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The self-slowing behavioral mechanism of pedestrians under normal and emergency conditions

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ABSTRACT

We study the similarities and differences between the headway-velocity relations under normal and emergency conditions to explore whether they can be described by a unified behavioral equation. We firstly performed a series of pedestrian experiments in three different scenes under normal and emergency conditions respectively to obtain the behavioral parameters of headway-velocity relations based on the visual hindrance field as well as the high precise trajectories of pedestrians. The strong similarities in the headway-velocity relations in both normal and emergency conditions suggest that a unified behavioral mechanism is at play in human-driven pedestrian traffic. This mechanism is essentially a safety-driven self-slowing behavior that pedestrians try to adopt a safe speed for a given spacing between them to avoid collisions and preserve their personal space. We notice that even in emergency escape situations, people still tend to slow down the speed and show defensive behavior when the headway approaches a critical value in order to decrease the collision level and protect the body from contact as much as possible. Moreover, the differences between normal and emergency conditions are also found in the experiments. Compared to normal condition, the free velocity of pedestrians is markedly higher while the minimum critical headway is much shorter in emergency situation. Especially, the proportionality constant, the reciprocal of which is safe response time, is higher under emergency condition. That means pedestrians will slow down the free speed to zero in a shorter safe response time in emergencies. A modified social force model is then proposed to incorporate this self-slowing behavioral mechanism, and different self-slowing behavioral parameters in the model under normal and emergency conditions both refer to the observed experimental data. Simulations with the same setup as the experiments were carried out for both normal and emergency conditions using the unified model with self-slowing, and the simulated spacetime diagrams as well as stop-and-go waves in circular movement under normal condition, the simulated evacuation efficiency in room evacuation under emergency condition and the simulated velocity profiles in corridor scene under normal and emergency conditions all demonstrate remarkable consistency with the experimental results.

1. Introduction

Modeling the characteristics of pedestrians in both normal and emergency conditions has attracted considerable attention, and the microscopic behaviors of pedestrians have been well reproduced by many statistical physics models, e.g. social force model [1–3], cellular automation models [4–6] and lattice gas models [7–10]. Generally speaking, pedestrians exhibit different dynamic characteristics under normal and emergency conditions. In order to provide important design guidelines for building environment as well as develop efficient pedestrian guiding strategies for both normal and emergency conditions, it is vital to understand the characteristics and behaviors of these two different kinds of situations as well as their relationships.

During the last decades, many researchers have investigated the characteristics of pedestrian movements from different aspects [11–16]. Especially, the behavioral differences of pedestrians between normal and emergency conditions have attracted wide attention of researchers [17–21]. However, so far a systematic comparison of self-stopping mechanism under normal and emergency conditions has been scarcely reported. Recently, Parisis et al. proposed a modification of the social force model that consists of a self-stopping mechanism to prevent a simulated pedestrian from continuously pushing over other pedestrians [22]. Lv et al. also developed a two-dimensional optimal velocity model with self-stopping mechanism based on pedestrian's visual hindrance infor-

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(a) N = 29 (b) N = 49 (c) N = 70

Fig. 1. Snapshots of circular movement experiments under normal condition with different participant number of (a) N = 29, (b) N = 49 and (c) N = 70, respectively.

mation [23]. But these findings are mainly based on the empirical data under normal condition, therefore it is still unknown whether the similar self-stopping behavior of pedestrians also exists in emergency condition, especially for those extreme panic situations in real-life earthquake or fire disasters. Another problem of these studies is that the behavior parameters in these models are arbitrarily set, lacking the validation of experimental data, thus further human experiments are indispensable in order to obtain more actual and accurate behavioral parameters of pedestrians under both normal and emergency conditions.

Given the fact that the pedestrian movements in normal and emergency conditions are both driven by human beings in well delineated environments with similar rules and goals, they may share some fundamental features that are intricately linked to human behaviors. Therefore, in this paper, to uncover the underlying similarities and differences between the headway-velocity relations of normal and emergency conditions and to study whether they can be described by a unified behavioral equation, we carry out a series of pedestrian experiments under normal and emergency conditions including normal circular movement, emergency room evacuation, normal corridor egress and emergency corridor evacuation. Our experimental evidence suggests that the strong similarities in the headway-velocity relations in both normal and emergency conditions are actually the result of a unified safety-driven self-slowing behavior of the pedestrians to balance the desire for speed and safety. That is, a person has to stop to avoid a collision and to preserve his personal space if his headway is below a critical value. Even in emergency escape situations, people still tend to slow down the speed and show defensive behavior when the headway approaches a critical value in order to protect the body from contact as much as possible. In addition, a person is also eager to reach the maximum desired velocity if the headway is large enough. When their motions are constrained by other pedestrians, the desired velocities of the pedestrians are studied and found to have a linear relationship with their headways. A modified social force model that incorporates this self-slowing behavioral mechanism is also proposed and simulations with the same setup as the experiments are carried out for both normal and emergency conditions.

The rest of the paper is then organized as follows. In Section 2, we describe the details of three experiment scenes for both normal and emergency situations from which we obtained high precise movement trajectories of pedestrians covering the whole experimental process based on the video tracking technology. In Section 3 we present the headway-velocity relations of normal and emergency conditions revealed from the experimental data, and propose a unified self-slowing behavioral mechanism to explain similarities and differences in the observed headway-velocity relations. In Section 4 we go one step further and propose a modified social force model to incorporate this self-slowing behavioral mechanism. Simulations with the same setup as the experiments were carried out in Section 5 using the unified model with self-slowing to reproduce the spacetime diagrams and stop-and-go waves in circular movement experiments, the average evacuation time as well as evacuation speed curves in room evacuation experiments and the velocity profiles in corridor experiments. Finally, we conclude the paper in Section 6 by providing a summary and discussion.

2. The human experiments under normal and emergency conditions

To obtain actual and accurate behavior parameters data of pedestrians under different kinds of situations, it is essential to carry out human movement experiments for both normal and emergency situations. In this work, in normal condition, a series of circular movement experiments were conducted on a circular track in China with different numbers of participants from N = 5 to N = 70. Similarly, in emergency condition, a series of room evacuation experiments with no obstacle and panel obstacle were performed in China. However, the above-mentioned experiments were carried out in two different scenes. To further investigate the self-slowing behavioral mechanism of pedestrians in the same scene, a series of human experiments were further performed in a corridor in China under both normal and emergency conditions.

2.1. The circular movement experiments under normal condition

The pedestrian movement experiments under normal condition have been conducted in a circular corridor in Germany [12]. However, the movement trajectories of pedestrians only covered a specific limited linearity range of 4 meters in the experiments in Germany, and the pedestrian trajectories covering the whole movement process on the entire circular track area were not recorded and considered.

Therefore, in this work, a new circular movement experiment was conducted by us in China. The participants were asked to walk in a normal fashion but not in lock step on a circular track with a circumference of 52 m. The participants in the pedestrian experiment were composed of female and male college students. A series of runs were carried out with different numbers of pedestrians from N = 5 to N = 70 in order to achieve varied ranges of global density on the circular track. The average shoulder width and weight of pedestrians are 0.40 m and 58 kg respectively. Fig. 1 shows the snapshots of new circular movement experiments in China under normal condition with different participant number of N = 29, N = 49 and N = 70, respectively.

2.2. The room evacuation experiments under emergency condition

To obtain the accurate behavior parameters of pedestrians under emergency condition, a series of room evacuation experiments

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