Trajectories and walking velocity of pedestrian walking through angled-corridors: A unidirectional scenario

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Abstract. When comparing corner and straight corridor to acute- and obtuse- angled-corridors, effects of later types of corridors on the pedestrian dynamics is rarely studied. Rationally, there will be changes to the pedestrian walking behavior when approaching and walking through angled-corridor due to the turning angle. This could trigger restrictions to the flow of walkers and causing congestion near that turning angle. Hence, this study is purposely to investigate empirically the characteristics of pedestrians when walking through different angled-corridors (60°, 90° and 135°). Controlled experiment of pedestrians walking through built angled-corridors was conducted at the Multipurpose Hall of USM, involving 60 local undergraduate students. Thirty walking tasks were performed by considering different number of pedestrians (NOP: 1, 15, 30, 45 and 60). Video-based tracking of pedestrian’s trajectories walking through angled-corridors was performed and effects on walking characteristics and velocity were discussed. It is found that, pedestrian not necessarily choose the shortest path while walking, but prefer to occupy all space available to suit their own speed and comfort. As the degree of corridor increases, the impacts to pedestrian walking velocity become less. However, in response to the increase in number of pedestrians, the development of changing track can be witnessed.

1. Introduction

There are many kinds of complex architectural configurations of walkways found in public buildings (i.e. train stations, shopping malls and parks) and one of its kinds is an angled-corridor. Angled-corridor can be defined as a pathway with a turning angle in between. Angled-corridor like a corner and a straight corridor are the most commonly one and many studies on the effect of both corridors on pedestrians dynamics and evacuation behavior have been conducted.

However, there are also other geometries of angled-corridor, but their effects on pedestrians dynamics and evacuation behavior are rarely researched. Guo and Tang (2012) [1] confirmed that the geometry and layout of the walkways do affect the behavior and property of pedestrians flow. Hence, immediate study needs to be performed in order to thoroughly understand the pedestrians behavior while walking through angled-corridor.

Angled-corridor can be classified as acute angled-corridor (turning angle of corridor between 0° and 90°), right angled-corridor (a.k.a L-shaped corridor or a corridor with turning angle of 90°) and obtuse angled-corridor (turning angle between 90° and 180°). Rationally, there will be changes to the
pedestrian walking behavior as an individual when approaching and walking through angled-corridor as pedestrians tend to slow down their motion due to the turning angle. This indirectly could trigger restrictions to the flow of walkers during high-density situation and causing congestion near that turning angle of corridor. As investigated by [2] in their oblique merging experiments for different angles of corridor (60°, 90° and 120°) and different speed of walkers, flow rates and headway distributions of walkers are affected during the merging of two streams of a pedestrian crowd.

Some studies have established the effects of straight corridor and bottleneck on pedestrian flow [i.e. 3 – 7]. Similarly, for the right-angled corridor, there were studies conducted especially in studying the effect on fundamental diagram, pedestrians dynamics and evacuation behavior [i.e. 8 – 11]. Meanwhile, studies the effects of acute and obtuse angled-corridors on pedestrians dynamics and evacuation behavior are still limited in open literature. Dias et al. (2014) [12] studied solo walking characteristics of individuals walking through different angled corridors and a straight corridor at different speeds (normal-speed walking, fast-speed walking, and slow running).

The authors suggested that an individual tends to reduce speeds within a fixed region on the angled path and the dimensions of this region were independent of turning angle but dependent on the individual’s desired speed. They did not mention in specific the angle of corridor, instead focusing on the turning angle of the motion: 45°, 60°, 90°, 135°, and 180°.

On the other hand, [14] empirically investigated the impact of angled paths (0°, 45°, 60° and 90°) on orderly crowd egress flows by taking into account the presence of groups and their proxemics behavior while walking. The authors found that in all scenarios (0°, 45°, 60° and 90° angles) the average walking speed of group members was 8.9% lower when comparing to the singles because of their need to stay close while walking. Furthermore, the angle path with 60° resulted in a large negative impact on the walking speed of both singles and group members (7.37% and 11.37% lower, respectively compared to the angle path with 45°).

Besides experimental works, several approaches in the literature have attempted to simulate pedestrian dynamics associated with angled corridors. Dias et al. (2014) [13] presented preliminary results of a modelling framework based on comprehensive experimental data for pedestrian walking behavior s through angled corridors. The proposed framework was based on a microscopic, force based, continuous model that can be combined with existing social force model. They claimed that the proposed model generates more realistic trajectories and speed profiles, thus capturing the bottleneck effect more realistically. Prior to [13] works, [1] developed a microscopic model for simulating pedestrian flow through walkways with not only perpendicular corners. Simulation results indicate that, under certain conditions, increasing the turning degree of corner has negative impact on the pedestrian queues and the flow-density relation of pedestrian walking through walkways with corners, compared with that of pedestrian flow through bottleneck, was more complex.

In this contribution, a controlled experiment was conducted to empirically evaluate the walking characteristics of pedestrians walking through angled-corridor specifically for unidirectional flow. This empirical evaluation is still relevant to be studied due to its immediate applications in many areas like building design, pedestrians facilities design, safety assessment and management of building egress. Furthermore, the empirical relation between density-flow-velocity of pedestrians stream still not completely analysed and has more to be discovered. Hence, three different types of angled-corridor were built (a 60°-, a 90°-, and a 135°- angled-corridors) to study the trajectories characteristics and walking velocity by considering different number of pedestrians (NOP: 1, 15, 30, 45 and 60).

2. Methods

2.1. Experimental setup

The experiment involved the participation from 60 young adults, including male and female in the range of age 19 to 23 years old, who act as pedestrians. All participants represented by local undergraduate students of Engineering Campus, Universiti Sains Malaysia (USM). The types of angled-corridor built in this experiment were limited to three types: (1) a 60°-; (2) a 90°-; and (3) a
135°- corridors. The selection of the corridor types was made based on common constructed corridors in Malaysia’s public facilities. The width of the corridor follows minimum required width for a building, 2.25 m as stated in the Malaysia Uniform Building by Law (UBBL, 1984). The full schematic of an angled-corridor is visualised in Figure 1.

Meanwhile, built-in corridors are as shown in Figure 2.

2.2. Walking tasks
The experiment of walking pedestrians through angled-corridor was conducted at Multipurpose Hall, USM for 2 consecutive days (Saturday and Sunday), on 5th and 6th November 2016.

Each participant was provided with red/blue cap and wearing a white shirt. Participants gathered at either ends S1 or E1 (Figure 1), and, the start of experiment was made at either ends. The inflow rate was set at random for all runs with different set of number of pedestrians (NOP = 1, 15, 30, 45 and 60).

All participants were asked to walk through built angled-corridor according to the walking tasks set earlier starting from S1 and ending at E1 or vice versa. Walking tasks are referring to the free walking activities through angled-corporidor. Altogether, there were 30 walking tasks with each type of corridor possesses 10 tasks, as summarised in Table 1.
Table 1. Ten unidirectional walking tasks for each type of angled-corridor.

| No.  | Tagging of the walking task | No. of pedestrians (NOP) |
|------|----------------------------|--------------------------|
| 1    | 33A 9A 25A                  | 1 (*15 runs)             |
| 2    | 34A 10A 26A                 | 15                       |
| 3    | 34B 10B 26B                 | 15                       |
| 4    | 34C 10C 26C                 | 15                       |
| 5    | 35A 11A 27A                 | 30                       |
| 6    | 35B 11B 27B                 | 30                       |
| 7    | 36A 12A 28A                 | 45                       |
| 8    | 36B 12B 28B                 | 45                       |
| 9    | 37A 13A 29A                 | 60                       |
| 10   | 37B 13B 29B                 | 60                       |

*15 runs = 15 repetitive of an individual walks through the built angled-corridor

2.3. Video data gathering
A GoPro Hero 5 Black video camera (GoPro) was used to record all walking tasks conducted. GoPro was used in this experiment due to its capability to cover full area of angled-corridors. Its small size gives advantage in terms of ease of camera installation. GoPro was mounted on the rack of the ceiling of the hall at the height of 6 m from the floor. A total of 30 videos were recorded in this experiment.

2.4. Video analysis
There were three stages involved in video analysis:

i.  Stage 1: The conversion of video image (mp4 format) into image sequence (PNG format) using Adobe After Effects CS4 software with the frame rate of 25 fps. Image sequence was used in tracking the trajectories of walking pedestrians.

ii. Stage 2: The tracking of pedestrians’ trajectories from image sequence. In tracking works, the trap measurement for tracking was set after 1 m of walking activities (starting from S2 to E2 or vice versa, in Figure 1). This to ensure pedestrians already achieved their desired walking speed. The trajectories of every pedestrian were recorded in term of path coordinates (x, y) by utilizing pedestrian-frame-based tracking method. A software named Autodesk MAYA 2016 with HBS plug-in (MAYA-HBS) was used in tracking work. The tracking of path coordinates for each pedestrian was performed across consecutive frames in MAYA-HBS. As the video was taken at 25 fps, the path coordinates of pedestrians were extracted for every 10 frames such that each track has an interval of 0.4 s. This interval is to ensure the tracking quality.

Each pedestrian was tracked from the time the participant enters the S2/E2 until he or she exits the E2/S2. The first time the pedestrian enters the S2/E2 was regarded as his/her first frame and the point was marked on the head of the pedestrian. Afterwards, the frame was moved to the next 0.4 s (10 frames) and the same pedestrian was marked again on his/her head. This process was continuous and took place until the pedestrian exits the corridor (E2/S2). The whole tracking procedure was repeated for other pedestrians who involved in the tasks.

iii. Stage 3: Determination of the average walking velocity from the path coordinates. The average walking velocity of each pedestrian was determined using conventional definition of velocity. Pedestrian vector velocity on the 2D-plane is given by equation 1:

\[
\mathbf{v}(t) = [v_x, v_y] \approx \left[ \frac{\Delta x}{\Delta t}, \frac{\Delta y}{\Delta t} \right]
\]  

(1)
3. Results and discussion

The results are discussed according to the following criteria: (1) pedestrian walking distribution; (2) trajectories of walking pedestrians; (3) walking velocity; and (4) acceleration and deceleration of walking velocity.

3.1. Empirical observation of pedestrian walking distribution

Pedestrian walking distribution was evaluated by evaluating pedestrians’ favourable track taken during walking through angled-corridor. For that, pathway of each angled-corridor was divided equally into three tracks (= 0.75 m width for each track) and numbered as 1, 2, and 3, starting from the outermost track to the innermost track of the corridor. For evaluating pedestrian walking distribution, the evaluation trap was set between line-SS to line-EE (Figure 3) and evaluation was made based on the track number the pedestrian started and finished. Similar procedure was applied to all types of angled-corridor. A total distance (in meter) of each track for each angled-corridor, measured from line-SS to line-EE is summarized in Table 2. Figure 3 shows the schematic of tracks for the 60° angled-corridor.

Figure 4 shows the distribution of pedestrian in each track for all angled-corridors based on the number of pedestrian (NOP). From the observation made, pedestrians tend to choose their own path (track) while walking based on perception and density on-site situation. From Figure 4(a), for 15 repetitive of single pedestrian walk through angled-corridors 60°, 90°, and 135°, 93.33% to 100% tend to use a middle track. Only 6.67% (1 participant) for 60° and 90° corridors, respectively, prefer to change his/her track while walking (from middle to outer). This happened due to a pedestrian perceived the availability of space to walk in the corridor without interference from other pedestrians and no hindrance for a pedestrian to walk in any tracks.

However, in response to the increase in NOP, pedestrians begin to occupy all space available. This is witnessed in the percentage distribution for all tracks (inner, middle, and outer) shown in Figure 4(b) to (e). It is observed that for the 135° angled-corridor, most pedestrians preferred the outer and middle tracks, meanwhile for the 90° angled-corridor, most pedestrians preferred the inner and middle tracks, as the NOP increases. The scenario in the 135° corridor can be associated to the configuration of the corridor is closely resembles a straight corridor configuration (0°). The difference of outer and middle tracks distances to the inner track are only 1.27 m and 0.64 m, respectively, which is quite small and could be the reason the pedestrians perceived no difference between outer, inner or middle tracks. Furthermore, in the 135° corridor, less turning motion (only 45°) need to be performed by the pedestrians, that make the pedestrians do not mind to use which track. Meanwhile, in the case of the 90° angled-corridor, pedestrians preferred shorter tracks (inner and middle) to minimize the walking distance since the pedestrians need to perform a turning movement of 90°. However, for the 60° corridor, no significance track preferences shown by the walkers, but the outer track is the frequent occupied track as the NOP increases.

On the other hand, there were a few pedestrians who show preferential behavior by changing track while walking to suit their own comfort. From video analysis, the change in track occurs from the middle track to the outer track or from the outer track to the middle track and proceeds to the inner track. This behavior can be clearly witness as the NOP increasing. This occurrence can be associated to the tendency of pedestrian to avoid collision with other pedestrians that walk nearer to or slower than them that prompting them to take other less occupied walking track.

Table 2. Total distance of each track for angled-corridors: 60°, 90° and 135°.

| Track       | 60° | 90° | 135° |
|-------------|-----|-----|------|
| 1 (Outer track) | 10.52 | 8.50 | 7.64 |
| 2 (Middle track) | 7.99  | 7.00 | 7.01 |
| 3 (Inner track)  | 5.43  | 5.50 | 6.37 |
Figure 3. Schematics (not to scale) of track and the evaluation trap for 60° angled-corridor.

(a) NOP = 1 (single)  
(b) NOP = 15  
(c) NOP = 30  
(d) NOP = 45  
(e) NOP = 60

Figure 4. Distribution of pedestrian based on different NOP for each track of all types of angled-corridors (60°, 90° and 135°).
3.2. Trajectories of pedestrian walking through angled-corridor

Trajectory is the path created by the pedestrians as they travel through spaces. Figure 5 to Figure 9 display the accumulated trajectories of the pedestrians for three different angled-corridors based on different NOP. As can be seen in all angled-corridors, a single pedestrian prefers using the middle track, and as the NOP increases, the pedestrians occupy all tracks. As for 90° and 135° corridors, the usage of all tracks are quite balance. Meanwhile, for the case of 60° corridor, for a low NOP (15 and 30), pedestrians are more concentrated in the inner and middle tracks as they approach the turning angle and use the middle and outer tracks as they pass the turning angle. However, as the NOP increase to 45 and 60, the pedestrians walk using the outer track either before or after the turning angle. This could be due to some pedestrians prefer to avoid the congestion at the turning angle.

Based on the previous and current findings, it can be concluded that a pedestrian does exhibit preferential behavior in choosing their walking path. Pedestrians not necessarily choose the shortest path while walking, but prefer to occupy all space available to suit their own speed and comfort. Singles prefer to walk at the middle of the path, and as the number of pedestrians increases, the pathway is occupied accordingly. Meanwhile, there are also changing track behavior shown by pedestrians while walking and this is due to pedestrians perceived the availability of space to walk in the corridor and to avoid any congestion apparent ahead.

3.3. Walking velocity of single and a group number of pedestrian

Figure 10 shows the average walking velocity for singles and a group of NOP for all types of angled-corridor. As expected, the highest average walking velocity is recorded for 135° corridor, followed by 90° corridor and 60° corridor. The 135° corridor configuration is almost in a straight manner (0°/180°) and this indicates that the pedestrian feels comfortable to travel and do not feel the urge to huddle together at the turning angle of corridor. As the angle of turning increases from 45° (in 135° corridor) to 120° (in 60° corridor), pedestrians tend to slow down at the turning. This factor can be witnessed in the next sub-chapter.

Singles tend to walk in a faster rate when comparing to pedestrian who walk in a group of NOP. This is because singles face little or no obstructions during their walking action, which gives them a freedom to quicken or step up their walking pace. Meanwhile, the individuals in a group of NOP, they feel the need to retain some distance to avoid collision. In 60° and 90° corridors, it can be observed that the average walking velocity of individuals in NOP = 45 and 60 are higher than NOP = 30. This can be associated to the previous findings where some pedestrians preferred to avoid the congestion at the turning angle and used the available space to suit their own speed and comfort.

Figure 5. Trajectories for single pedestrian for each angled-corridor: (a) 60°, (b) 90° and (c) 135°.
**Figure 6.** Trajectories for NOP = 15 for each angled-corridor: (a) 60°, (b) 90° and (c) 135°.

**Figure 7.** Trajectories for NOP = 30 for each angled-corridor: (a) 60°, (b) 90° and (c) 135°.
Figure 8. Trajectories for NOP = 45 for each angled-corridor: (a) 60°, (b) 90° and (c) 135°.

Figure 9. Trajectories for NOP = 60 for each angled-corridor: (a) 60°, (b) 90° and (c) 135°.

Figure 10. The average walking velocity of singles and group of pedestrian.
3.4. **Acceleration and deceleration of walking velocity in different angled-corridor**

Table 3 summarizes the average walking velocity of pedestrians in relation to turning motion for each angled-corridor with different NOP. In overall, the average walking velocity before the turning motion is higher when comparing with the average walking velocity during and after the turning motion in all angled-corridors and NOP. This confirmed findings obtained by Dias et al., 2014. Pedestrians tend to reduce the walking velocity when approaching turning angle of the corridor. Furthermore, the velocity continuously reduces even after the turning motion. This can be concluded that the configuration of the walkways does affect the walking behavior of pedestrians.

Among the three types of corridors, the 60° corridor shows the lowest velocity, followed by the 90° corridor and the 135° corridor. As an example, $v_b$ for single pedestrian is 1.43 m/s, but it decreases to 1.33 m/s when approaching the turning angle and continue decrease to 1.18 m/s after the turning motion. The percentage decreases of velocity are -6.89% and -11.55%, respectively. It can be concluded that angled-corridor have negative impact to the pedestrians walking behavior due to pedestrian tend to reduce his/her walking velocity when approaching the turning angle of corridor.

**Table 3.** The average walking velocity of pedestrians in relation to turning motion for each angled-corridor with different NOP.

| Average velocity of pedestrian (m/s) |
|--------------------------------------|
| NOP   | 1   | 15  | 30  | 45  | 60  |
|-------|-----|-----|-----|-----|-----|
| Before turning motion, ($v_b$)   | 1.43| 1.19| 1.00| 0.99| 0.96|
| During turning motion, ($v_d$)    | 1.33| 1.11| 0.95| 0.99| 0.92|
| After turning motion, ($v_a$)     | 1.18| 0.94| 0.93| 0.87| 0.81|

(a) A 60° angled-corridor

| Average velocity of pedestrian (m/s) |
|--------------------------------------|
| NOP   | 1   | 15  | 30  | 45  | 60  |
|-------|-----|-----|-----|-----|-----|
| Before turning motion, ($v_b$)   | 1.53| 1.31| 1.00| 1.10| 1.12|
| During turning motion, ($v_d$)    | 1.37| 1.13| 0.97| 1.05| 1.06|
| After turning motion, ($v_a$)     | 1.23| 0.91| 0.90| 0.86| 0.80|

(b) A 90° angled-corridor

| Average velocity of pedestrian (m/s) |
|--------------------------------------|
| NOP   | 1   | 15  | 30  | 45  | 60  |
|-------|-----|-----|-----|-----|-----|
| Before turning motion, ($v_b$)   | 1.76| 1.41| 1.30| 1.25| 1.25|
| During turning motion, ($v_d$)    | 1.65| 1.31| 1.25| 1.22| 1.19|
| After turning motion, ($v_a$)     | 1.49| 1.12| 1.23| 1.06| 0.98|

(c) A 135° angled-corridor

4. **Conclusion and recommendations**

In this contribution, an experimental work was conducted to investigate the walking behavior of pedestrians while walking through angled corridors (60°, 90° and 135°). It is found that, pedestrian not necessarily choose the shortest path while walking, but prefer to occupy all space available to suit their own speed and comfort. As the degree of corridor increases, the impacts to pedestrian walking velocity become less. However, in response to the increase in number of pedestrian, the development of changing track can be witnessed. This occurrence is associated to the tendency of pedestrian to avoid collision with other pedestrians that walk nearer or slower. Singles tend to walk in a faster rate when comparing to a group of number of pedestrians. This because singles face little obstructions during their walking action, which gives them the freedom to quicken their walking pace. The highest average
walking velocity recorded for pedestrian (single and a group of NOP) is observed for 135° corridor indicating that pedestrian is comfortable to travel since the 135° corridor is almost similar to a straight corridor.

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