear when the participants avoided the obstacles, and the variation could be described as a body sway, which will be represented by  $k$ . For each participant ( $i$ ), the  $k$  at time step ( $t$ ) is defined as  $k_i(t)$ , which is calculated based on the individuals coordination with a step of five frames, as presented in Eq. 2:

$$k_i(t) = \left| \frac{y_i(t + 2\Delta t) - y_i(t - 2\Delta t)}{x_i(t + 2\Delta t) - x_i(t - 2\Delta t)} \right| \quad (2)$$

Therefore, we calculated the slope  $k$  of all of the pedestrians for each experiment. This describes the walking behavior of the pedestrians in the x-axis and  $k$  values in the y-axis, as the corresponding slope curve behaves, which can also be like periodic waves, which caused by the natural oscillation of human beings who moves his/her legs for steps in left and right to move forward. These movements could describe the body sway based on the movement of steps, as presented in the experiment trajectories of Fig. 2. This behavior could be interpreted as the swaying steps in each experiment in walking and running.

The negative correlation mentioned in our literature review [27] in  $k$  and velocity is seen in Fig. 10, where we compare the average  $k$  for all of the experiments in both speeds experiments. The average slope  $k$  for all the experiments is presented as a red line in Fig. 10, which was 0.12. The average  $k$  was less in all the HS conditions compared to the LS conditions in the LF and MF experiments, indicating a significant difference in the  $k$  value for both speeds. However, this behavior disappeared when the participants were in the HF rate HF & 4.8 m, and the  $k$  value became equal under both speed conditions.



**Figure 10** A comparison of average ( $k$ ) slopes with error bars: LS vs HS in LF, (LF & 1.2 m, LF & 2.4 m, LF & 3.6 m and LF & 4.8 m), MF (MF & 1.2 m, MF & 2.4 m, MF & 3.6 m and MF & 4.8 m) and HF (HF & 3.6 m and HF & 4.8 m) experiments. The error bar means the standard deviation.

Also, the average  $k$  increased when the obstacles size increased. For example, the average value of  $k$  in LF & 1.2 m was less than that in FL & 2.4 m, the average of  $k$  in LF & 2.4 m was less than that in LF & 3.6 m, the average of  $k$  in LF & 3.6 m was less than that in LF & 4.8 m, and so on for the MF experiments when the participants passed by differently sized obstacles. However, the  $k$  value became equal under both speed conditions in the HF rate HF & 4.8 m when the participants passed the 4.8 m obstacle. The reason for the  $k$  value being so small is due to the inflow rate; it was about 5.0 Ped/s in both experiments according to Fig. 2, and this number increased interactions at the entrance, which reduced  $k$ .

## 4 Discussion and Conclusion

Understanding the human characteristics associated with nearby physical objects, such as obstacles, is important for gaining a better understanding of the effects these objects have on the traits of human movement. With the results from this study, the movement characteristics of pedestrians can be modelled with the empirical data of different speed and flow rates. In this study, we have illustrated the general features of avoidance behavior in relation to collective movement. These 20 experiments have enabled us to gain a comprehensive understanding of the characteristics of collective motion around common physical objects such as obstacles. The outcome of this study could develop and validate simulation models.

To our knowledge, this is the first time that empirical data regarding several of the

characteristics of collective human behavior and collective motion when passing different obstacles has been explored. Many studies have been conducted using simulation tools [1]. Authors in Ref [1] stated that they could not use real data for this work because of the difficulties they faced in obtaining real data due to lacking an efficient method for data collection. Therefore, they used modelling elements and a simulation approach to present their work. They also detailed two of the main methodologies to describe the agents involved in entry, using behavior in simulation tools and the capabilities of agent-based simulations. Various factors have been investigated to determine whether pedestrians are affected by obstacles of different sizes.

Another study [25] in the classification of pedestrian behavior section involved experiments aimed to explore a pedestrians behavior when evading an obstacle using only one density and speed level (walking scenarios). This study also mentioned that its pedestrians had walked a distance before changing their walking direction to the left or the right from 0.8 m to 1.5 m and from 2.0 m to 2.64 m, respectively [26]. However, in this paper, our results show that pedestrians respond to obstacles at an early stage, preparing to avoid any objects, according to the average trajectories of each experiment in LS and HS conditions. The participants reacted to the obstacles at an early stage; pedestrians changed their walking or running direction to avoid objects at the entrances in all the LF, MF and HF rate experiments. The reasons for this behavior may relate to the width of the experimental scenarios. In our study, the width of the observational chamber was free, while the width in the experiment of Ref [25] was only 3.0 m. According to the literature [1], the most significant parameter that affects behavior is speed, and our results showed that the velocity in the LF experiments was a little higher than in the LF and HF experiments. The velocity decreased with an increase in obstacle size for each experiment in the three flow levels, so obstacle size affected flow and speed levels.

Regarding travel time, the outcome of this study suggests that the effects of an obstacle size on average pedestrian travel time is unclear. There is no constant upward or downward trend with different obstacle sizes. However, the results could change from one experiment to another depending on a pedestrians speed and their interaction with other objects, such as obstacles, other pedestrians or the environment [39]. In terms of the *ITD*, our data showed that there were no significant differences between the different flow rate experiments or for both speed conditions, even though the data highlights that the *ITD* in the HS conditions was smaller than that under the LS conditions.

This study shows differences at the edges of obstacles, which is described as the lateral space or lateral distance. This space ranged from 0.3 m to 0.7 m in both LS and HS conditions. The average lateral distance for all the experiments has also been presented and was 0.45 m, which will be used as a calibration parameter for our future work. The outcome of the lateral distance in our study fits well with the findings of some related studies. For example, the average lateral distance was 0.4 m in all the arrangements [25] and was 0.45 m in the study conducted by Hoogendoorn and Daamen [27]. Finally, in the swaying discussion, it was observed that obstacles have more impact on body sway in LF rate experiments and MF rate experiments. This impact appeared in *k* values, which increased when the obstacle size was raised; this behavior disappeared in the HF experiments and for both speed conditions. This indicates that swaying and speed correlates

with an entrance width between 0.5 m and 1.5 m and an obstacle size of 3.6 m or less. Beyond this range, the  $k$  will be less affected by speed.

The outcomes of this study contribute to the modelling and simulation field and can validate and support various simulation systems, such as an agent-based crowd simulation model. The outcomes describe the characteristic behaviors of an agent speed under several flow levels and under walking and running conditions. Different speed values of the trajectories have been presented in this study. From these results, future studies will provide a more detailed definition of human behavior or will provide more evidence regarding the perceptive capabilities and behavioral specification of every agent relative to their interpretations of the other elements in the system, such as other static or dynamic objects (agents or obstacles) [40]. The novelty of this work is that it investigates the trajectory of these experiments, which produces additional information related to the effects of obstacles on humans, and our future works will aim to model and validate these collective movements with a simulation.

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