Contrastive study on the single-file pedestrian movement of the elderly and other age groups

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Abstract. The worldwide population is aging, and countries are facing ongoing challenges in improving the safety of elderly pedestrians. In this work, the single-file movement of the elderly is experimentally compared with that of different age groups. The findings indicate that the age is not the only factor influencing pedestrian dynamics. The heterogeneity of the crowd composition and familiarity among neighboring pedestrians also have significant effects. The existence of three regimes in the relationship between headway and speed is confirmed. In the strongly constrained regime, the slope of the relationship between the headway and speed of the elderly is bigger than that of the young, which means that the elderly are more sensitive to the spatial headway than the young when adapting their speeds. However, the difference of the slopes in the weakly constrained regime is small, which indicates a weak dependency between age and the adaption time. The elderly need a longer headway during the transformation of the motion state. Besides, the ‘active cease’ behavior of pedestrians, which is explained with the least effort principle, is observed in the experiment. The findings offer empirical data of the elderly under high densities and can be useful for the improvement of the pedestrian modelling and the construction of elderly friendly facilities.

Keywords: traffic and crowd dynamics

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1. Introduction

Studies on pedestrian movement, which can help to realize safer transportation environments and effective evacuation in emergencies, have aroused growing concerns. Compared with young people, elders with mobility impairments and additional disease related impairments are faced with higher risks in their daily life, especially on the transportation system. The study of the movement properties of elderly pedestrians is of great significance as the aging of the population is a social phenomenon around the world.

Experiments under well controlled, but varying conditions were carried out previously [1–10] to study the characteristics of pedestrian movement by considering different influence factors such as age, gender, building structure, movement motivation, data collection method and so on. However, a pedestrian crowd is a complex system affected by several factors including experiment setup, facility geometry, and pedestrian movement motivation and so on. Experiments [11–16] on single-file pedestrian movement can reduce the influence of experiment conditions and the lateral interactions among pedestrians and focus on the influence of certain factors on the characteristics of pedestrian movement. Research on pedestrian single-file movement mainly focuses on the time-space diagram, fundamental diagram and the relationship of headway and speed, etc. Zeng et al [17] revealed the relationship between step length and step frequency under different headways. Cao et al [18] studied the influence of the limited visibility on the single-file movement and found that the speed distribution in different conditions conforms to Gaussian distribution. Gulhare et al [19] studied the differences of the single-file motion in the field observations and controlled experiments. They noted that the boundary might have an influence on the results.

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The discrepancies of the fundamental diagrams of pedestrian movement \cite{20, 21} were investigated in different aspects including the shape of the walking path \cite{14}, age composition \cite{11, 13, 15, 22}, as well as cultural difference \cite{23} with a series of experiments. Seyfried \textit{et al} \cite{11} measured the fundamental diagrams for the densities up to 2 m$^{-1}$ and found that two differing speed phases existed. In France, Jelic \textit{et al} \cite{14, 24} conducted experiment inside a ring and the density reached 3 m$^{-1}$. Beside the free flow regime and congested regime, they observed a third regime named weakly constrained regime in the relation of headway and speed. However, from an experiment of pedestrians with different ages in China \cite{15} three regimes were observed in a mixed group of old and young people but only two regimes were observed in a young students group. This indicates that the heterogeneity of the crowd may lead to different characteristics of pedestrian flow. Unfortunately, the quantitative relation of headway and speed for the old group in the strongly constrained regime were not presented due to the lack of data for older people’s movement, especially at the high densities. It is obvious that most of the experiments focused on young pedestrians and the studies on elderly movement were fewer.

Besides, the stop-and-go wave was observed under high densities situations and reproduced in several laboratory experiments \cite{15, 25, 26} and simulation models \cite{27}. Portz \textit{et al} \cite{27–29} analyzed the stop-and-go waves by experiment and modeling qualitatively. An adaptive velocity model with reaction time was also proposed in \cite{28}, which is able to reproduce the stop-and-go waves qualitatively as observed in the experiments. Fang \textit{et al} \cite{29}, who verified the similar behavior between pedestrians and vehicles, proposed the slow reaction (SR) model to describe the pedestrian’s delayed reaction and reproduced the phenomena of uneven distribution in single-file movement. However, the stop-and-go waves of the elderly population are studied less and further experimental data are still required to verify the abovementioned models.

Based on these considerations, we performed laboratory experiments to investigate the movement of elderly pedestrian under different densities with the emphasis on high density. The aim of our study is to compare the characteristics of an elderly group with that of the groups with different age compositions to understand the influence of age on the pedestrian movement. The rest of this paper is structured as follows: The setup of the experiment is described in section 2. The trajectories extracted from the experiment videos are displayed and the effects of different boundaries are discussed in section 3. Then we introduce the measurement methods and analyze the results in section 4. Finally, section 5 summarizes the paper and makes a conclusion.

2. Setup of experiment

The experiments were carried out in March 2018 in Hefei, China. In total 73 volunteers without physical impairment for normal movement were recruited from a senior center in Hefei. As shown in figure 1, the mean age of them is 69.7 $\pm$ 7 years old, ranging from 52 to 81 years old and the ratio of the male to the female is about 1:2.5 (21 males and 52 females). The heights of the participants range from 150-175 cm with an average of 163 cm.
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Figure 1. The distribution of age (left) and gender (right) of the pedestrians in the experiments.

Figure 2 shows an illustration and a screenshot of the experimental scenario, which is composed of two 5 m long straight corridors and two semicircle corridors with the inner radius 2.1 m and outer radius 2.9 m. The width of the corridors was set as 0.8 m to avoid overtaking during movement. These experimental setups were the same as the experimental setup in [15] to allow easy comparison. The circumference of the central line of the corridor, which was supposed as the walking route of the test subjects, is about 25.7 m. Area one is a semi-closed boundary formed by setting up 1.8 m high boards at outer side of the corridor, while area three is a closed boundary constructed with boards on both sides to prevent pedestrians from crossing the border. For area two and four, the rough lines marked on the ground were used to bind the path of pedestrians. At the beginning, the participants distributed along the 0.8 m wide oval circuit uniformly. Then they went ahead at their normal pace when we gave the order for the experiment to begin. As shown in table 1, six runs with different numbers of the participants in the corridor were performed to form different global density. Considering the limited length and patience, we only realize one time for each run.

Two digital cameras mounted on the roof of a building about 10 m high were used to record these experiments. Each participant wore a red or blue hat for easy recognition from video recordings (see figure 2). The software PeTrack [30] 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. The error of the extracted position given by the software is within 0.1 m [31], which is caused by insufficient calibration (0.05 m in maximum), colored caps marker (0.02 m in maximum) and the pedestrian height selection (0.02 m in maximum).

3. Trajectories and the effect of the boundary

By means of digital image processing, we obtained the pedestrian trajectories under different scenarios. In order to study the 1D characteristics of single-file pedestrian movement further, the method mentioned in [25] is used to convert the original oval scenarios to straight ones approximately 25.7 m long and 0.8 m wide. In the new coordinate system, $y = 0$ corresponds to the central line of the corridor, and $y < 0$ (resp.
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Figure 2. The sketch (left) and a screenshot (right) of the scenario, we changed the number of pedestrian to form different densities in the single-file.

Table 1. Details of the runs of our experiment.

| Index | Name       | Number of elders (N) | Duration time (s) | Global density \( \rho_g \) (m\(^{-1}\)) |
|-------|------------|----------------------|-------------------|------------------------------------------|
| 01    | Elders-08  | 8                    | 123               | 0.31                                     |
| 02    | Elders-20  | 20                   | 95                | 0.78                                     |
| 03    | Elders-30  | 30                   | 120               | 1.17                                     |
| 04    | Elders-39  | 39                   | 95                | 1.52                                     |
| 05    | Elders-48  | 48                   | 160               | 1.87                                     |
| 06    | Elders-56  | 56                   | 148               | 2.18                                     |

\( y > 0 \) corresponds to the area which was inside (resp. outside) this oval central line before. We did not filter out the steps before the study any more.

The converted trajectories with instantaneous speeds which are indicated by the color coded are displayed in figure 3. In area one, pedestrians are inclined to the side without a vertical boundary and keep a distance with the wall, while the pedestrian trajectories in area three are more concentrated and less fluctuant due to the constraint of the board boundaries on both sides. In areas two and four, the trajectories show relatively large fluctuations due to the lack of the constraint effect of the vertical boundaries. Some pedestrians even crossed the boundary and the occurring frequency increased with the increasing density in the corridor, which is caused by the overlapping of pedestrians under high density. Interestingly, the trajectories show a certain radian in the semicircle paths. Figure 4(a) shows the graphic analysis of trajectory on the curve. Pedestrians are closer to the inner side of the curved corridor at the beginning of turning \( B \) while move outward gradually. After arriving around the vertex \( H \), pedestrians no longer continue to move outward but gradually move inward. One of the reasons may be that pedestrians tend to increase the radius of their path to reduce the effect of inertia on the turning of the body. When approaching the vertex \( H \) of the semicircle, pedestrians made another path decision and move inward gradually to enter into the straight corridor by the shortest path. This may be a strategy for pedestrians moving on a curve to adapt to the constantly changing direction, which still needs further experimental data to prove.

At the first glance, there are obvious differences of speeds in different areas of the scenarios Elders-08 and Elders-20 whose global densities are relatively low. Quantitatively, we further calculate the mean speeds with the standard deviation of different areas in
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Figure 3. The adjusted trajectories with instantaneous speed, which is indicated by color in the new coordinate system. The horizontal dotted line represents the center line of the corridor and the three vertical ones are used to distinguish the different regions. From left to right are area one, area two, area three and area four. The thicker lines are obtained by averaging y values at 0.1 m intervals in the x direction and the shade represents the standard deviation. (a) Elders-08. (b) Elders-20. (c) Elders-30. (d) Elders-39. (e) Elders-48. (f) Elders-56.

Figure 4. The graphic analysis of trajectory of pedestrians on the curve (a) and the mean speeds with the standard deviation of different areas in each run (b).

Each run as displayed in table 2 and figure 4(b). The T-test is applied on the SPSS platform to test the significance of the difference and \( p < 0.05 \) represents that there is a statistically significant difference between the samples. The detailed results of the \( P \) values are listed in table 3 and \( p < 0.05 \) for all of the T-test. It can be concluded that
the shape of the path and the boundaries do affect the speed of pedestrians, but mainly at low-density situations. The speeds at the curved parts are relatively low compared to that in the straight part. Interestingly, it is higher in the straight area with boundaries on both sides. The reasons may be as follows: as interpreted in [32], the wall of structure has a repellent effect on pedestrians. When pedestrians walk in the narrow corridor, area three, the repulsive force from vertical walls in both sides makes them uncomfortable and thus they accelerate to leave there quickly, which is also confirmed by the fact that trajectories of pedestrians in area one are inclined to the side without a wall. When pedestrians enter the curve parts with relatively higher speeds, they need to decelerate to turn their bodies and keep balance during the continuous change of the movement direction. Otherwise, if they enter the curved section with a lower speed under higher densities, it is easy to keep balance and deceleration is not so necessary any more.

4. Analysis and results

4.1. Fundamental diagrams

4.1.1. Measurement methods. In this study, we analyze the variables like density and speed from both micro and macro aspects. At the micro level, the individual density $\rho_i(t)$ (N m$^{-1}$) is calculated as:

$$\rho_i(t) = 1/d_{h,i}(t)$$

(1)

where $d_{h,i}(t) = x_{i-1}(t) - x_i(t)$ which means that the headway $d_{h,i}(t)$ for a pedestrian $i$ at time $t$ is defined as the distance between the centers of pedestrian $i$ and his/her predecessor $i-1$. In addition, the index ‘$h$’ represents that the distance is calculated based on the headway. Note that, not all of the three systematic errors mentioned above happen at the same time and deviate to different direction. Thus, the error of the headway calculated from the trajectories within 0.1 m.
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The speed $v_i(t)$ (m s$^{-1}$) of pedestrian $i$ is calculated as:

$$v_i(t) = \frac{x_i(t + \Delta t/2) - x_i(t - \Delta t/2)}{\Delta t}$$  

(2)

where the time interval to calculate the speed $\Delta t = 0.8\text{ s}$ is adopted according to the analysis [33].

At the macro level, the average density $\rho(t)$ (N m$^{-1}$) and speed $v(t)$ (m s$^{-1}$) in the measurement area are defined as follows:

$$\rho(t) = \frac{\sum n(t) l_i(t)}{l_m}$$

(3)

$$v(t) = \frac{\sum n(t) l_i(t)v_i(t)}{l_m}$$

(4)

where $l_i(t) = \frac{1}{2}(x_{i-1}(t) - x_i(t)) + \frac{1}{2}(x_i(t) - x_{i+1}(t)) = \frac{1}{2}(d_{h,i}(t) + d_{h,i+1}(t))$ which means that $l_i(t)$ represents the personal space (the distance from the center of $x_i$ and $x_{i-1}$ to the center of $x_i$ and $x_{i+1}$) of pedestrian $i$ overlap with the measurement area. And $l_m$ represents the length of the measurement area, $n(t)$ indicates the number of pedestrians in the measurement area at time $t$.

4.1.2. The fundamental diagrams of elders. Although the speed calculated by equation (2) showed a slight difference due to the different boundary conditions and geometry of the paths, we observed no significant difference in the fundamental diagrams from the macro level of area one, area two and area three except for different fluctuations. The effects of individual differences and fewer sample points for Elders-08 and Elders-20 make it necessary to analyze the macroscopic fundamental diagrams in a greater measurement area. We decided to choose half of the circuit length as the measurement area and it is better to include all the types of boundary. As a result, the measurement area ($4\text{ m}, 17\text{ m}$) is selected for all six runs for the following analysis to minimize the fluctuation in speed and density. Moreover, we only consider the data in steady state eliminating the initial and final transient to remove the impact of the start and stop phases.

The headway and speed distribution of each run are statistically analyzed in figure 5 and the insets show the average and standard deviation values of the headway and speed in each run. It seems that these two variables fit with Gaussian distribution in different runs with different average values and deviations, except for the speed of the run Elders-56, where two peaks can be obviously observed around $v_{i,t} \approx 0\text{ m s}^{-1}$ and $v_{i,t} \approx 0.2\text{ m s}^{-1}$ which represent the stopping and going motion states. This proves the existence of stop-and-go waves, which will be analyzed in detail in section 4.2. From the insets in figure 5, the headway and speed are declining with the increase of the number of participants. However, the magnitude of the change decrease especially when the number of pedestrians is greater than 39 (the global density $>1.52\text{ m}^{-1}$).

Figure 6 shows the fundamental diagrams of single-file pedestrian flow for the elderly from the micro and macro methods respectively. The number of points in figure 6(a) are controlled to be consistent for different runs by changing the sampling frequency. While in figure 6(b) we selected the data from the relatively stable stage and only used
one per ten frames to guarantee the independence of the samples. Even if the maximal density is about 2.3 m$^{-1}$ at the macro level but reaches up to 5 m$^{-1}$ at the micro level, a similar trend can be observed from these two fundamental diagrams except for different resolutions, which corresponds with the findings in [15] with different age compositions. It is worth noting that the pedestrian movement properties of elders under higher densities are obtained in this study.

The scatter diagram figure 7(a) shows the relation between individual headway $d_{h,i}(t)$ and speed $v_i(t)$, while in figure 7(b) the fitting result is compared with the results in [14] with the same binning procedure as they mentioned. When the headway is

Figure 5. The distribution of the headway (a) and speed of the pedestrians (b) in different runs. The vertical line represents $v = 0.05$ m s$^{-1}$. And the insets are the headway and speed versus the number of pedestrians.

Figure 6. The fundamental diagrams of the elders from (a) the micro level and (b) the macro level. At the micro-level, the density is obtained based on headway $d_{h,i}(t)$ while the speed $v_{i,t}$ is the instantaneous speed of each individuals as calculated in the equations (1) and (2). At the macro-level, the density and speed are calculated with the equations (3) and (4).
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greater than 4m, the speed of pedestrians fluctuates greatly and the data points are few, so we did not take these data into account in the fitting analysis. Three regimes (the strong constrained regime, weakly constrained regime and the free regime) can be observed for both the Chinese elders and the French students and they have the same turning points \((d_h = 1.1 \text{ m and } d_h = 2.6 \text{ m})\). As interpreted in [14], pedestrian’s movement is restricted when the headway is small in the constrained regime and they need to adjust the speed to avoid collision with their predecessor. While in the free regime, the headway is large enough and individuals can move with free speed. However, significant differences can be found quantitatively for these two groups. Table 4 shows the slopes and the intercepts of the fitting lines. When fitting the lines, data from the vertical binning are considered in the strong constrained regime and data from the horizontal binning are considered in the other two regimes. Overall, the speeds of the elders are lower than that of the French students under the same headway especially in the free and weakly constrained regimes. When the headway is greater than 2.6 m, the speed is independent from the headway for both groups. The mean free speed is about 0.94 m s\(^{-1}\) for the elders and 1.15 m s\(^{-1}\) for French students respectively. The larger fluctuation for the elders in the free regime can be contributed to the large differences of their mobility and flexibility due to the larger age span. In the strong constrained regime, the main difference for the two groups is that the slope for elders is bigger, but the intercept is smaller. It means that the elders adapt their speed to the available space in front of them more strongly. In the weakly constrained regime, the speeds of pedestrians depend less on the spatial headway than the strong constrained regime. It is interesting that the slopes of the two groups are similar, which may mean that the influence of the headway on pedestrian speed is independent of age in this regime.

Figure 7. The relation between headway and speed. (a) The scatter diagrams of the instantaneous individual speed \(v_i(t)\) and headway \(d_{h,i}(t)\). (b) Comparison for the relation for the elders with that for the French students in [14] using the binning procedure, and the horizontal lines represent headway \(d_h = 1.1 \text{ m and } d_h = 2.6 \text{ m}\).
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4.1.3. Comparison with different age compositions. In this paper, five groups of pedestrians are compared to recognize the influence of age composition on the single-file movement. In order to make a clearer distinction we listed the detailed information of each group in table 5.

Firstly, we compare the relationship of speed and density (which is represented by the reciprocal of the headway) of elders group with that of the old adults and mixed group in [15] from the micro and macro aspects. As shown in figure 8, the speed of elders is lower than that of older adults for the same headway, while it is difficult to observe the difference in the micro scatters of the elderly and the mixed group. For the convenience to compare the scattered points, we show the fitting results in figure 8. It can be found that when the headway is longer than 0.5m, the mixed group have a higher speed than the elderly. The reasons can be explained by the mobility of these groups which can be reflected by the free speed and the familiarity between the pedestrians. The free speed of elderly pedestrians is 0.94 ± 0.15 m s⁻¹ calculated when the headway is between 2.5 m and 4.0 m and that of the old adults group (0.95 ± 0.16 m s⁻¹), which is lower than that of the mixed group (1.05 ± 0.16 m s⁻¹) in [15] which can be found in figure 9. On the other hand, the similarity of the fundamental diagram for the elders and mixed groups may be due to not only the mobility but also the familiarity between neighboring pedestrians in the crowd. Compared to the old adults group and the young, the elders show obviously lower mobility but are familiar with each other. Whereas for the mixed group formed by the old adults and the young students, the age shows two peaks distribution (16 to 18 for the young and 36 to 75 years for the aged old adults with an average age of 52). The obvious different age span led to different life styles and social status. With the mixed mode of the group, the students and old adults were arranged in the corridor alternately with a ratio of 1:1 in the mixed group while the elders distributed freely without strict division of their ages. The young people usually show respect and humility to the elders. They try to keep a

### Table 4. Slopes and intercept points between different regimes of speed binning.

| Regime                        | Elders | French students | Elders | French students |
|-------------------------------|--------|-----------------|--------|-----------------|
| Intercept (m)                 | 0.10   | 0.25            | —      | —               |
| Slope (s)                     | 1.11   | 0.74            | 4.41   | 5.32            |

### Table 5. The mean speeds with the standard deviation of different measurement areas in each run.

| Group          | Elders | French students | Old adults | Mixed | Young |
|----------------|--------|-----------------|------------|-------|-------|
| Source         | Our experiment | Jelic et al [14] | Cao et al | Cao et al [15] | Cao et al [15] |
| Age            | 69.7 (52–81) | Not mentioned | 52 (45–73) | —     | 17 (16–18) |
| Social status  | Senior center | Students | Residential districts | Old adults + young | Students |

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longer distance from the old people to avoid bumping into them and causing injury. As a result, the decrease of speed became very obvious and the different movement speed caused by the physical mobility becomes weak. Reflecting on the fundamental diagram, the similarity is observed.

To analyze the differences of headway and speed between different groups, we adopted the method of averaging the speed with distance headway 0.1 m as a segment to fit the three different age groups and then the method of linear fitting mentioned

Figure 8. Compare the headway-speed of elders with the old adults group and the mixed group. The dashed lines are the fitting results of the scatter from the micro aspect. The fitting formula is $y = \sqrt{a/x + b}$ according to the nonlinear fitting results in figure 9(b).

Figure 9. Relationship of the headway-speed using the horizontal procedure with the linear fitting (a) and the nonlinear fitting with quadratic function (b).
before is adopted. What should be mentioned is that the vertical binning is more suitable for the leftmost data (figure 7). While for the convenience of comparison, we only exhibit the horizontal binning results in figure 9. To exclude the effect of the leftmost data with large fluctuation, only data of the speed beyond 0.2 m s\(^{-1}\) are considered in the linear fitting. The results can be seen in figure 9(a) and we compare the linear fitting results of different groups in table 6 in which the results of mixed and young group are from [15]. As mentioned in [14], the slope has the dimension of time and represents the sensitivity to the spatial headway. It is also called as the adaptation time which is available to react before being at the minimal distance from the current predecessor. It can be seen that elders have the biggest slope and they need longer adaptation time than the other groups.

It is worth noting that the relationships of headway and speed for all of the groups including elderly group in our experiment, French students group in [14] and the mixed group in [15] have the same transition points (\(d_h = 1.1 \text{ m}\) and \(d_h = 2.6 \text{ m}\)). From the relationship of step length and headway in [17, 34], we can see that the pedestrian stride is strongly influenced by the predecessors when the headway is smaller than around 1.1 m, whereas the step length remains steady for \(d_h > 1.1 \text{ m}\). The transition around 2.6 m can be explained as following. Although the pedestrian stride is independent on the space in front for \(1.1 < d_h < 2.6 \text{ m}\), it is still necessary to adjust their movement rhythms to keep similar pace with others and avoid collisions. When the headway is larger than 2.6 m, however, the pedestrians can move freely and not be concerned about the space and other pedestrians in their movement direction. The same transition point of different age groups indicates that the effect of headway on pedestrians’ stride law is independent of age.

The movement of pedestrians in the single file can be compared to the car-following behavior in the traffic flow. It can be found in [35] that the safe distance for braking is proportional to the square of speed. While for pedestrian movement, the headway is equivalent to the safe distance of cars to avoid collisions. According to this consideration, method of nonlinear fitting is adopted and the quadratic function is selected to describe the relationship of headway and speed except for the free regime. As mentioned before, only data of the speed beyond 0.2 m s\(^{-1}\) are considered in the nonlinear fitting. Figure 9(b) shows the results and we can see that these data have a high degree of fitting for \(R^2\) is beyond 0.96. In the nonlinear fitting, the sensitivity increases with the increase of speed continuously rather than a mutation in the linear relationship and the elders have a larger increase range than the others. The relationship of headway-speed and adaptation time can be calculated using the expression in table 7.

### Table 6. Details of the linear fitting of different groups with different age compositions.

| Regime            | Strong constrained regime | Weakly constrained regime |
|-------------------|---------------------------|---------------------------|
|                   | Elders | Mixed | Young | Elders | Mixed | Young |
| Intercept (m)     | 0.10   | 0.25  | 0.25  | —      | —     | —     |
| \(t_a\) (s)       | 1.71   | 1.40  | 0.69  | 4.41   | 4.25  | —     |

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4.2. Time-space diagram

As the density increases, the so-called stop-and-go is observed from the experiment. Reflected in the speed distribution (figure 5(b)), two peaks which represent the stopping and going states of pedestrians appear especially in the scenario of Elders-56 whose \( \rho_g = 2.18 \text{ m}^{-1} \). The two states seem to be separated around \( v_i(t) = 0.05 \text{ m s}^{-1} \) (the vertical line in figure 6(b)). As a result, we suppose that the pedestrians with \( v_i(t) < 0.05 \text{ m s}^{-1} \) are under stop state and those with \( v_i(t) > 0.05 \text{ m s}^{-1} \) are in going state to visualize it in the time-space diagram. The stop-and-go wave formed by a consecutive sequence of one or more stopping pedestrians. Figures 10(a)–(d) shows the stop-and-go waves of the elders group in four different runs. No stopping occurred in the scenarios for \( \rho_g < 1.17 \text{ m}^{-1} \) (the number of the participants \( N < 30 \)), whereas obvious stop-and-go waves are observed frequently during the experiment for the global density \( \rho_g > 1.52 \text{ m}^{-1} \) (\( N = 39, 48 \) and \( 56 \)). Furthermore, the sizes and frequencies increase with the increment of the density. The speeds in which the stop-and-go wave propagates in the opposite direction to the movement of pedestrians are indicated by the absolute values of the slope of the black lines. They are approximately \( 0.37 \text{ m s}^{-1} \) for both runs of \( \rho_g = 1.87 \text{ m}^{-1} \) and \( \rho_g = 2.18 \text{ m}^{-1} \) (Elders-48 and Elders-56), while it is \( 0.5 \text{ m s}^{-1} \) for \( \rho_g = 1.52 \text{ m}^{-1} \) (Elders-39). Compared to that of the young and mixed group under high densities in [15], the stop state appears more frequently and lasts a longer time at the same global density situations (see figures 10(e)–(h)). For further quantitative comparison of the differences in stop-and-go among different age groups, we made statistics on the stop duration of the stopping and going of the same number of people in different densities within 90 s. The duration of stopping includes reaction time and waiting time. As shown in figure 11, the stopping time of the elders group is longer than the others obviously. This indicates, to some extent, that density is not the only reason for the emergence of stop-and-go waves, but the movement ability is an important factor.

Besides, if all pedestrians move in the single-file synchronously, the time-space diagram should be a group of parallel curves. However, some apparent gaps in the diagram of the elders group appear as marked by the black circles in figures 10(b)–(d). From the video recordings, it is observed that some elders did not start to ‘go’ synchronously with his or her predecessor after some stopping but waited several seconds till a certain amount of space in front and then start to ‘go’ again (e.g., the two marked pedestrians in figure 12(a)). We define this phenomenon as ‘active cease’ behavior of pedestrians. To study the ‘active cease’ behavior of pedestrians quantitatively, we calculate the headway of pedestrian in the moment of the transition from stopping to going under high density which is defined as \( h_{s-g} \).

\[
h_{s-g}(i, t_{s-g}) = x_{i+1}(t_{s-g}) - x_i(t_{s-g})
\]
Figure 10. The time-space of the runs in our experiment and the previous experiment. The red indicates the speed higher than 0.05 m s$^{-1}$, while the small speeds are presented in blue. (a) Elders-30. (b) Elders-39. (c) Elders-48. (d) Elders-56. (e) Mixed-46. (f) Mixed-60. (g) Young-45. (h) Young-61.

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where $i$ is the selected reference pedestrian, $i + 1$ is the predecessor of $i$, and $t_{s-g}$ is the changing moment of pedestrian motion state which needs to meet the following condition:

$$t_{s-g} = t \left\{ v_i(t) 0.05 \text{ ms}^{-1} \quad \text{and} \quad v_i(t + 1) 0.05 \text{ m s}^{-1} \right\}$$

where 0.05 m s$^{-1}$ is the critical speed for judging whether the pedestrian is stopping or going.

The statistical results of the $h_{s-g}$ of all of the pedestrian in runs of Elders-48 and Elders-56 within 90s are shown in figure 12(b) and table 7 displays the details. It can be found from the inserts that the $h_{s-g}$ is in accordance with the normal distribution with large fluctuation range (for the standard deviation is 0.17 m and 0.16 m). The $h_{s-g}$ of run Elders-56 (0.49 ± 0.16 m) is shorter than that of Elders-48 (0.53 ± 0.17 m).

**Figure 11.** Quantitative statistics of the duration time of ‘stopping’ and ‘going’ states respectively of different age groups in 90s. The stopping time of elders group is longer than the others obviously. Left: 46 pedestrians are selected from these three groups of the run of elders-48, mixed-46 and young-50. Right: 56 pedestrians are selected from these three groups of the run of elders-56, mixed-60 and young-60.

**Figure 12.** (a) These two pedestrians in the black circles are in the ‘active cease’ when the stopping is not due to the space limitation. (b) The statistical results of $h_{s-g}$ for Elders-48 and Elders-56, where the box charts are used to show the numerical distribution and the solid points filled with red represent the headway of ‘active cease’ pedestrian. In addition, the scatter and histogram inserts exhibit the raw data and its distribution.
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Figure 13. The statistical results of $h_{s-g}$ for groups with different age compositions.

Table 8. Details of the $h_{s-g}$ of different runs with different age compositions.

| Runs        | Elders-48 | Mixed-46 | Young-45 | Elders-56 | Mixed-60 | Young-61 |
|-------------|-----------|----------|----------|-----------|----------|----------|
| Mean of $h_{s-g}$ (m) | 0.53 ± 0.17 | 0.52 ± 0.16 | 0.44 ± 0.12 | 0.49 ± 0.16 | 0.43 ± 0.11 | 0.37 ± 0.11 |
| Median of $h_{s-g}$ (m) | 0.51 | 0.50 | 0.43 | 0.47 | 0.42 | 0.36 |
| Number of $h_{s-g}$/ per capita | 1362/28.38 | 982/21.35 | 127/2.82 | 1744/31 | 3438/58 | 1951/31.98 |
| Number of bigger outliers/ per capita | 37/0.77 | 32/0.70 | 42/0.75 | 87/1.45 | 63/1.03 |
| Percentage of bigger outliers | 2.72 | 3.26 | 2.41 | 2.53 | 3.23 |

m) for $p = 0.000$ in the $T$-test, where $p$ is the probability that the difference between samples is due to the sampling error and $p < 0.05$ represents a statistically significant difference. There were statistically significant differences. Pedestrians decrease the $h_{s-g}$ and follow their predecessors under the pressure from the rear pedestrian when the density increases, which is similar to the driving behavior. While the stopping duration time and the average number of $h_{s-g}$ per pedestrian increases as the density increases, which can be observed from figure 11 and table 7 respectively. This is also the reason why the higher the density is, the more obvious the stop-and-go wave will be. In addition, some outliers which are represented by the solid points beyond the upper edge are caused by the headways of pedestrians with obvious ‘active cease’ behavior that is significantly longer than that of others. The reason for this kind of ‘active cease’ can be explained from the aspect of the least effort principle. We know that the acceleration of a moving body is proportional to the force exerted on it in physics. Similarly, for pedestrians in the single file movement they consume more energy to accelerate or decelerate during the alternation between stopping and going than in a steady state of motion like stopping for a long time or walking at a constant pace continuously. When pedestrians adopt ‘active cease’ strategy, the frequency of transition from stopping to going is reduced because they reserve space for more continuous walking by increasing the stop time, which leads to the reduction of energy consuming.

To investigate the effect of age on the ‘active cease’ behavior, we analyze and compare the $h_{s-g}$ of elders, mixed and young groups respectively and the results can

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be found in figure 13 and table 8. We can see that elders have the biggest mean and median value of $h_{s-g}$ compared with the other groups at the same density which indicates that the elderly need a longer headway at the moment of transformation from stopping to going. The longer $h_{s-g}$ makes the elderly show a more obvious stop-and-go wave compared with the others. The per capita $h_{s-g}$ increases with density, but the rate of increase is affected by age for it is 9.23%, 171.66%, 1034.75% for the elderly, the mixed and the young group respectively. Correspondingly, the per capita outliers of the mixed and young groups increased significantly, which makes the stop-and-go wave of these two groups more obvious at the higher density. In addition, the ‘active cease’ can be found in all of these three groups. The fluctuation of $h_{s-g}$ for the elderly group are larger than that of the other groups. What is interesting is that the percentage of bigger outliers decreases with the density increase for the elderly and mixed group. This also reflects the pressure effect from crowd density. Additionally, the value of the highest outliers for the elderly is larger than that of the other groups. The reason may be that elders have weaker physical strength than the others which makes them more likely to reduce energy consuming by taking longer ‘active cease’ for longer continuous walking once they start to move.

In conclusion, the stopping duration and times, and the number of the ‘active cease’ increase with the increasing density, while the value of $h_{s-g}$ and the proportion of the ‘active cease’ decreases. The magnitude of the change depends on age and groups with different age compositions show different tolerance for densities. It is speculated that the value of $h_{s-g}$ remains unchanged, the stopping duration increases, but the amount of the stopping times decreases when the density is greater than the critical. However, our experiment cannot reach higher density which requires further research.

5. Summary

In this study, a single-file walking experiment of an elderly population in a 0.8 m wide circuit was performed under controlled conditions. The main aim of the study is to conduct comprehensive comparative studies among different age groups at high densities. 73 people over 60 years old participated in the experiment, and the global density ranges from 0.31 m$^{-1}$ to 2.18 m$^{-1}$.

A closed boundary, semi-closed boundary and open boundary were set up to study their influence on pedestrian movement. Based on the trajectories extracted by the software PeTrack, it is observed that the pedestrians were inclined to the side without a wall in the semi-closed boundary area while it fluctuated greatly in the open boundary and concentrated more in the closed boundary. The speeds of these elderly pedestrians in the closed boundary were higher than that in the other parts under low density (Elders-08, Elders-20). The headway and speed distributions of the elderly pedestrians under different global densities are both normally distributed. Bimodal phenomena of the speed, which represents the existence of stop-and-go waves, was observed under high density.

By comparing the fundamental diagrams of elders in our experiment and that of the French youth in [14], three linear regimes (free, weakly constrained and strongly
contrasted regime) are obtained in both studies. In the free regime (when the headway is larger than 2.6 m), the elders have the mean free speed of 0.94 m s\(^{-1}\) which is lower than that of the French youth whose free speed is 1.15 m s\(^{-1}\). In the weakly constrained regime, the elders have a lower speed under the same headway. Interestingly, the small differences of the slopes indicate the neglectable influence of the headway on pedestrian speed. While in the strongly constrained regime (when the headway is smaller than 1.1 m), the adaptation time of elders is longer than that of the young, which implies that elders adapt their speed to the available space more strongly. Then, we compared the fundamental diagrams of elders group with the groups in [15] from the micro and macro aspects. The elders showed a lower speed than the old adults under low density situations, while no obvious difference was observed between the elders and mixed group. The reason is explained from the heterogeneity of the crowd and the similarity among pedestrians. Besides, both linear and nonlinear fitting methods were adopted to analyze the relation between headway and speed.

From the time-space diagram, we observed the stop-and-go waves, which propagate in the opposite direction to the pedestrian movement with speeds roughly 0.37 m s\(^{-1}\) for \(\rho_g \approx 1.87 \text{ m}^{-1}\) and \(\rho_g \approx 2.18 \text{ m}^{-1}\). Compared to the results in [15], the stop-and-go waves occur more frequently and last a longer time in elders group, which indicates the density is not the only reason for the emergence of stop-and-go waves, but the movement ability is an important factor. In addition, noticeable ‘active cease’ behavior were observed in the experiment. The duration and times of stopping, and the number of the ‘active cease’ increase with the increasing density, while the value of \(h_s-g\) and the proportion of the ‘active cease’ decreases. The elderly take longer ‘active cease’ and need longer headway at the moment of motion state transformation (\(h_s-g\)), which is also the reason why the elderly show more obvious stop-and-go compared with the other groups under the same density.

The experiment in this paper supplies abundant data for the movement dynamics of the elderly, which is useful for the establishment of computer models, the design and construction of pedestrian facilities that are better suited to the elders in the future. Strictly divided age range of participants need to be considered to eliminate individual differences and to study the influence of the age on pedestrian movement characteristics in the future.

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