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Examining influence of merging architectural features on pedestrian crowd movement

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ABSTRACT

Architectural features such as merging corridors form an important component in floor plans of any major public infrastructure. Previous studies on documented crowd disasters have highlighted that passage restriction such as merging corridors can have negative impacts on the efficiency of evacuation process. However, limited data exists on merging process in the literature. This study aims to address this issue through empirical data collection and analysis of merging process in a controlled laboratory walking experiments.

A series of experiments were conducted with different merging angles (60°, 90° and 180°) and with different desired speed (normal and slow running). The experiments indicated that pedestrians tend to reduce speeds within merging areas. With higher merging angle, there is greater reduction in speed in the merging area. Speed reduction is statistically significant with merging angles and desired speed. The speed reduction had an effect on the flow rate with reduced flow rate observed for higher merging angle. The empirical results from this study can be used to develop and test pedestrian crowd simulation models.

1. Introduction

Pedestrian's movement forms an important component of a multi-modal transportation system. Besides, promoting walking is an important part of the shift to more sustainable transport. However, it is a great challenge to planners or managers of emergency response to ensure efficient, comfortable and safe walking operations of pedestrian's movements in public places such as multimodal points, shopping malls, stadiums and concert venues. Modelling and empirical study of pedestrian behaviour is imperative to analyse and assess safety precautions for those situations.

One of the important characteristics of pedestrian's movement is merging behaviour as observed in the transit stations, buildings or any other indoor or outdoor public areas. This phenomenon usually occurs when crowd movements from multi directions join to form a single pedestrian stream and hence considered as a combination of turning and weaving movements (Roess et al., 2004). Such complex movement can result in travel delays and comfort reductions, thereby reducing efficiency of passenger transit facilities (Daamen, 2004). Also during an emergency evacuation, merging movement of pedestrian crowd is crucial as they change the direction of their escape route abruptly while merging from different corridors (Chertkoff and Kushigian, 1999; Still, 2000). Previous studies on documented crowd disasters have highlighted that sudden change in the egress direction in a restricted passage due to merging and turning could initiate trampling and stampede as people rush to escape (Chertkoff and Kushigian, 1999). It is very important to identify the use of space and movement pathways in preventing crowd stampede (Fruin, 1993; Shiwakoti et al., 2014). Although merging flows may have an implication on the efficiency and safety during evacuation process or crowd management, limited data exists on merging process in the literature. This study aims to address this issue through empirical data collection and analysis of merging process in a controlled laboratory walking experiments.

The paper starts with a review of relevant literature, followed by a description of the experiments on merging behaviour. Results are described and conclusions are presented including a summary of key findings and a discussion of their implications for future research.

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2. Literature review

To understand the complex phenomena of crowd movement, investigations have been carried out by researchers using mathematical modelling, simulation and empirical approaches (Daamen, 2004). Mathematical modelling and simulation can be further classified as microscopic, mesoscopic and macroscopic depending on the level of detail. Complementary data are required to test the theoretical models quantitatively for their validity and reliability and also to compare the performance of alternative models. The experimental studies on pedestrian crowds have been carried out mostly with human subjects (Daamen and Hoogendoorn, 2003; Helbing et al., 2005; Ko et al., 2007; Kretz, 2007). Most experiments with human crowd aim to understand the behaviour and characteristics of pedestrian flow under congested and non-emergency conditions. Such experiments are of fundamental importance in understanding the behaviour of people under emergency conditions. Similarly, some studies have focussed on non-human organisms, especially under stressed conditions (Altshuler et al., 2005; Burd et al., 2010; Shiwakoti et al., 2011; Soria et al., 2012; Shiwakoti and Sarvi, 2013) to study collective dynamics. Those studies concluded that animal models may have the potential to provide an alternative means of empirically testing and verifying human pedestrian models, particularly when human subjects cannot easily or ethically be employed. However it is important to further explore the physical and behavioural similarities and dissimilarities among these different biological entities and how they may help to unlock the complexities of collective dynamics that may not be fully captured in existing mathematical models.

Empirical approaches for understanding complex pedestrian crowd behaviours such as turning (Dias et al., 2014), crossing (Helbing et al., 2005; Asano et al., 2009; Dias et al., 2013) and weaving (Wu and Lu, 2013) have been conducted in the past to study collective pedestrian dynamics. However, regarding merging crowd flows, experimental studies (and also modelling) is limited in literature.

Tajima and Nagatani (2002) applied a lattice-gas model of biased random walkers to simulate the pedestrian merging flows in a T-shaped channel. They found that clogging can occur at either channel or both channels. In another study, by using a cellular automata procedure with multi-floor fields, Peng and Chou (2011) state the formation of congestion at a merging "T" intersection. Likewise computer simulations have been used to demonstrate the importance of merging process in floor-stairs interface in multi-floor buildings (Galea et al., 2008). In terms of empirical analysis, Zhang et al. (2012) performed a series of controlled experiments with human participants in straight corridors and T-junctions. Based on the experiments, they established fundamental diagrams of the two geometrical layouts and studied their performance. With respect to non-human organism approach, a series of experiments with panicking ants to investigate the impact of complex configurations like turning, crossing and merging on the collective egress have been performed (Shiwakoti et al., 2012; Dias et al., 2013). These studies on non-human biological entities concluded that the complex architectural configurations can potentially lead to inefficient egress. However, there have been no empirical studies on human crowds that have examined the impact of merging angle to the pedestrian crowd flow in a merging area. Therefore, this paper investigates the influence of merging angle on the performance of pedestrian flows at merging corridors. In the next section, the experimental setup is described.

3. Experiments

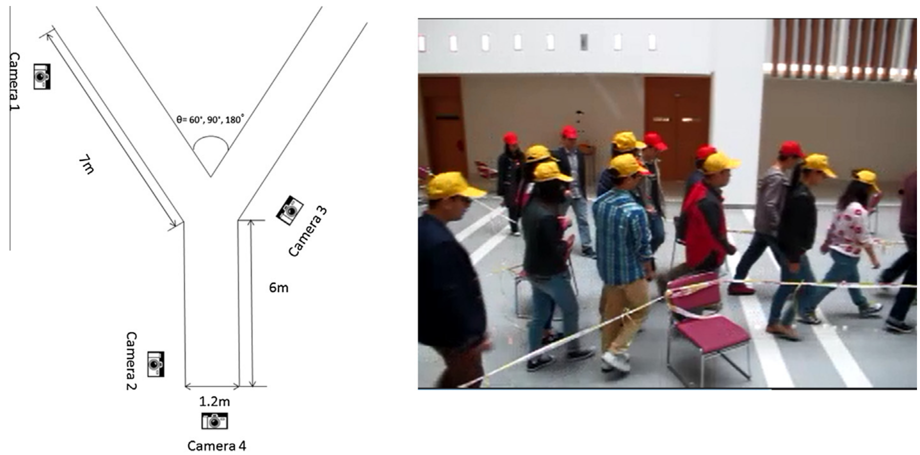
A series of experiments were conducted with different merging angles (60°, 90° and 180°) and with different desired speed (normal and slow running) with 22 participants (6 female and 16 male) in total. The experiments were carried out inside a building at the Southeast University, Suzhou, China in May 2014. All the participants were students selected from the Southeast University and were aged between 22 and 26 years. These merging angles (60°/90°/180°) were chosen as these angles were more frequently noticed in the merging section of several buildings and train stations in China. While normal walking would be relevant to the congested situation in day to day pedestrian activities or special events, slow running or faster walking may be more representative when people are in hurry (as observed in train stations) or in normal evacuation process (Daamen, 2004). Due to ethical and safety concerns, it is not possible to conduct experiments with running participants which could be relevant to highly competitive behaviour and emergency situation. The number of participants considered in this experimental setup was enough to create Level of Service E (>0.7–1.4 m^2/pedestrian, HCM, 2000) in the merging corridor. It thus represented a congested but stable flow suitable for the intended study. Three repetitions were conducted for each angle and desired speed resulting in total 18 experimental trials. Although higher number of repetitions may be desirable for statistical analysis; considering resource and cost constraints, three to five repetitions have been sufficient to conduct relevant analysis for laboratory walking experiments (Asano et al., 2009, 2007; Kretz 2007).

The experimental layout consisted of two corridors (7 m) merging to a one common corridor (6 m). All the corridors had width of 1.2 m as shown in Fig. 1. The corridors were created using chairs and ropes, a similar logistics used by Helbing et al. (2005), where they used classroom desks to create a corridor to study crossing behaviours of pedestrians. Also researches on pedestrian walking behaviour have shown that pedestrian usually keep some safe distance (also referred as shy distance) from the wall or boundary while walking (HCM, 2000). Hence, unless pedestrian behaviour is very competitive and pushing each other, use of chairs and ropes for laboratory walking experiments as presented in this study is a stable configuration (i.e. risk of pedestrian pushing through the ropes/chair is low). To reduce the degrees of freedom, the effect of blocked vision (due to walls) was excluded by setting out the corridors only with chairs and tapes. Such logistic arrangements for reducing the degree of freedom have been used for several experimental studies on pedestrian walking behaviour (Helbing et al., 2005; Asano et al., 2009; Dias et al., 2014). By reducing the degree of freedom, it is easier first to explore the global behaviour resulting from pedestrian's local interactions rather than the overlapping complexity introduced by the external interactions (such as blocked vision). The effect of blocked vision can be studied later once the fundamental understanding of pedestrian's interactions is clear.

Participants were divided into two similar groups considering gender and body size. To avoid a perfect symmetry (in terms of number of participants), one group consisted of 12 participants while the other group had 10 participants. This setup replicates more realistic situation (in real world) as rarely there would be a situation where there are equal number of pedestrians in each of the merging corridors.

Before the start of the experiments, participants were instructed where to gather, when to start walking and where to walk. However, no information was provided to the participants regarding the research aims of the study. Few warm up walking trials were conducted to ensure that participants were comfortable in walking through the corridor and follow the instruction. A lunch meal voucher was offered to the participants after the experiments as a token of appreciation for participating in the experiments.

Two groups of participants were held separately behind a waiting line that was 0.5 m away from the entrance of the each



(a) (b)

Fig. 1. Schematic diagram showing the dimensions of corridors for experiments (a) and a sample snapshot from the experiment showing the merging process in a 90° merging corridor (b).

corridor so that homogeneous flow could be formed when entering the corridors. A whistle signal (similar process as used in Asano et al., 2007) was used to initiate the movement and the participants returned to the waiting area for next repetition after going through the exit corridor. Participants were first asked to walk with their normal walking speed and the experiments were conducted for each merging angle for three repetitions. After that, participants were asked to walk faster (slow running) and the experiments were repeated for each merging angle three times similar like normal walking. When each group of pedestrians return to the waiting area, the groups were instructed to remain at their original waiting area or reshuffle their waiting area (i.e. group in left merging corridor move to right and vice versa) for the next trial on random basis. Care was also taken to ensure that the position of the individuals within the group was randomly located for the next trial (for e.g. pedestrians who were at front/back in one trial, randomly locate to middle or front in next trial). This process was intended to minimise the cumulative learning behaviour of participants by introducing the randomness in their location.

The entire experiments were recorded by four synchronised video cameras as shown in Fig. 1. Camera No. 1, No. 2 and No. 3 were fixed in a tripod that was resting on the top of a stable bench (in the same floor where experiment was conducted) while camera 4 was fixed in a tripod at second floor. Camera No. 1 and Camera No. 3 were used to closely observe the interactions at the merging section. Camera No. 2 recorded the flow rate at the exit while Camera 4 covered the whole experiment. Each group of participants were provided with yellow and red hats for better visualisation during data extraction.

Coordinates of pedestrian's movement were extracted from the image sequences at the frame rate of 25 frames per second of recorded videos. Since the camera was firmly fixed in a tripod, there were no issues of errors introduced by shaking of camera. However, as the camera angle was not perpendicular to the floor, pixel coordinates from the video cannot represent pedestrians' movements in real world situations and hence conversion of video coordinates to real world coordinates was required (for obtaining the real world trajectories of pedestrians). To minimise the effect of height difference and swaying, a direct linear transformation algorithm was applied based on Wolf and Dewitt (2000). Selecting the lower left corner of the video image as the coordinate origin, the relevant plane projection transformation formulas are as follows (Eqs. (1) and (2)):

$$u + \frac{l_1 x + l_2 y + l_3}{l_7 x + l_8 y + 1} = 0 \tag{1}$$

$$v + \frac{l_4 x + l_5 y + l_6}{l_7 x + l_8 y + 1} = 0 \tag{2}$$

where (u, v) is the pixel coordinate, (x, y) is the real world coordinate and l_1–l_8 are conversion coefficients.

As the transformation process is undertaken purely in plane coordinate system, eight real world reference points measured in the experiment sites are selected along with the corresponding pixel coordinates. Four points pairs are used to calculate the conversion coefficient and the remaining four are applied for examining the errors. Using this method, we obtained R-squared value as 0.98 for the actual and estimated coordinates confirming the high accuracy. Since we will be discussing our results based on relative values for different setups rather than absolute values, the small errors introduced due to coordinate transformation will not have an impact on the conclusions derived from the results.

For batch transformation of the coordinates, an orthogonal transformation process was applied and the resulting formulas with respect to conversion coefficients are as follows:

$$xl_1 + yl_2 + l_3 + uxl_7 + uyl_8 + u = 0 \tag{3}$$

$$xl_4 + yl_5 + l_6 + vxl_7 + vyl_8 + v = 0 \tag{4}$$

Based on Eqs. (3) and (4), the analytical matrices for conversion coefficients can be established as follows:

$$\begin{bmatrix} x_1 & y_1 & 1 & 0 & 0 & 0 & u_1x_1 & u_1y_1 \\ 0 & 0 & 0 & x_1 & y_1 & 1 & v_1x_1 & v_1y_1 \\ x_2 & y_2 & 1 & 0 & 0 & 0 & u_2x_2 & u_2y_2 \\ 0 & 0 & 0 & x_2 & y_2 & 1 & v_2x_2 & v_2y_2 \\ x_3 & y_3 & 1 & 0 & 0 & 0 & u_3x_3 & u_3y_3 \\ 0 & 0 & 0 & x_3 & y_3 & 1 & v_3x_3 & v_3y_3 \\ x_4 & y_4 & 1 & 0 & 0 & 0 & u_4x_4 & u_4y_4 \\ 0 & 0 & 0 & x_4 & y_4 & 1 & v_4x_4 & v_4y_4 \end{bmatrix} \begin{bmatrix} l_1 \\ l_2 \\ l_3 \\ l_4 \\ l_5 \\ l_6 \\ l_7 \\ l_8 \end{bmatrix} = \begin{bmatrix} -u_1 \\ -v_1 \\ -u_2 \\ -v_2 \\ -u_3 \\ -v_3 \\ -u_4 \\ -v_4 \end{bmatrix} \tag{5}$$

Eq. (5) can be simplified as follows to get the vector sets for conversion coefficients.

$$[\mathrm{A}][l] = [\mathrm{B}] \tag{6}$$

$$[l] = [\mathrm{A}]^{-1}[\mathrm{B}] \tag{7}$$

where [A] is the coefficient matrix for conversion coefficients (l_1–l_8), [B] is the vector set for pixel coordinates and [l] is the vector set for conversion coefficients.

With these transformed coordinates; trajectories, time distance plots and instantaneous speeds could be then acquired which would be useful in analysing the temporal spatial distributions of pedestrian flows. The analysis will be described in the following section.

4. Results

4.1. Trajectories

Fig. 2 shows sample of two dimensional trajectories (based on x and y coordinates) for normal walking for 60° and 180° merging angles. From the trajectories, at the downstream side, it was observed that two streams of pedestrians continued to prefer to stay on their original side of movement thereby trying to minimise the potential conflicts at merging point. Also, the movement pattern in 180° corridor was observed to be more chaotic than in 60° corridor as demonstrated by more irregular trajectories in 180° case. Similar observations were noted for slow running for all the three merging corridors (60°, 90° and 180°, not shown here). The trajectories analysis demonstrated that pedestrians usually try to exhibit self-organised behaviour by avoiding conflicts. However, despite their desire to stay on their current path, at the merging areas turning and weaving occurred (demonstrated by the conflicts in trajectories) which may potentially lead to speed reduction or pushing behaviour in an emergency situation. To study further the impact of merging angle on speed reduction, detailed speed analysis has been presented in the next section.

4.2. Speed analysis

To conduct the speed analysis, the merging process was separated into three sections: merging initiation point, merging area and merging completion point as shown in Fig. 3. Merging initiation point was located based on the change in substantial change in pedestrians direction (i.e. start of turning). Likewise the merging area was where the turning (and weaving) occurred. Lastly, the merging completion point was identified as a location when the turning was completed and the pedestrian movement started to be stable. A two metres arbitrary area (as shown in Fig. 3) was then identified from the merging initiation point (and also from merging completion point) to estimate the average speed of pedestrians. These arbitrary areas ('before merging' 'merging' and 'after merging') were chosen as the flow was stable and the external influence of any initial inputs or final outputs of pedestrians were minimised.

Sample plots of temporal transition of instantaneous speed (v) along the corridor for 60° and 180° corridors are shown in Fig. 4. With the help of these plots as well as from the observation of video data, merging initiation and merging completion points (as described above) were located for speed data analysis. In Fig. 4, a smoothed line has also been drawn for better visualisation that shows the general trend in decline in speed between merging initiation and merging completion. From the figure, it is noticeable that reduction in speed in merging area is more for 180° as compared to 60° angle.

The trend of speed reduction is also clearly visible from the sample plots of time-distance diagrams as shown in Fig. 5. In these time–space plots, same time scaling from one independent experiment has been used. Also a solid arrow line has been drawn showing the general trend of the speed (slope of the distance–time plot line). Two grey bands in Fig. 5 represent the 'before merging' and 'after merging' areas respectively while the white band (in between two grey bands) show the 'merging' area. These plots demonstrate that speed reductions occur in the merging area (flatter slope in the white band) during pedestrians' walking processes and reduction rates varies with different merging angles (more reduction in 180° as compared to 60° angle). Further discussions on speed reduction with respect to merging angle and desired speed are presented in the following paragraph.

Average speeds of pedestrians were calculated for the measurements area defined earlier (refer Fig. 3) and the results are shown in Fig. 6. It can be clearly seen that on the merging area, there is drastic change in speed as compared to after merging (or before merging) for both normal walking and slow running. The speed reduction in merging area increases with the increase in merging angle and is greatest for 180° merging corridor. If we consider 60° as a standard design, there is a relative reduction of speed of about 25% and 34% respectively for 90° and 180° merging corridor for normal walking. Similar trend can be observed for slow running as well. It is interesting to note that for 180° merging corridor, the speed before the merge is lower than the speed after the merge during normal walking while it is nearly equal in case of slow running. One possible explanation to this observation could be that

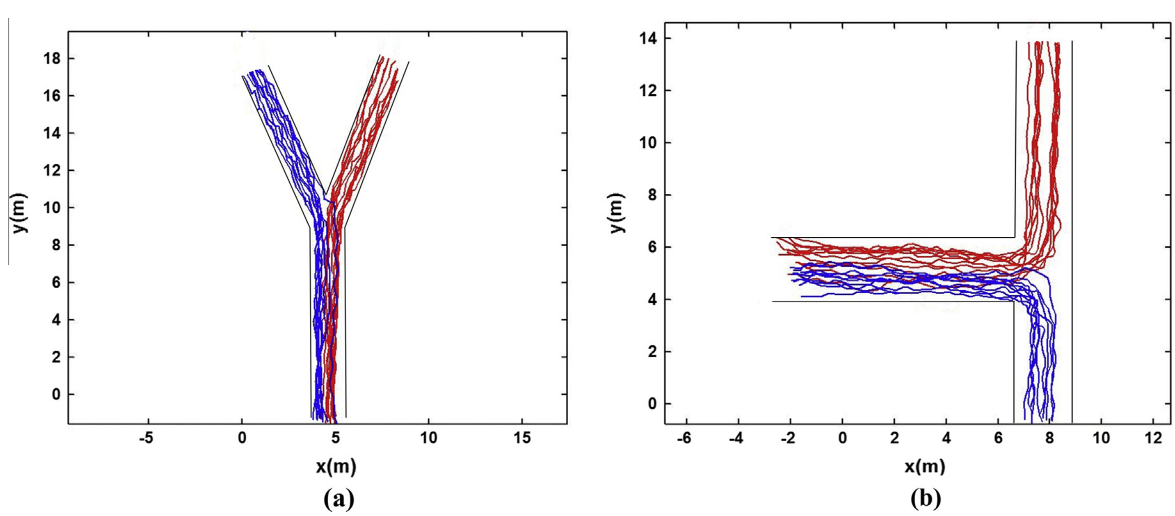


Fig. 2. Sample trajectories for 60° and 180° corridors for normal walking.

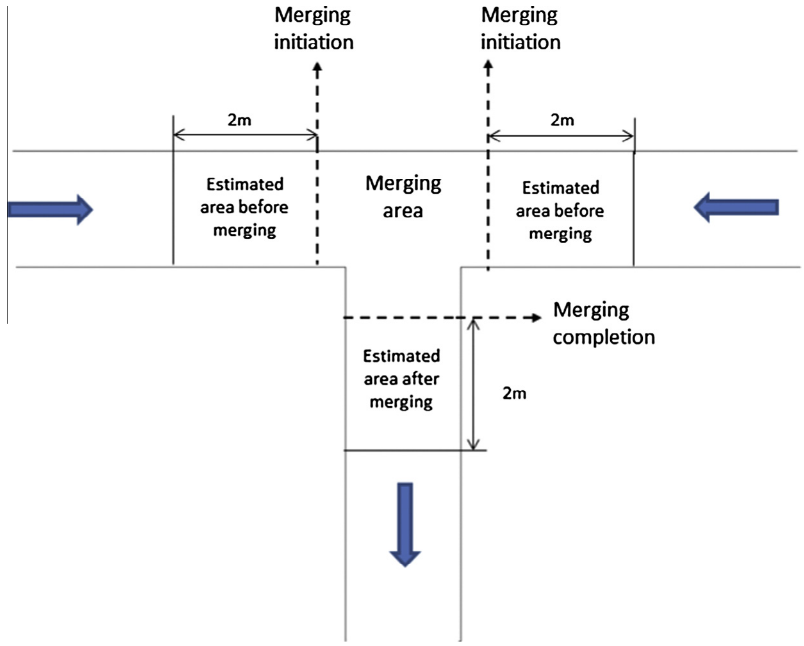


Fig. 3. Identification of 'before merging', 'merging' and 'after merging' areas for speed data analysis.

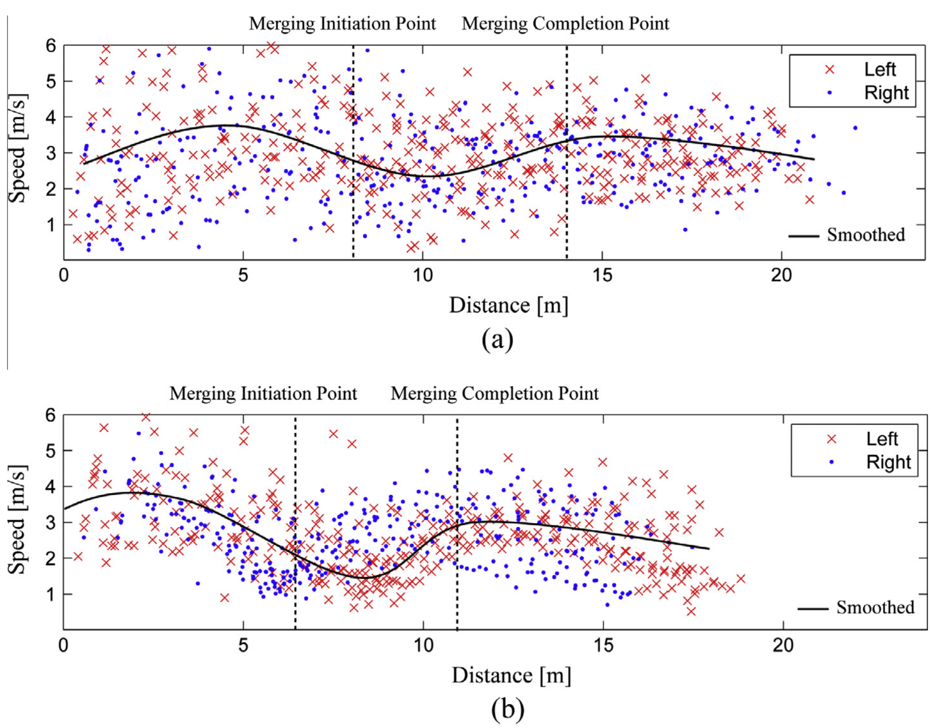


Fig. 4. Sample instantaneous speed and distance plot for 60° (a) and 180° (b) corridors for slow running showing the speed reduction trend in merging areas.

the pedestrians try to compensate the speed reduction at the merging area by walking faster after the merging area. Since the speed reduction is quite high at 180° corridor, perhaps there is psychological tendency of the pedestrians to walk faster after the merging area in 180° corridor as compared to 60° or 90° corridor. Further experiments with greater number of participants and more repetitions are necessary in future to verify this observation.

Non-parametric *Kruskal–Wallis* test was conducted for each speed category to analyse the impact of different merging angles on speed reduction. Speed reduction value is statistically significant with merging angles ($p < 0.05$). The speed reduction had an effect on the average flow rate and the results (average flow rate along with standard deviations) are presented in the Table 1. As it can be seen the flow rate (pedestrians/s/metre width) decreased

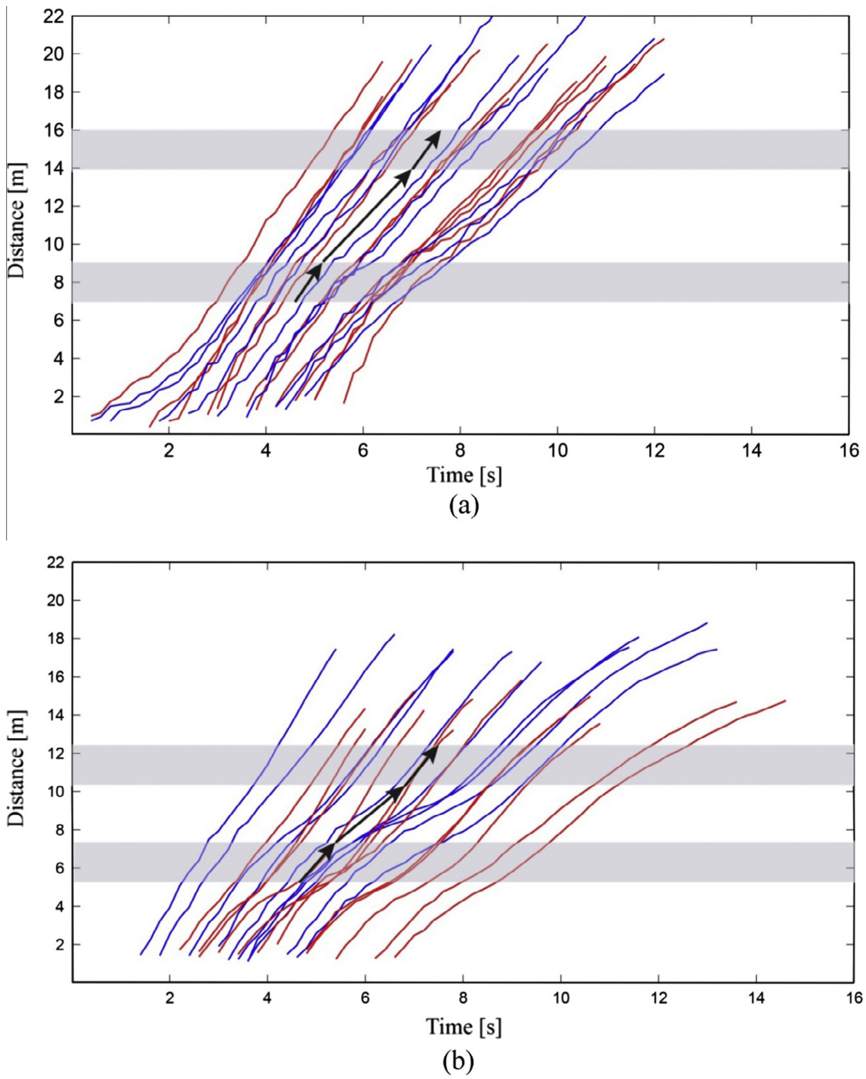


Fig. 5. Sample time distance plot for 60° (a) and 180° (b) corridors for slow running showing the reduction of speed in merging area.

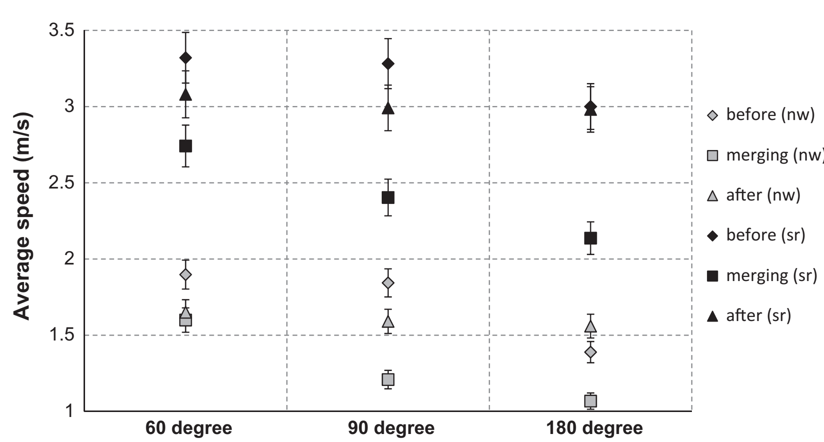


Fig. 6. Comparison of average speed (±SE) in 'before merging', 'merging' and 'after merging' areas for different merging angle: normal walking (nw) and slow running (sr).

with the increase in merging angle for both normal walking and slow running. The 180° corridor is clearly the worst among the three corridors. Higher reduction in flow rate for slow running for 180° demonstrates how critical the merging areas could be in emergency evacuation when pedestrians try to walk faster or run.

5. Conclusion

Architectural features such as merging corridors form an important component in floor plans of any major public infrastructure such as transit stations, shopping malls and stadiums or any outdoor

Table 1
Average flow rate for different merging corridor.

Average flow rate (ped./s/m)	60°	90°	180°
Normal walking	2.1 (±0.22)	2.0 (±0.19)	1.8 (±0.15)
Slow running	3.2 (±0.26)	3.1 (±0.25)	2.6 (±0.23)

public events. Angled paths and merging areas have been identified as a critical bottleneck from documented case studies of several pedestrian's crowd disasters. However, in literature very little data exists on the pedestrian merging process and its impact on the overall efficiency and safety of the crowd movement. Specifically, the influence of merging angle on the performance of pedestrian flows at merging corridors is missing in the literature. This study attempted to fulfil that gap by identifying merging angle as a key variable to evaluate the operation of pedestrian flows at merging area.

In this paper, a series of controlled experiments were conducted to study the pedestrian merging flows under normal and slow running conditions and with different merging angles (60°, 90° and 180°). The results suggested that pedestrian walking speed reduced significantly in the merging area. This reduction in speed was observed for both normal walking and slow running and the reduction rate rose with the increase in merging angles. For example, for normal walking, as compared to 60°, the speed reduction rate was around 25% and 34% respectively for 90° and 180° corridors and was statistically significant. Similar observations were noted for slow running. As a consequence, it had an effect on the walking time and flow rate on the corridor with higher merging angle resulting in more reduction of pedestrian flow.

It is to be noted here that as age distribution of participants, setup of boundary walls (avoidance of blocked vision) may not be representative for average population; our conclusions are based on relative flow values and the relative variation of speed for different experimental setups rather than the absolute values of pedestrians flow and speed.

In future studies, there are several improvements that can be followed up which will enable to quantify the effects of different influencing factors along with merging angle and walking speed. In this study, to reduce the degrees of freedom, the effect of blocked vision was not considered. This setup is relevant in case of open events where crowds are controlled by temporary structure such as steel hand rails/barriers and pedestrians are able to see each other. However, blocked vision may be relevant for merging layout created by fixed walls as seen in buildings and stations. Although for 180° corridor, pedestrians may see each other but for other angles such as 60° and 90°, pedestrian crowd in each corridor will not be able to see each other. This may create more conflicts at the merging area which perhaps may not have been captured fully in the present study. It is recommended that more sophisticated experiment that includes the effect of blocked vision be conducted in future.

Due to the resource and cost constraints, the present study only considered limited range of merging angle (60°, 90° and 180°). In future, a wider selection of merging angles could be conducted (for e.g. 45°, 60°, 90°, 120°, 150°, 180°) and with greater number of repetitions. However, with greater number of repetitions, there is a risk that participants may exhibit learned behaviour which may not be realistic unless different set of participants are used in the experiment. This can have a bearing on the costs and resources for the experiments. Likewise, the effect of different corridor width and length can be explored.

Another setup could be to test the effect of different flow ratio in the merging corridors. In this study, we conducted nearly equal number of participants in each merging corridor. However, experimental design can be developed that includes different proportion of flow (of participants) in the merging corridor (for e.g. 20:80, 40:60, 50:50, 30:70). It would be interesting to observe how the minor flow in one merging corridor has an effect on the major flow in other corridor or vice versa. Would minor stream of pedestrians be blocked by major stream for considerable duration resulting in disproportionate flow at merging area? For such experimental setup, large number of participants (around 100) may be required rather than the 22 participants considered in this study.

Other area that could be improved is to consider the diverse range of participants in the experiments. In this study we considered only the adults (between 22 and 26 years). However in real world, pedestrian crowd is heterogeneous and consists of children, teenage, elderly and disabled people which may have an influence on the outflow at the merging corridors.

Nevertheless, the results from our study demonstrate that due considerations need to be given in the selection of merging angle for designing any public infrastructure where large number of pedestrians can be expected. Specially, in the case of dense crowd and in emergency situations, the speed reduction and clogging could be vital. As such, architects and planners/managers of emergency response need be made aware how small structural features in an escape area can make a big difference in terms of efficiency and safety of crowd management and evacuation process. Also the results obtained from this study can be used to develop and test pedestrian crowd simulation models.

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