The fundamental diagrams of elderly pedestrian flow in straight corridors under different densities

Xiangxia Ren\(^1\), Jun Zhang\(^{1,3}\), Weiguo Song\(^1\) and Shuchao Cao\(^2\)

\(^1\) State Key Laboratory of Fire Science, University of Science and Technology of China, Hefei 230027, People’s Republic of China
\(^2\) School of Automotive and Traffic Engineering, Jiangsu University, Zhenjiang 212013, People’s Republic of China
E-mail: junz@ustc.edu.cn

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Abstract. The worldwide population is aging and countries are facing ongoing challenges in meeting the transportation demand of the elderly. In this study, we investigate the movement characteristics of the elderly in the straight corridor and compare them with those of young adults. The free speeds of the elderly (about 1.28 m s\(^{-1}\)) are obviously slower than those of the young people (about 1.4 m s\(^{-1}\)) in the laboratory experiments. It is found that the fundamental diagram of the elderly shows a similar trend compared with that of young pedestrians. However, at the same densities the speeds of the elderly are always lower than those of the young pedestrians in the observed density range (<3.0 m\(^{-2}\)). When the mean velocity calculated from pedestrian movement at low densities is considered, the two normalized fundamental diagrams agree quite well. The reasons for the differences are explored by analyzing the border distance, the nearest neighbors as well as the spatial distribution areas of the pedestrians. Our findings can be useful for the improvement of pedestrian modelling and design of pedestrian facilities that are much friendlier to the elderly.

Keywords: traffic and crowd dynamics

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\(^3\) Author to whom any correspondence should be addressed.
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1. Introduction

Research on pedestrian dynamics is the key to realizing safer transportation environments and effective evacuation in emergencies. Pedestrian experiments under well-controlled but various conditions were carried out to study the movement of pedestrians [1–7]. The current research indicates that the building structure, the motivation of the crowd and the data collection methods have obvious influences on the fundamental diagram of the pedestrian movement [2, 8, 9]. The experiment of pedestrians walking in the corridors was carried out to study the relationship between movement characteristics and corridor conditions [1, 10, 11]. Based on the experimental data, some simulation models [12–14] were developed to study the characteristics of pedestrian dynamics deeply, especially some experimental conditions that cannot be realized in practice.

On the other hand, the aging of the population is a social phenomenon around the world. Compared with young people, the elderly are a vulnerable group and faced with higher risks in daily life especially in transportation due to their poor mobility, vision, hearing, strength and sensory ability. An evacuation experiment of moving downstairs conducted by Kuligowski [15] showed that elderly people have lower velocities and longer evacuation time requirements. The elderly transportation demand is increasing day by day and it is of great significance to study the motion characteristics of the elderly population and to design more friendly facilities so as to improve the safety of the elderly. How to realize efficient evacuation and safer traffic of the elderly by considering their special physical conditions is a great challenge for public safety work. However, there are few studies on the movement behavior and characteristics of the elderly.

Most data in the field of pedestrian dynamics is on young and middle-aged people. The differences between the movement dynamic characteristics between the elderly and
The fundamental diagrams of elderly pedestrian flow in straight corridors under different densities are still not clear. Observational experiments [16–19] were carried out in different places to observe the fundamental characteristics of elderly pedestrians and it is found that factors such as gender, disease, educational level and grip strength can affect walking speed. The results of the field observation conducted by Gorrini et al [20] in a crowded urban walkway show that in the situation of irregular flows, elderly pedestrians walked 40% slower than adults, but the influence of group and environment on the movement cannot be ruled out. Data from the single-file experiment in [21, 22] showed that there are significant differences in the fundamental diagrams between the elderly and mixed group and the ratio of the elderly in the group has a different influence. Further, the curvature of trajectory is analyzed [23] and it is found that the elderly have larger step widths because they have a weaker ability to control the lateral movement, where the step width was defined as the lateral distance between two consecutive steps. However, this experiment only considered single-file scenarios and lacks high-density data.

Spatial-temporal distribution is an important self-organization feature of pedestrians. It is found that there are symptoms of strong correlations between positions of closely located pedestrians [24]. The age, gender, and mobility also play important roles in interpersonal distance [25]. Compared with young people, the elderly need farther international distance [26]. However, there is still a lack of quantitative description, and the specific expression of spatial distribution in the crowd also deserves our attention, especially for the elderly.

Some of the simulations take the age parameters into account [27–29]. Shimura et al built a CA model according to the characteristics of the pedestrians’ mobility when the elderly and the young are mixed to gain some basic phenomena of dynamics [30]. But at the moment, motion models for the elderly are still very limited due to the lack of basic empirical data. Research on the dynamics of the elderly needs to be supported by richer data and the effect of age on the movement characteristics of the group is still lacking in-depth study.

Based on these considerations, we implemented an experiment to investigate the movement of elderly pedestrians in straight corridors under different densities. The aim of our study is to compare the fundamental diagrams of an elderly group with groups of different ages and analyze the influence of age on the crowd movement in the corridors. The structure of this paper is as follows. In section 2 we describe the setup of the experiment and the trajectories in different scenes. We analyze the fundamental diagrams of the elderly movement in a straight corridor and compare the results with previous studies on young adults in section 3. Finally, section 4 summarizes the paper and makes a conclusion.

2. Setup of experiment

The experiments were carried out on March 2018 in Hefei, China. We recruited 73 volunteers from a senior center in Hefei. Figure 1 shows the distribution of age and gender of the participants. They are between 52 to 81 years old with the mean age of 69.7 ± 7 years old. Their heights range from 150 cm to 175 cm, with an average of 163 cm. The
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Figure 1. The distribution of age and gender of the pedestrians in the experiments.

ratio of male and female is about 1:2.5 (21 males and 52 females). Even though they have no physical problems with normal movement, we did not ask them to participate in each run of the experiment by taking account of their demands for rest.

Figure 2 shows the illustration and a screenshot of the experimental scenario. We studied the movement of the elderly in a straight corridor under controlled conditions. The length and the width of the channel is 10 m and 1.8 m respectively. In order to regulate and control the density in the corridor, nine runs were designed by changing the sizes of the entrances and exits of the corridors. The detailed information on each scenario setup can be found in table 1. Before the formal experiment, we asked each participant to walk through the corridor once to measure their free movement speed afterward. When the experiment started, they were asked to walk through the corridor in a normal way from the waiting area 2 m away from the entrance. Note that a few participants asked to have a rest after some runs due to their physical abilities. This is the reason why the number of pedestrians in different runs did not remain the same. At the end of the experiment, a short questionnaire was used to collect their personal information including age, sex, height, weight and so on.

We used two digital cameras mounted on the roof of a building about 10 m high to record the process of these experiments. Each participant was asked to wear a red or blue hat for ease of recognition from video recordings (see figure 2). The software PeTrack [31] was used to extract the trajectories automatically and the average height of 163 cm was used for data transformation from pixel coordinates to physical coordinates.

Figure 3 shows the pedestrian trajectories obtained from the video recordings with instantaneous speed in different scenarios. In the process of the movement, the pedestrians formed three lanes and converged around the outlet. With the decrease of the outlet width more fluctuations appear in the trajectories, since pedestrians exhibit a physical swing during the process of waiting and finding the path under high densities. At the same time, the velocity of the crowd is decreasing, especially in the area near the exit. There is a sharp drop in velocity at the inside of the corner. It can be found from these graphs that the narrower the exit, the greater the impact on pedestrian
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velocity. These trajectories also indicate that some people have a higher velocity, for they get through the entrance as quickly as possible in order to avoid congestion. By observing the experiment video, we found that these pedestrians are those with better physical conditions and higher participation enthusiasm in the experiment. Based on these trajectories, movement characteristics of the elderly such as density, velocity and flow at any time and position can be calculated.

3. Analysis and results

3.1. Fundamental diagram

Firstly, we study the fundamental diagrams of unidirectional flow of the elderly in the corridor using the Voronoi-based method introduced in [9]. In order to investigate
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Figure 3. Trajectories with instantaneous velocity in different scenarios.
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Table 2. The detail of the measurement areas that were selected to measure the fundamental diagrams.

| Index | Range of $x$ (m) | Range of $y$ (m) |
|-------|----------------|----------------|
| $a$   | 2–4            | 0–1.8          |
| $b$   | 3–5            | 0–1.8          |
| $c$   | 4–6            | 0–1.8          |
| $d$   | 5–7            | 0–1.8          |
| $e$   | 6–8            | 0–1.8          |

the effect of different measurement areas on the results, densities and velocities in five different areas with the size of $2 \text{ m} \times 1.8 \text{ m}$ in the corridor along the movement direction are measured. The detailed locations of the measurement areas are listed in table 2. To determine the fundamental diagram, only data from stationary flows are used which are selected by analyzing the time series of density and velocity (see appendix). To compare with previous data, the same time interval $\Delta t = 0.4 \text{s}$ (corresponding to 10 frames) is selected to calculate the instantaneous velocity of each elder. In figure 4 we show only one point per 10 frames to limit the number of sample points and to guarantee their independence. We can see that the fundamental diagrams obtained from different measurement areas agree well except for the difference in data range. When the measurement area is closer to the exit, higher and more continuous densities can be obtained, which makes the fundamental diagram smoother. The shape of the fundamental diagram is similar to that in previous studies on young pedestrian movement [9]. Note that these young people are German, it is not clear how the cultural differences would influence the results. With the increasing density, the velocity of the crowd declines continuously while the specific flow $J_s$ first increases and then decreases. The critical density where the specific flow reaches the maximum is about $1.5 \text{ m}^{-2}$, which is smaller than that of young pedestrian flow. However, the minimum width of the exit (about 1.3 m, see appendix) for reaching the maximal $J_s$ is consistent with Hankin’s findings [32]. He found that above a certain minimum of about 4 ft (about 1.22 m) the maximum flow in subways is directly proportional to the width of the corridor.

Since the same dimension of the experimental corridor was set, it is possible to compare the difference of the fundamental diagrams of unidirectional flow for the elderly and German young people in [9]. The same size of the measurement areas ($\Delta x \in [4 \text{ m}, 6 \text{ m}]$ for the elderly, $\Delta x \in [3 \text{ m}, 5 \text{ m}]$ for the young) in the middle of the channels are selected in both experiments and the same data analysis process is used here. From figure 5, we can see that the shapes of fundamental diagrams for both kinds of population are similar from the scatter diagrams. The difference is that the data points for the elderly are always below that of the young. In other words, at the same density, the velocity and specific flow rate ($J$) of the elderly is lower than that of the young. The observed difference confirms the truth that the elderly have lower athletic ability than young pedestrians. Under the same situation, the capacity of accessing a facility is lower for the elderly.

What’s more, the velocity difference becomes smaller with the increase of the density in the density-velocity diagram. It implies that the influence of mobility on pedestrian flow decreases when the density becomes higher. When the density is relatively
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small, there is enough space for pedestrians to move freely. Pedestrian movement depends more on the individual mobility and the difference between the two groups is relatively large. As the density increases, the distance among pedestrians becomes shorter and interactions among them get stronger.

To understand the mechanism of the different phenomena, we analyzed the movement characteristics from the aspects of free speed, boundary distance and spatial distribution in the following sections.

3.2. Statistic analysis of free speed

The velocities of each pedestrian over the entire length of the channel were calculated, we found that the differences between the pedestrians are relatively large (figure 6). In consideration of the small sample size, different measurement areas were adopted to statistics of the pedestrian free speed. The details of the measurement area are shown in table 3. In order to increase the sample capacity, we computed the velocities of every pedestrian in an 0.5 m long area (3 m–3.5 m, 6 m–6.5 m), 1 m long area (5 m–6 m), 2 m long area (0 m–2 m, 2 m–4 m, 4 m–6 m, 6 m–8 m), 3 m long area (0 m–3 m, 3 m–6 m,

Figure 4. Fundamental diagrams obtained from three different measurement areas. (a). Relationship between velocity and density. (b) Relationship between specific flow and density.

Figure 5. Comparison of the fundamental diagrams of unidirectional flow of the elderly and the young.
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Figure 6. The free velocity of each pedestrian in the entire corridor. The squares represent velocity of males and the full circles represent that of females.

Table 3. The details of the measurement areas selected to calculate the free velocity of each pedestrian.

| Length of the measurement area (m) | Specific X-axis range | Index |
|------------------------------------|-----------------------|-------|
| 0.5                                | 3–3.5 m               | a     |
|                                    | 6–6.5 m               | b     |
| 1                                  | 5–6 m                 | c     |
| 2                                  | 0–2 m                 | d     |
|                                    | 2–4 m                 | e     |
|                                    | 4–6 m                 | f     |
|                                    | 6–8 m                 | g     |
| 3                                  | 0–3 m                 | h     |
|                                    | 3–6 m                 | i     |
|                                    | 6–9 m                 | j     |
| 4                                  | 0–4 m                 | k     |
|                                    | 4–8 m                 | l     |
| 8                                  | 0–8 m                 | m     |

Figure 7. Free velocity of each participant in different measurement area.
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6 m–9 m), 4 m long area (0 m–4 m, 4 m–8 m), and 8 m length range in the channel (0 m–8 m). Half of the participants were selected to show the effects of regional changes on free velocity. It can be seen from figure 7(a) that the velocity value of each measurement area does not fluctuate widely. In this way, we can get the numerical distribution of the free velocity of a pedestrian in a different length range and different passage area (figure 7(b)). The average free velocity of a female is $1.30 \pm 0.18 \text{ m s}^{-1}$, while it is $1.22 \pm 0.21 \text{ m s}^{-1}$ for a male. We got $p = 0.000$ through T-test which represents a significant difference between these two groups of velocities. The speed of the elderly is significantly lower than that of young people ($1.4 \text{ m s}^{-1}$). From the scatter plots and distribution maps, we can see that most of the elders have a speed of less than $1.4 \text{ m s}^{-1}$. Moreover, their speeds are roughly in line with the normal distribution.

Overall, the elderly have a lower free speed than the young. The female elders are slightly faster than the male, for the most important thing is that women are more active than men in our experiment area. In addition, most of the women have peers and they form a weak competition between them. On the other hand, this can be attributed to women aging slower than men, so the inhomogeneity of older women is more pronounced than with older men. Due to the small sample size and unbalanced sex ratio, the results only apply to this experiment and general applicability of the results remains to be verified.

To explore the impact of free velocity on the movement characteristics of the elderly and the young further, we normalize the velocity based on the free velocity and replot the fundamental diagrams in two ways as shown in figure 8. Firstly, we use the directly measured free velocities $V_f^1$ before experiment: $1.28 \text{ m s}^{-1}$ for the elderly group in our experiment and $1.4 \text{ m s}^{-1}$ for the young adults. As shown in figure 8(a), the difference between the two sets of data is significantly reduced. Nevertheless, the data point for the elderly is still below that of the young. Furthermore, we suppose that the pedestrians move in free speed $V_f^2$ when the density is less than $0.7 \text{ m}^{-2}$, where the velocity seems independent of density. Consequently, the mean value of the free velocity for the elderly and young adult experiment are $1.07 \text{ m s}^{-1}$ and $1.37 \text{ m s}^{-1}$ respectively. Therefore, the expected velocity relation coefficient between the two groups of pedestrians is 1.28. The normalized fundamental diagrams shown in figure 8(b) agree very well excepting when the density is higher than $2.5 \text{ m}^{-2}$ where the small amount of data caused the error. The differences of the two normalizations can be analyzed from the following aspects. The mean velocities $V_f^2$ in low density takes the weak interactions among people into account, which reflects the free movement of the crowd better than individual movement. The free velocities $V_f^1$ were measured by asking the pedestrian to walk in the corridor individually at the beginning of the experiment. When one was asked to walk alone, he or she would be in a relative excitement state to maintain a better personal image. Besides, physical strength is another point that needs to be mentioned. As the experiment went on, the fatigue would easily increase and the enthusiasm decrease, especially for the elderly.

3.3. Distance from the boundary

People unconsciously keep a certain distance from walls when walking. Compared with the trajectories in [33] whose participants were $25 \pm 5.7$ years old, the elderly in this
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The experiment are farther away from the boundary. In the video, it can be observed that the participants deliberately keep their distance from both walls to avoid collisions. In order to quantify it accurately, the distances for each pedestrian to their nearest wall are calculated under different global densities. It is noticed that we assume the average shoulder width of the pedestrians is 0.4 m here. Then the distance $d_{pw}$ from the shoulder of a pedestrian at the border of the crowd to the wall is calculated. To make a comparison, we calculate the time series of the mean distances to the wall under four different densities ($\approx 1.6 \text{ m}^{-2}, 1.8 \text{ m}^{-2}, 2.0 \text{ m}^{-2}$ and $2.2 \text{ m}^{-2}$) from the experiments with elderly and young people respectively. In order to quantify the size relationship between the elderly and young people further, both the mean distance to the wall and the variance were plotted in figure 9. And table 4 shows the specific value of the different densities and boundary distance for the two groups under the four situations. Obviously, the distance $d_{pw}$ for the elderly is always larger than that for the young for all four different densities. Further, $d_{pw}$ can be regarded as a constant especially for the elderly. However, the standard deviation of $d_{pw}$ is relatively large under each density due to the swing phenomenon.

We conjecture that the larger $d_{pw}$ of the elderly mainly results from the following three aspects: physical conditions, environmental factors, and psychological effects. Firstly, the body sizes of the elderly in our experiment are thinner than that of the young adults in [33]. In the corridor with a given width, a pedestrian with a larger body

Figure 8. Normalized fundamental diagrams based on the free velocities obtained in two different ways, (a) directly measured free velocity from individual movement, (b) the mean velocity for pedestrian movement under low densities.
occupies more space that can lead the neighbors to be close to the wall. Unfortunately, the participants’ body sizes were not measured in both experiments and we could not quantify the effect of body size on $d_{pw}$ in this study. Secondly, it can be attributed to the adaptability of different groups to the environment and different mental mechanisms. The elderly are more alert to the unfamiliar circumstances compared to young people. They confirmed the purpose and safety of the experiment many times before the experiment, although we had given a full explanation and informed them of the security measures taken. They need to be ready for any potential dangers constantly.

**Table 4.** The mean border distance $d_{pw}$ under different densities.

| Index | Density of the elderly | Distance of the elderly | Density of the young | Distance of the young |
|-------|------------------------|-------------------------|----------------------|-----------------------|
| $a$   | 1.64 m$^{-2}$          | 0.23 ± 0.09 m           | 1.68 m$^{-2}$        | 0.17 ± 0.09 m         |
| $b$   | 1.83 m$^{-2}$          | 0.25 ± 0.08 m           | 1.79 m$^{-2}$        | 0.16 ± 0.09 m         |
| $c$   | 1.99 m$^{-2}$          | 0.24 ± 0.11 m           | 1.97 m$^{-2}$        | 0.14 ± 0.06 m         |
| $d$   | 2.21 m$^{-2}$          | 0.24 ± 0.09 m           | 2.22 m$^{-2}$        | 0.17 ± 0.08 m         |

**Figure 9.** Distances to the wall of the elderly compared with that of the young in same densities, (a)–(d) correspond to four densities (around 1.6 m$^{-2}$, 1.8 m$^{-2}$, 2.0 m$^{-2}$ and 2.2 m$^{-2}$).

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because of the loss of athletic ability, so they prefer to stay much closer to the other familiar pedestrians and away from the walls. Contrarily, young people are more independently and display a different behavior. These reasons will not only cause the different $d_{pw}$ between the two groups, but also cause the difference in the spatial distribution of the population.

3.4. Spatial distribution distance

In this section, we analyze the spatial distribution distance of the two groups of people. The pedestrians influence each other during the movement, which is related to the spatial distribution distance between pedestrians. Therefore, it is valuable to pay attention to the concrete expression of the spatial distribution between pedestrians during the walking movement and the difference between elderly people and young people. We analyzed the distances between individuals to their neighbors from the trajectories.

One pedestrian has to be selected as the reference to calculate the distance and relative position of other pedestrians in the corridor. We have analyzed before that the boundary of both sides will affect the spatial distribution of pedestrians. In view of this, we select the pedestrians in the center of the crowd as the reference pedestrians. Considering that, the movement of the pedestrians is greatly affected by the pedestrians in front and on both sides, distances and locations of pedestrian distributed at angles from $0^\circ$ to $180^\circ$ were analyzed. Here $0^\circ$ represents the right side of a pedestrian and $90^\circ$ represents the movement direction along the corridor. In the same way, we can calculate the nearest neighbors for all the pedestrians at any time $t_i$ under the relatively stable periods during which the global density of the crowd had no significant change. From figures 10 and 11, we can see that the spatial distribution of the first nearest neighbors for the elderly is similar to a half ellipse, whereas it is open for the young in the movement direction. It means that the number of nearest neighbors directly in front of the elderly is greater than that of the young. From the distribution histograms, it can be seen that the mean distance between the elderly is smaller than that of the young. We got $p = 0.000$ in $T$-test which shows that the elderly have smaller distances between them than the young people do.

If we suppose a pedestrian occupies a circle with the diameter of 0.4 m, the gap between two pedestrians $d_{pp}$ can be approximated as the distance between the head centers subtracting 0.4 m. In figure 12 we compare the $d_{pp}$ and $d_{pw}$ between the elderly and the young under two different densities (1.6 m$^{-2}$ and 2.2 m$^{-2}$). In the case of low density, there is no significant difference between $d_{pp}$ and $d_{pw}$ of the elderly, whereas the $d_{pp}$ is obviously larger than $d_{pw}$ for the young people. The young pedestrians preferred to be closer to the walls than to other pedestrians. However, with the increasing density the $d_{pp}$ decreases significantly while the $d_{pw}$ remains unchanged for both the young and the elderly. What’s more, there is no significant difference between $d_{pp}$ and $d_{pw}$ for the young people, but the $d_{pp}$ is obviously smaller than $d_{pw}$ for the elderly. The repulsive force of the border is greater for the elderly than for the young people.

The reasons are analyzed from the following three aspects. First, the distrust of the environment of the elderly leads to greater vigilance causing the boundary exclusion effect to be more obvious. Secondly, the familiarity among the participants could be a potential reason. The elderly volunteers were recruited from a senior center. They were relatively familiar with each other compared to the young pedestrians in the other experiment, which led to
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Figure 10. The distance and position distribution of the nearest neighbors for the density of 1.6 m$^{-2}$. (a) The nearest neighbors of the elderly. (b) Distribution of the nearest distance. (c) The nearest neighbors of the young.

Figure 11. The distance and position distribution of the nearest neighbors for the density of 2.2 m$^{-2}$. (a) The nearest neighbors of the elderly. (b) Distribution of the nearest distance. (c) The nearest neighbors of the young.

Figure 12. Comparison of $d_{pp}$ and $d_{pw}$ between the elderly and the young for density = 1.6 m$^{-2}$ (above) and density = 2.2 m$^{-2}$ (below).
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Figure 13. The polygon consisting of six nearest neighbors of any pedestrian.

Table 5. The polygon area values in different conditions.

| Index | Density of the elderly | Area of the elderly | Density of the young | Area of the young |
|-------|------------------------|---------------------|---------------------|--------------------|
| a     | 1.64 m\(^{-2}\)       | 1.11 ± 0.25 m\(^2\) | 1.68 m\(^{-2}\)     | 1.43 ± 0.29 m\(^2\) |
| b     | 1.83 m\(^{-2}\)       | 1.08 ± 0.24 m\(^2\) | 1.79 m\(^{-2}\)     | 1.39 ± 0.29 m\(^2\) |
| c     | 1.99 m\(^{-2}\)       | 0.88 ± 0.23 m\(^2\) | 1.97 m\(^{-2}\)     | 1.19 ± 0.22 m\(^2\) |
| d     | 2.21 m\(^{-2}\)       | 0.81 ± 0.18 m\(^2\) | 2.22 m\(^{-2}\)     | 1.12 ± 0.21 m\(^2\) |

Figure 14. Comparison of the time series of the spatial areas between the elderly and the young people under the same densities, (a)–(d) correspond to densities (around 1.6 m\(^{-2}\), 1.8 m\(^{-2}\), 2.0 m\(^{-2}\) and 2.2 m\(^{-2}\)).

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[Image 107x581 to 516x725]

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a greater repulsive effect among the young people. Third, the effects of body size cannot be ignored, though we cannot quantify them yet. The larger body size of the young people from Germany may result in a bigger $d_{pp}$. However, this needs to be checked in the future.

3.5. Spatial distribution area

Both the nearest neighbor and others around affect the movement velocities of pedestrians. In view of this, we search for the top six nearest neighbors of the reference pedestrians by sorting the distance between pedestrians and calculate the area of the polygons these six nearest neighbors make. The schematic diagram of the polygon is shown in figure 13. The same method is used to calculate the polygon area composed by neighbors around the young adults. The specific values are presented in table 5. It can be seen that the spatial areas of both groups decrease with the increasing density. Furthermore, the areas for the elderly are always smaller than those of the young adults under the same global density (details can be seen from figure 14). This again proves that the elderly people preferred to stay closer to each other and away from the walls, which leads to relatively smaller $d_{pp}$ and larger $d_{pw}$ correspondingly. One possible reason for this phenomenon is that they are more familiar with each other than the young adults are.

Besides, we compare the spatial areas of the two groups under the same velocities (for example, around 0.35 m s$^{-1}$ and 0.60 m s$^{-1}$). Under these two situations, the densities in the corridor are relatively high and pedestrians are distributed in three rows, which is fine to calculate the spatial area compared to low densities. As shown in figure 15, interestingly there are no obvious difference between the elderly and the young for both velocities. This seems to imply that the movement under high densities is less influenced by the movement ability of the pedestrian. The speed can be constant if the spatial area for a pedestrian is the same, regardless of age.

Figure 15. Comparison of the time series of the spatial area between the elderly and young people under the similar velocities. (a) 0.36 m s$^{-1}$ for the elderly and 0.34 m s$^{-1}$ for the young; (b) 0.57 m s$^{-1}$ for the elderly and 0.59 m s$^{-1}$ for the young.
4. Summary

In this study, a walking experiment of an elderly population in a straight corridor was performed under controlled conditions. In total, 70 elderly people over 60 years old participated in the experiment. We achieve different densities in the channel by changing the width of the entrance and exit and the experiment included nine different test scenarios. Compared with the young adults, the elderly show small steps, low pace and passive wait. Based on the pedestrian trajectories, the fundamental diagrams of the elderly are studied. It is found that the closer the measurement area is to the exit, the better the continuity of the fundamental diagram due to more data points. The basic shape of the fundamental diagram for the unidirectional flow of the elderly is consistent with that in the previous researches. However, the speed and flow for the elderly are always smaller than for the young adults under the same density situation. This proves that the elders in the same access facilities have lower capacity than young people. We normalized the fundamental diagrams by considering the free velocity obtained in two different ways for the two groups. When the mean velocity calculated from pedestrian movement at very low densities is used, the two fundamental diagrams agree well under the observed density range.

Besides, in our experiment the average speed of the elderly is 1.218 m s$^{-1}$ for men and 1.304 m s$^{-1}$ for women, which is significantly lower than that of the young adults (1.4 m s$^{-1}$). It is found that the elderly keep a larger distance from the walls than the young adults. We selected the pedestrian in the middle of the corridor at the steady state to calculate the distances and angles to his neighbors. Like the young, the nearest neighbor in the front of the elderly is oval-shaped. However, the spatial distance of the elderly is smaller than that of the young for an 1.8 m wide corridor. Furthermore, the area of the hexagon made up of the nearest six neighbors is calculated and compared. In the case of the same density, elderly people have smaller areas than young people do, but there is no significant difference at the same speed. The elderly gather much closer than the young do during walking, which causes a greater mutual influence and further affects the velocity. We believe that differences in mobility lead to differences in spatial distribution between the two groups, which in turn reduces the speed and flow of the elderly population. The movement characteristics of the elderly obtained in the analysis can be useful for the design and construction of pedestrian facilities that are friendlier to the elderly in the future. It is worth mentioning that the data used to compare with the elderly are from German students. The cultural differences between German and Chinese participants are not considered in this study and may also play a part on the results, which will be improved in future work.

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Appendix

Figure A1. The two vertical lines indicate the beginning and the end of stationary states. (a) Stationary states of C-180-180-180. (b) Stationary states of C-180-180-160. (c) Stationary states of C-180-180-130.

Figure A2. The fundamental diagrams obtained from different measurement areas ((a) 2–4 m, (b) 3–5 m, (c) 4–6 m, (d) 5–7 m, (e) 6–8 m). Left: the relationship between density and velocity. Right: the relationship between density and specific flow.
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Figure A2. (Continued)

Figure A3. Comparison of Fundamental diagram of the elderly and the young using a binning procedure for figure 5. The mean values with error bars are obtained by subsection with a density of 0.1 m$^{-2}$. (a) Relationship of velocity and density. (b) Relationship of specific flow and density.

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