Lattice gas simulation of experimentally studied evacuation dynamics

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We study the evacuation process from a classroom by means of experiments and simulations. The evacuation of students from a classroom is observed by video cameras, and the escape time of each student is measured. Our experimental results are compared with simulations based on a lattice gas model of pedestrian flows. We find that the empirically identified inefficiencies of the evacuation process can be well reproduced. Our particular focus is on the spatial dependence of the escape times on the initial positions, which is highly significant. The escape time distribution turns out to be rather broad due to a jamming (queuing) of the students at the exit, which determines not only the saturation flow (capacity) but also the temporal characteristics of the evacuation dynamics.

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During the last decade, many observed self-organization phenomena in traffic flows [1–5] and pedestrian streams [6–8] have been successfully reproduced with physical methods. This has not only stimulated research in granular, biological, and colloid physics [9–11], it has also encouraged physicists to study evacuation processes [12–17]. The empirical observations have many common features with driven granular media [16]. Other phenomena such as "freezing by heating" [17] are even more surprising. In pedestrian counterstreams, it describes the breakdown of the typical segregation pattern characterized by fluid lanes of uniform walking direction. This gives rise to blockages by opposing groups of pedestrians [18–20].

One of the problems related to evacuation simulation is the calibration of model parameters in order to reproduce not only the qualitative features but also the quantitative outcomes, which is relevant for reliable predictions and planning guidelines. In this study, we therefore focus on the investigation of a practically relevant situation, namely, the evacuation of a classroom. For this purpose, we have evaluated video recordings and measurements of individual escape times, which were obtained with a well-controlled experiment. This experiment is then reproduced with a lattice gas model of pedestrian flows. More importantly, it reflects the inefficiencies in the evacuation dynamics that unexpectedly occurred in our evacuation experiment. Our simulation model can, therefore, serve to identify problematic geometries and to figure out safer usage patterns of rooms, which are more suitable for escape or emergency situations.

We have experimentally studied the evacuation of students from a classroom, which is schematically illustrated in Fig. 1. The exact width of the classroom was $W = 5.85$ m and its length $L = 6.75$ m. There were 30 desks and 30 chairs in six rows and five columns. The longitudinal distance between desks was 0.9 m, while the transverse distance was 1.35 m. There was only one exit in the back of the classroom. The width of this exit was 0.5 m, when only one door was used in our experiment. Two video cameras 1 and 2 were located within and in front of the classroom. A cameraman was able to observe 13 students numbered 1 to 13 by video camera 1. The other cameraman could observe the students who escaped through the exit by video camera 2. At $t = 0$, there were 30 students in the classroom, and each student was sitting on a chair. All students stood up from their chairs and hurried toward the exit as soon as a cameraman shouted a word of command. The evacuation process was then recorded by the two video cameras. As soon as the students hurried to the exit, queuing occurred near the exit. This jamming was due to the inflow exceeding the outflow at the exit. By careful analysis of the video recordings, we determined the escape times of the students. The individual escape time was defined as the time elapsed between the shouting of the command and the moment when the respective student left the room through the exit. Our main focus was to study the distribution of escape times as a function of

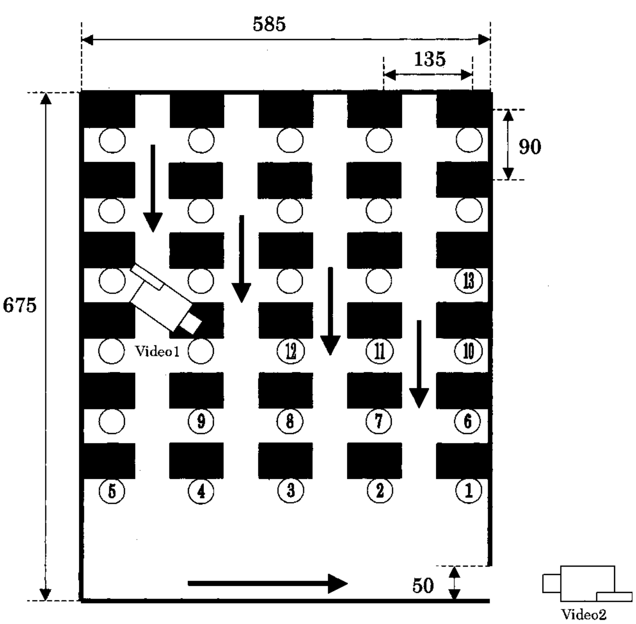

FIG. 1. Schematic illustration of a classroom of width $w = 5.85$ m and length $L = 6.75$ m. It contains 30 desks and chairs in five columns and six rows. The open circles indicate students sitting on their chairs, while the full squares represent desks. There is only one exit, in the back of the classroom.

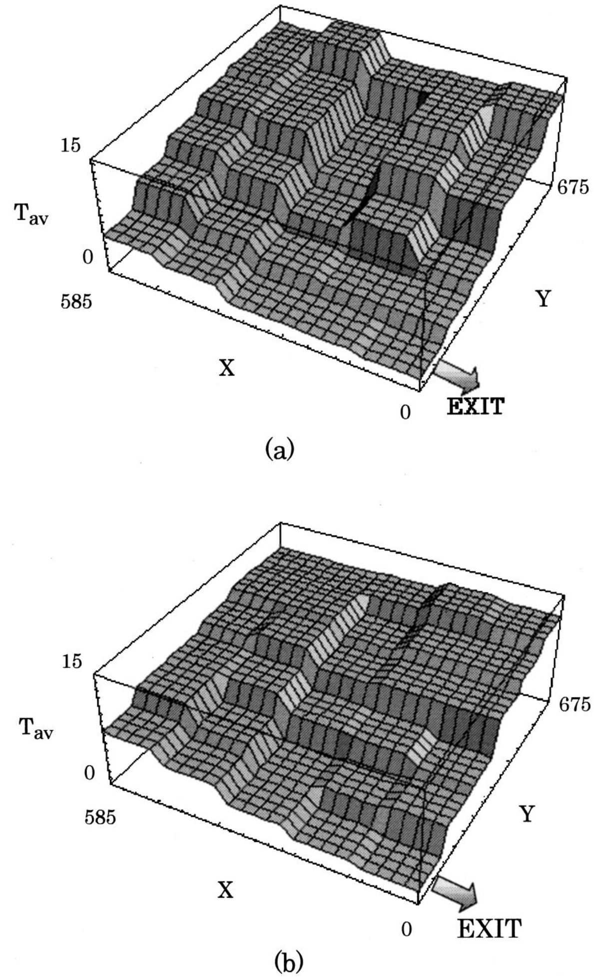

FIG. 2. Plot of escape times as a function of the initial position: (a) experimental and (b) simulation results.

the initial position, which is illustrated in Fig. 2. Diagrams (a) and (b) indicate the experimental and the simulation results, respectively. The escape times of the students were obtained by averaging over five samples.

The average escape time of the 30 students was 7.94 s. However, the lowest escape time was 1.33 s for the student at desk 1 (see Fig. 1), while the highest value was 15.16 s for the student at the second desk in the back of the classroom. Thus, the distribution of escape times was rather wide. Moreover, the escape time increased approximately with the initial distance from the exit, but the students in the second column needed an overproportional amount of time to escape. This points to an inefficient configuration of desks in the classroom despite its regularity. Finally, we could identify the reason for this unexpected inefficiency: the students were naturally using the passageway between the columns of tables which was closer to the door, i.e., normally the one to their left (with regard to their direction of motion). Therefore, the rightmost column of tables in Fig. 1 had to share the passageway with the next column of tables, which increased the density and escape times. The students in the third, fourth, and fifth columns had separate passageways (see Fig. 1), so they could leave relatively efficiently. As a consequence, the students in the third column managed to leave

TABLE I. Escape times from all desks (i.e., initial positions) shown in Fig. 1. Desks 1–13 are numbered according to the persons sitting at them. The two numerical values below the desk numbers (or empty headings) indicate the average escape times obtained in the experiment and the simulation, respectively.

12.90	15.16	12.02	12.25	13.09
11.40	11.30	11.53	12.58	12.11
12.65	11.65	7.31	12.35	9.20
11.60	11.54	9.59	10.59	10.56
				13
12.10	11.60	6.42	10.68	8.94
10.46	11.18	9.00	9.56	9.46
		12	11	10
10.21	8.31	5.17	7.06	3.77
9.45	9.06	6.77	6.53	5.38
	9	8	7	6
8.19	5.08	3.16	2.64	2.73
9.33	6.59	3.88	4.35	4.94
5	4	3	2	1
4.85	3.74	1.83	1.78	1.33
7.45	5.73	3.62	2.36	1.80

earlier (on average) than the students in the second column, who were closer to the exit [see Fig. 2(a)]. Another surprise was the fact that the students in column 1 had shorter escape times than the students in the second column, although they had the same distance to walk and the same passageway to use. Nevertheless, our simulations reproduced these particular features not only qualitatively [see Fig. 2(b)], but even in a semiquantitative way. Table I displays the escape times for all desks. The numerical values indicate the escape times obtained from the experiment (on the top) and from the simulations (below). The table entries correspond to the positions of the desks in Fig. 1. Desks 1–13 are represented by the numbers of the marked students sitting at them.

Let us now study the flow rate J of students leaving the classroom. One can derive this flow rate by analyzing the recordings of video camera 2. Figure 3 shows the plot of the escape flow rate (persons/s) against the time (s). Full circles represent the experimental data, while the solid line corresponds to the simulation result. The experimental data were averaged over five samples and 0.5 s. Furthermore, the value was averaged over seven points to smooth the flow rate. Note that the escape flow rate increases rapidly with time and saturates at about $t=2.0$ s. It then keeps a constant value of about 2 persons/s until about $t=13$ s. After $t=13$ s, the flow rate decreases rapidly with increasing time. After about 16 s, all students had left the classroom. Our interpretation of the experimental findings is as follows. Two persons/s is the saturation flow, which defines the capacity of the exit. When the arrival rate of persons exceeds this value, people are queuing, i.e., a crowd of people is forming in front of the exit due to jamming. In the discussed experiment, the outflow is continuous and given by the capacity, although a much more complicated dynamics with variable outflows was expected to occur. From simulations published in [16] and other ex-

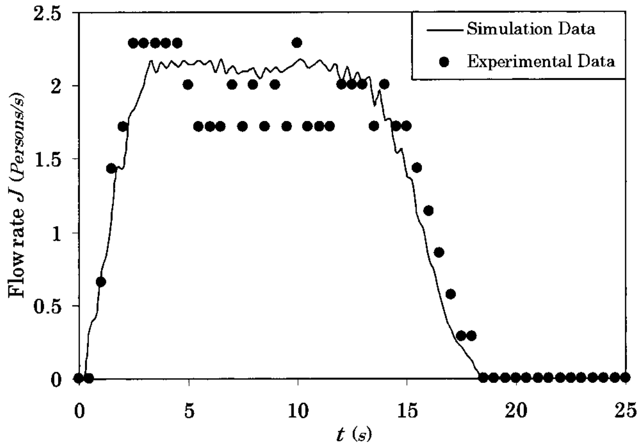

FIG. 3. Plot of the escape flow rate (persons/s) against time (s). The full circles represent experimental data, while the solid line corresponds to the average simulation result for the reference scenario.

periments, it is known that arching and clogging can appear at doors under conditions of panic. The related outflows are irregular rather than continuous, characterized by groups of people of various sizes who manage to leave at about the same time. Computer simulations suggest that the size distribution follows a power law. This behavior was definitely not found in our experiment, as the students were disciplined and did not push very strongly. The result may have been different for a higher number of test persons, but this would have been a serious risk to their health.

In the following, we describe a model that allows us to reproduce our experimental findings for the evacuation of a classroom in a semiquantitative way. We simulate the pedestrian flow by use of a lattice gas model. Each student is represented by a biased-random walker on a square lattice with $L \times W$ sites reflecting the classroom. We choose the lattice spacing as 0.45 m, since the typical space occupied by a pedestrian in a dense crowd is about $0.4 \times 0.4\ \mathrm{m}^2$. We therefore use $L=15$ sites and $W=13$ sites. The classroom is connected to the outer space through a single exit with one site. In an early stage, an individual student is assumed to move in the desired (preferential) direction with no back step. The desired direction of the students is indicated by arrows. It points toward the front (bottom of Fig. 1) at the beginning, but toward the exit as soon as the desk-free area in front of the classroom is reached. Back steps are allowed for the students who have reached this front area. Each site contains only one individual student or is empty.

For each random walker we assume a bias (drift) in the desired direction. Since the desired direction varies with the instant position of the walker, the x and y components of the drift of a walker depend on the respective position. As long as a walker is moving in the passageways between the desks, the drift D is assumed to be constant. However, as soon as a walker has reached the wide front area of the classroom, the drift direction may change from position to position. The strength D of the drift represents a measure of the haste of the students. With increasing D, the walkers try to move faster toward the exit. In our simulations, we set $D=0.99$, as the students were asked to hurry toward the exit. The transition probabilities of a walker to the adjacent sites are determined by the configuration of other walkers in the nearest-neighbor sites. The transition probabilities for the configurations are determined in a unified way. They are specified in Ref. [12]. Initially (at $t=0$), all students are assumed to sit on their chairs in the classroom. In the next time step ($t>0$), all the students start moving in order to escape from the classroom. Each individual student performs a biased random walk according to the model sketched above. All walkers are updated once every time step in a random sequential way, as the students moved asynchronously. When a walker moves toward the exit, the desks and chairs are avoided. Therefore, when a walker reaches a wall, desk, or chair, it is reflected. When a walker reaches the exit, it is removed from the system.

Our simulation results are displayed in Table I and Figs. 2(b) and 3. Empirically, the mean speed of a pedestrian is about 1.0 m/s under normal conditions. When people are in a hurry, the pedestrian speed will be about 2.0 m/s. So one time step in our simulation corresponds to approximately 0.25 s. Figure 2(b) shows the spatial distribution of the mean escape times obtained from the simulation. The escape times are averaged over 50 runs. The numerical values are listed in Table I as the second entries. Despite the simplicity of the model, the simulation results agree surprisingly well with the experiment. The predicted average escape time of all students is 8.32 s as compared to a value of 7.94 s in our experiment. The escape time does not increase monotonically with the distance from the door. Instead, we find systematically higher escape times in the second column from the exit compared to the third one. This effect was not anticipated, due to the totally symmetrical configuration of desks which is typically used. It would not have been discovered without our experiment. The reason for this effect was successfully reproduced and explained (two columns were using the same corridor). An improved configuration can be derived from this (one needs a corridor along the wall closest to the exit, while a corridor along the opposite wall does not make any sense). We have also calculated the average escape flow rate of students in our simulation (see the solid line in Fig. 3). The simulation result is well consistent with the experiment.

In order to study the effect of the distance on the evacuation process, we have carried out simulations for different initial positions A and B of the 30 students. Figure 4 shows the related escape flow rates as a function of time. The flow rates and escape times were averaged over 50 runs. For comparison with our previous reference scenario, we also show the escape flow for the initial distribution illustrated in Fig. 1 (see the solid line in the middle in Fig. 4). In scenario A, where the students were initially gathering in the most distant corner of the classroom, the flow rate increased later than in the reference scenario, saturated at the same constant value, and decreased later. The average escape time of all students was 11.05 s. This value is to be compared with 8.32 s for the reference scenario. In scenario B, where the students were initially gathering in the front area of the classroom, the flow rate increased earlier than that in Fig. 1, saturated at the

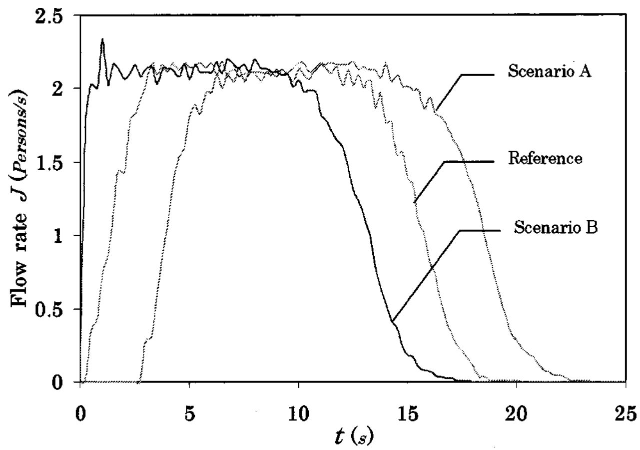

FIG. 4. Plot of the escape flow rates in scenarios *A* and *B* as a function of time.

same constant value, and decreased earlier than in the reference scenario. The average escape time of all students was 5.83 s. Altogether, the average evacuation time of students was roughly proportional to the average distance to the exit.

In summary, we have presented experimental results on the evacuation of a classroom, focusing on the individual escape times and the escape flow rates as a function of time. Despite the stochastic nature of pedestrian flows, the empirical observations could be semiquantitatively reproduced by a simple lattice gas model, i.e., a stochastic many-particle approach. We found that the outflow from the classroom saturated at a constant value defining the capacity of the exit, which was related to queue formation in front of the exit. This capacity determined the dynamics of the evacuation process in the sense that the flow profile as a function of time had a characteristic shape. The average escape time (and, therefore, the time shift of this profile) was mainly given by the average initial distance from the exit. Our model also allowed us to draw conclusions about the individual escape times as a function of the initial position in the room. In particularly, we could successfully reproduce observed inefficiencies in the configuration of the classroom which we did not anticipate before. As a consequence, the model could be used to identify not only expected escape times as a function of the pattern of room usage and the number of people in the room, but also to help identify inefficiencies and improved configurations. Our approach can give hints as to the safest places in a room in terms of individual evacuation times.

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