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Discussion

Typical features of pedestrian spatial distribution in the inflow process

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ABSTRACT

Pedestrian inflow is frequently observed in various pedestrian facilities. In this work, we first proposed four hypotheses concerning the inflow process. Then, we performed a series of experiments to test the hypotheses. With several analytical methods, e.g., the proxemics theory and Voronoi diagram method, the features of pedestrian inflow are analyzed in detail. Results demonstrate that the distribution of pedestrians in the room is not uniform. Boundaries are attractive for these pedestrians. The impact of two factors of the inflow are analyzed, i.e., movement rule, and first-out reward. It is found pedestrians can enter the room more effectively under the random rule or two queues. Under some hurry circumstances, pedestrians may prefer to gather around the door, and the spatial distribution is not uniform, leading to the imbalance use of the room. Practical suggestions are given for pedestrians to improve the travel efficiency in the inflow process. This experimental study is meaningful to reveal some fundamental phenomena of inflow process, which can provide the realistic basis for building the theory and mathematical–physical models.

1. Introduction

Pedestrian dynamics has become an intensive research subject in recent decades. Many kinds of approaches, such as experiments [1–6] and modeling [7–12], are applied to the study of pedestrian behaviors at different places or under varying circumstances. In the research field of pedestrian dynamics, pedestrian evacuation has been vigorously studied since it is of vital importance for the safety of people's lives, especially under emergency situations [13–15]. Evacuation process presents the form of people escaping from the inside of a certain area to the outside, which can be called "outflow". While the boarding in people's daily life presents a form of "inflow", i.e., people enter a confined space and remain steady when they acquire comfortable positions [16], for example, passengers board on the bus, subway or elevator. Significant difference exists between these two forms: people have clear destinations in the evacuation process and their aspiration is to reach the safe area as soon as possible [17]. However, there is no definite destination for people in the inflow process and they have to distribute themselves in the certain area. The study of the inflow process can be beneficial to the safety of people's lives because it occurs so frequently in our daily life. Furthermore, the design of buildings, transport facilities and many other infrastructures can be improved with the help of the research of this process.

Compared to the outflow process, the inflow process has been rarely investigated, especially the characteristics and intrinsic mechanism of the inflow process. Was et al. [18] established cellular automaton models to study passenger dynamics in trams. The interaction force between pedestrians was described by "social distance force" which was stemmed from proxemics theory introduced by Hall [19,20]. Based on the theory of proxemics, a lot of models [21–23] were developed to simulate the pedestrian dynamics. Among them, Manenti et al. [21] built an agent-based model that encompasses abstractions and mechanisms accounting based on fundamental considerations about proxemics and basic group behavior in pedestrians. Ezaki et al. [23] presented a discrete model and discussed the inflow process. The proxemic effect was considered as a predominant factor in this model, and it is concluded that pedestrians were attracted to boundaries for their repulsion effect. They [17] further conducted an inflow experiment. Liu et al. [16] performed two kinds of experiments to study the characteristics of pedestrian inflow in a room with a separate entrance and exit. Pedestrians' spatial distribution was analyzed in detail. As the pedestrian distribution can not only affect crowding in facilities, but also traffic efficiency, it plays an important role in the inflow process.

Experimental study of the inflow process is meaningful to reveal some fundamental phenomena, which can provide the re-

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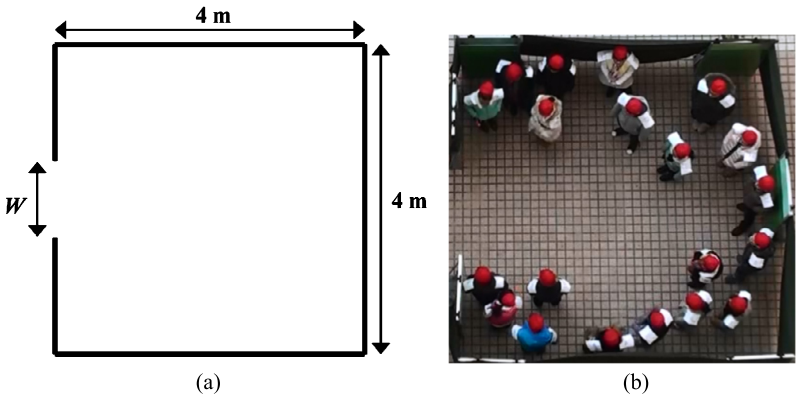

Fig. 1. (a) The geometry of the experiment; (b) a snapshot of the experiment. (For interpretation of the references to color in this figure, the reader is referred to the web version of this article.)

alistic basis for building the theory and mathematical–physical models. Much more work is needed to investigate the characteristics and intrinsic mechanism of the inflow process. Based on the report of the inflow model [23] that pedestrians prefer for boundaries during the distribution of the inflow process, we propose the Hypothesis 1 that pedestrians have some preference when distributing in the limited area, and therefore their distribution in the inflow process is not uniform. The inflow order has an evident influence on the pedestrian's location in the experiment conducted in a rectangular room [16], so we speculate that the order of pedestrians in the inflow process may have some relationship with their final distribution, and this is the Hypothesis 2 we raise. When entering a limited area in our daily life, pedestrians may stand in queues and walk in order, but also may enter disorderly in hurry circumstances. Therefore, we put forward the Hypothesis 3 that the travel efficiency may vary a lot under different movement rules and the number of queues also affects the efficiency. In many circumstances, pedestrians may not only consider the inflow process but also the outflow process. For instance, passengers consider their destinations when distributing in the public transport vehicles. Similarly, people may be influenced by their target floors during the inflow process in an elevator. The Hypothesis 4 is hence proposed that considering the outflow process, pedestrians' distribution is different with the result under the normal situation.

In this paper, we present a series of pedestrian experiments in a square room to test the above hypotheses we proposed. The aim is to reveal the typical features of the inflow process, especially the characteristics of pedestrian spatial distribution. The impact of several factors, such as the number of pedestrians, door width, and movement type on the inflow process are investigated.

2. Experimental setup and method

Controlled experiments were conducted in a square room with a size of 4 m × 4 m at a university in China, see Fig. 1(a). The room had an entrance in the middle of the left boundary, and the door width (W) ranged from 0.5 m to 1.5 m. Above the room, two HD cameras were mounted to record the whole experimental process. A snapshot of video scenes is shown in Fig. 1(b).

2.1. Experiment arrangement

There are 40 participants in the experiments, and all of them are students. Four kinds of experiment were performed in the square room, and the number of participants, door width, and movement type are different in each experiment, see Table 1. In the pedestrian inflow experiment, participants gathered outside the entrance before each trial. They entered the room through the entrance when each trial began, and they were informed to stop at any place they liked. The inflow process was terminated when all participants stand steady. After a period of time, they moved out of the room through the entrance, which was the outflow process. Each experiment was repeated three times, and each trial comprised three parts, i.e., the inflow, steady and outflow processes.

Table 1
Overview of the experiments.

Name	Number of participants	Door width (m)	Movement type
Experiment 1	5, 10, 20, 30, 40	1	Random
Experiment 2	40	1	Sequential
Experiment 3	20	0.5, 1.0, 1.5	Movement rule
Experiment 4	20	1	First-out reward

2.2. Analytical method

The participants were requested to wear red hats for the convenience of detecting and tracking, as shown in Fig. 1(b). With the mean-shift tracking algorithm [24], pedestrians' trajectories can be extracted. Based on pedestrians' original trajectory data, more personal data can be obtained, such as the inflow time, outflow time, steady time, inflow order, outflow order and velocity. The inflow (outflow) time is the time all pedestrians need to enter (leave) the room, i.e., it is the time difference between the first and last pedestrian's entrance (exit) time. The inflow order is defined as the order of pedestrians' entrance into the room. With the trajectory $s_i(t)$ of a person i, the velocity of person i at time t can be calculated as follows:

$$v_i(t) = \frac{s_i(t+\Delta t/2) - s_i(t-\Delta t/2)}{\Delta t} \tag{1}$$

To study the distribution of pedestrians in a steady state, we calculate pedestrians' spatial parameters, such as steady time, distance to the entrance, distance to the boundary, and proxemic value [16]. Steady time is a period of time between the moment the first pedestrian enters the room and the moment the last pedestrian begins to remain still, and the steady state represents that all pedestrians stand still in the room, i.e., pedestrians do not move their feet any more in our experiments. The tracking method is based on the movement data of pedestrians' heads, and velocity may not reach zero, since some pedestrians may sway their heads, even though they do not move their feet. Pedestrians' movement may be influenced by mutual repulsion between each other. The proxemic value is proposed to describe the repulsion between pedestrians [16]. Furthermore, the profile of the proxemic value in the room is obtained by dividing the room into small cells