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PAPER

Redefining the role of obstacles in pedestrian evacuation

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Abstract

The placement of obstacles in front of doors is believed to be an effective strategy to increase the flow of pedestrians, hence improving the evacuation process. Since it was first suggested, this counter-intuitive feature is considered a hallmark of pedestrian flows through bottlenecks. Indeed, despite the little experimental evidence, the placement of an obstacle has been hailed as the panacea for solving evacuation problems. In this work, we challenge this idea and experimentally demonstrate that the pedestrians flow rate is not necessarily altered by the presence of an obstacle. This result—which is at odds with recent demonstrations on its suitability for the cases of granular media, sheep and mice—differs from the outcomes of most of existing numerical models, and warns about the risks of carelessly extrapolating animal behaviour to humans. Our experimental findings also reveal an unnoticed phenomenon in relation with the crowd movement in front of the exit: in competitive evacuations, an obstacle attenuates the development of collective transversal rushes, which are hazardous as they might cause falls.

1. Introduction

When a crowd tries to escape from a room in a life-and-death situation the passage through doors becomes crucial in determining the evacuation efficacy [1–7]. In some extreme cases, the accumulation of people in front of an emergency exit and the instinctive pushing reaction of the individuals, leads to door obstruction or clogging. Pedestrian systems are probably the most dramatic example of clogging, but this phenomenon is rather general for systems composed of many discrete particles that flow through constrictions. Indeed, this topic has been the focus of research in a variety of fields such as microbial populations [8], colloids [9], droplets [10], granular matter [11] or robots [12]. Recently a phase diagram has been proposed to encompass clogging in such many different systems [13].

In addition, the relationship between clogging and jamming is being a topic of discussion in the last years [14–16]. Basically, depending on the conditions, clogging may end up with the development of a completely jammed system [17] where the contact forces among particles increase notably in duration and intensity; for the pedestrian case, this process may often results in fatalities. Additionally, the emergence of contact forces within the crowd is believed to be the origin of sudden and unintended collective motions [5, 18–22] which are—in most circumstances—behind the occurrence of falls, the main cause of injuries in crowd accidents.

A smart solution that has been proposed to lessen clogging problems is the placement of obstacles [1] (such as columns or barriers) in front of exists (figure 1). Although at first sight this alternative might seem prejudicial for the evacuation, the idea is that obstacles can absorb the crowd pressure and reduce it to a level that will not cause harmful effects. Furthermore, decreasing pressure is thought to favour the conflict solution of pedestrians coinciding at the exit and competing for the same space; so that clogging can be minimized. Indeed, the

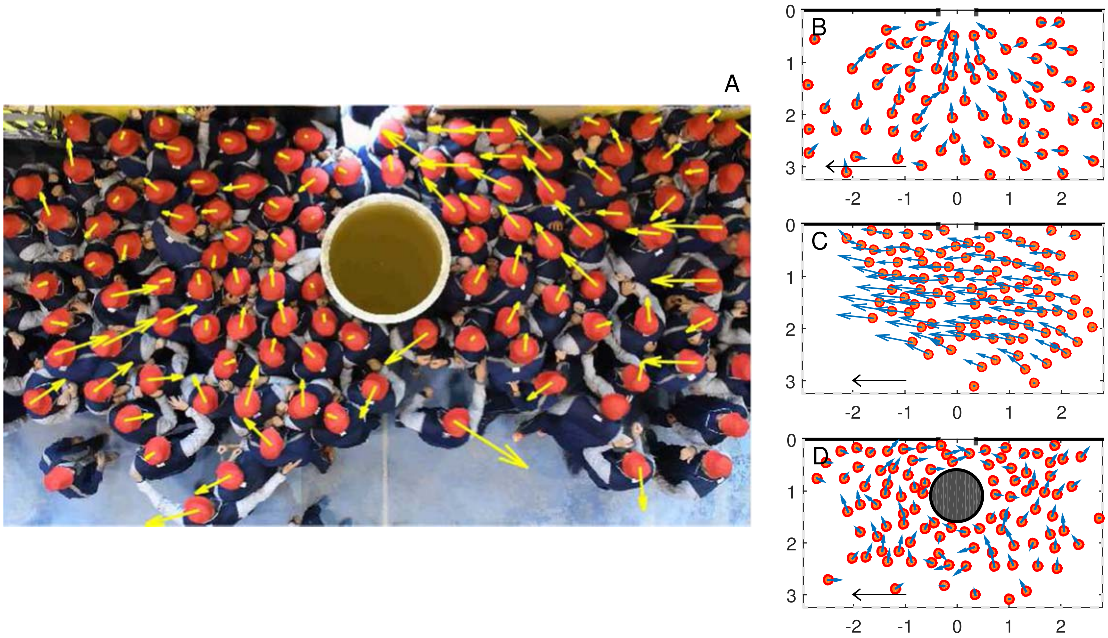

Figure 1. Experimental setup and pedestrian trajectories. (A) Picture corresponding to the third series of experiments where 180 soldiers evacuated a room through the door seen at the top of the photograph. Red hats were tracked and instantaneous positions and velocities (*yellow arrows*) were obtained by an image processing algorithm. (B)–(D) Examples of the pedestrians instantaneous velocities (*blue arrows*) in three different scenarios: (B) low competitiveness, meaning that participants avoid intentional physical contact; (C) high competitiveness where pushing is allowed; and (D) high competitiveness with a 100 cm diameter obstacle placed 60 cm before the door. The reference vector of 1 m s^{-1} at the left bottom of each panel provides the scale of the measured velocities.

improvement of bottleneck flow by placement of obstacles is being reproduced by most of the recently proposed models of pedestrian dynamics [23–28]. In addition, the beneficial role of the obstacle in clogging prevention has been taken as a genuine feature of many-particle systems passing through constrictions. Notably, it has been experimentally proved for granular matter discharged from a silo [29, 30], and the passage of different animals (such as sheep [13, 31] and mice [32]) through narrow doors. Nevertheless, apart from some inconclusive results [3, 33–35], an experimental confirmation of this feature in real pedestrian tests is still lacking.

2. Materials and methods

2.1. Evacuation drills

We conducted three series of evacuation drills on different days as summarized in table 1. All involved young volunteers that could opt out of the exercises at any time (this is the cause for small variations in the number of persons at each rehearsal). The participants gathered for a whole morning and after being instructed on the procedures, they performed around 30 evacuations. These consisted of leaving the room through a door as soon as possible. Door edges were always covered with soft linen so the widths given are approximate to about 1 cm. For safety reasons, at least one staff member for every 12 participants was placed at strategic spots; any participant or staff member could issue a signal that immediately stopped the exercise (for instance, in case of a fall or any other potentially dangerous situation). A staff member also participated occasionally in an evacuation drill to make sure that instructions were being followed correctly. Some blank drills were performed to make participants familiar and confident with the procedure before data collection began. Participants gathered at a rectangle marked on the floor, with the door centred at the long side of the rectangle, so that a density of about 4 persons per square metre was the initial condition for the beginning of the evacuation drill. The evacuations took place uneventfully. A detailed description of the procedures and the analysis of the pedestrian flow through the door can be found in previous works [22, 36–38].

The first two series of evacuations were performed at the indoor gym of the University of Navarra. The participants in the first one were around 90 students aged about 22 years old. The door width was 75 cm. The students did 5 evacuations without intentional physical contact (low competitiveness), 8 evacuations with moderate pushing allowed (to simulate high competitiveness), and 16 in which moderate pushing was allowed, with an obstacle placed before the door. This obstacle was a cylindrical column made with six lorry tyres loaded with 300 kg of ballast, and the outer surface lined with a carpet. The diameter was of approximately 100 cm, and the height was about 2 m. The obstacle was placed centred with the door and at 100 cm in front of it (obstacle

Table 1. Summary of evacuation drills. **Series**: 1: students (1st group) ; 2: students (2nd group); 3: soldiers. **C**: competitiveness (low, LC; high, HC). **O**: obstacle (NO, no obstacle; otherwise, obstacle position given in cm from the door). **N**: number of drills performed. **P**: number of people per drill (volunteers could opt out at any time, hence small variations occur). **DW**: door width in cm.

Series	C	O	N	P	DW
1	LC	NO	5	85	75
1	HC	NO	8	86	75
1	HC	100	16	88	75
2	LC	NO	10	72	69
2	HC	NO	10	72	69
2	HC	70	10	72	69
3	LC	NO	3	176	75
3	HC	NO	7	175	75
3	HC	50	6	176	75
3	LC	60	3	165	75
3	HC	60	6	167	75
3	HC	70	6	179	75

distances were measured from the closest point of the obstacle to the door). During the evacuations, the obstacle was moved backwards due to the force exerted by participants, sometimes by as much as 10 cm; therefore these results must be taken with caution. The second set of evacuations was performed by 72 students who were 20–23 years old. They took place at the same room, but in this case the door was 69 cm wide. They did 10 evacuations without intentional physical contact, 10 evacuations under high competitiveness (moderate pushing allowed), and 10 evacuations with an obstacle before the door under high competitiveness. In this case, the obstacle was a 2 m high cylindrical tank made of resin, with a polished wall. It was fixed in the desired position by placing it on top of a non-slip rubber sheet and filling it with about one ton of water. Its outer diameter was 100 cm, and the distance to the door was 70 cm. This time, the obstacle did not move at all.

Finally, the third set of evacuations was performed by 180 soldiers in the América 66 regiment of the Spanish army, at their barracks in Aizoáin (Navarra). Officers were present at the proceedings and a few participated in the evacuations to ensure that no risk was being taken. The door was 75 cm wide and the obstacle was the same 100 cm diameter resin container filled with a ton of water described above. Evacuations were performed in different conditions: (a) 3 evacuations without intentional physical contact and without obstacle; (b) 3 evacuations without intentional physical contact, with an obstacle placed 60 cm before the door; (c) 7 evacuations where pushing was allowed and without obstacle; (d) 6 evacuations where pushing was allowed, with an obstacle placed at 70 cm before the door; (e) 6 evacuations where pushing was allowed, with an obstacle placed at 60 cm before the door; and (f) 6 evacuations where pushing was allowed, with an obstacle placed at 50 cm before the door.

Although the instructions given to participants accounted only to the competitiveness level (in all cases they were asked to evacuate the room as fast as possible, with or without pushing) the analysis of the trajectories revealed that in most of the cases the individuals chose to avoid the obstacle through one side, and the number of times in which the participants change their decision was insignificant. Also, we observed that none of the participants decided to stand behind the obstacle pushing it towards the door as it happens in very simple models of pedestrians that do not consider choice at that short distances.

Another methodological aspect that should be considered in these kind of experiments concerns the repeatability of the conditions among the several drills that have been performed in '*a priori*' the same competitiveness degree [4]. To this end, we rely on the results of the pressure measured at the doorjambs which, as reported in a previous work [37], nicely correlate with the competitiveness levels demanded to participants. From the outcomes displayed in figure 1 of [37] we can guarantee that, within a certain range, the competitiveness degree was maintained in the different tests performed with the same conditions. Remarkably, the fluctuations of the pressure measurements increase with the competitiveness.

2.2. Image processing

In all cases, a video camera was installed at the room ceiling, pointing downwards, and a region of 6 × 3.2 m was recorded. For the first two series of evacuations (students at the University of Navarra) a camera was used with a spatial resolution of 2250 × 1200 pixels. For the third set of evacuations (performed by soldiers) a 4 K resolution camera (3840 × 2160 pixels) and 25 frames per second was used. The optical system was calibrated for distance measurement and the primary aberrations were posteriorly corrected by image processing so that absolute positions can be obtained directly from the images. The volunteers were instructed to wear dark clothes and they were given a red hat, that can be tracked with an image processing software [22] reaching an absolute position accuracy of ± 10 cm, the main source of error being the relative motion of the head with respect to the body. Outside of the door, a standard video camera (704×576 pixels) was placed above the exit pointing downwards. This allowed us to detect the passage time for each participant with an accuracy of ± 0.04 s. Therefore, for each evacuation drill, a file with time-stamped absolute positions for each participant is obtained for the trajectory inside the room, along with the passage times logged at the exit. Instantaneous velocities for each person inside the room (see figure 1) were calculated directly from the positions, using a time interval of 1 s to reduce spurious noise. The results are quite insensitive to this choice (we also tested 0.64 s and 1.44 s without finding significant differences).

2.3. Data analysis

As the persons are trying to reach the door, a natural way to display the velocity is in polar coordinates (v_r, v_θ) with the origin ($r = 0$) at the door centre. We have taken positive velocities when r decreases, i.e. persons approach the door. The angle increment is positive in the counterclockwise direction. If persons proceed unimpeded towards the door, as expected under low competitiveness, v_θ should be low. We have not filtered the small left and right oscillations due to the gait, so a residual v_θ will always be present. Note that as the radial velocity will increase linearly in average when approaching the door, due to mass conservation, we have multiplied v_r by r in order to rescale all the velocities and obtain the statistical distributions of these velocities with respect to the average, which is indicated as Δ in figures 3(J), (K). The sampling rate for the velocity is 25 measurements per second (one measurement for each video frame) but, as said above, velocities were calculated in time intervals of 1 s.

When dealing with flocks, or active matter in general, polarization is often used to describe the global velocity alignment of individuals [39, 40]. This magnitude is defined as

$$\phi = \left\| \frac{1}{N} \sum_{i=1}^{N} \frac{\vec{v}_i}{|\vec{v}_i|} \right\|$$

which tends to zero for random motions and is equal to one if all the individuals move in exactly the same direction. We have also calculated the alignment of pedestrians velocity respect to the desired direction of motion $\vec{u}_i$ (which is assumed to be towards the door). To this end we have defined the 'alignment parameter':

$$\phi_d = \left\| \frac{1}{N} \sum_{i=1}^{N} \frac{\vec{v}_i \cdot \vec{u}_i}{|\vec{v}_i|} \right\|$$

that would be one if all the participants head towards the door. Note that the range of this quantity is $[-1, 1]$.

The correlation for the velocity directions is calculated with the formula

$$C(r) = \frac{1}{C_0} \frac{\sum_{ij} \vec{u}_i \cdot \vec{u}_j \; \delta(r - r_{ij})}{\sum_{ij} \delta(r - r_{ij})},$$

where C_0 is a normalizing factor, r is the distance from the individual i, $\delta(r - r_{ij})$ is a smoothed Dirac delta function, and u is the velocity. Note that C would be one if all the individuals head in the same direction, and that finite size effects will appear at the scale of the recorded zone (a few metres).

See supplementary material is available online at stacks.iop.org/NJP/20/123025/mmedia for a movie showing the temporal evolution of the pedestrians, along with ϕ and ϕ_d, for three different situations: under low competitiveness, under high competitiveness, and under high competitiveness with an obstacle placed at 60 cm from the door.

3. Results and discussion

In this work, we present the results of three series of drills in which we have not succeeded in achieving an experimental proof of the hypothesis that an obstacle in front of an exit may favours the evacuation performance (hence challenging its validity). Unexpectedly, we have discovered a possible benefit of the obstacle regarding prevention of falls. In the first series of experiments (series 1, table 1) we observed that the presence of the obstacle had not any perceptible impact in the evacuation times. This unexpected behaviour was attributed to the obstacle being placed too far from the exit. Also, we found that the 300 kg obstacle was not secured fast enough and it was displaced backwards (away from the door) by the students in their way out the room. In the next series of experiments (series 2, table 1) we amended this problem by designing a one-ton obstacle which was tightly secured in place. This time the obstacle did not move but, again, its role in the evacuation times was

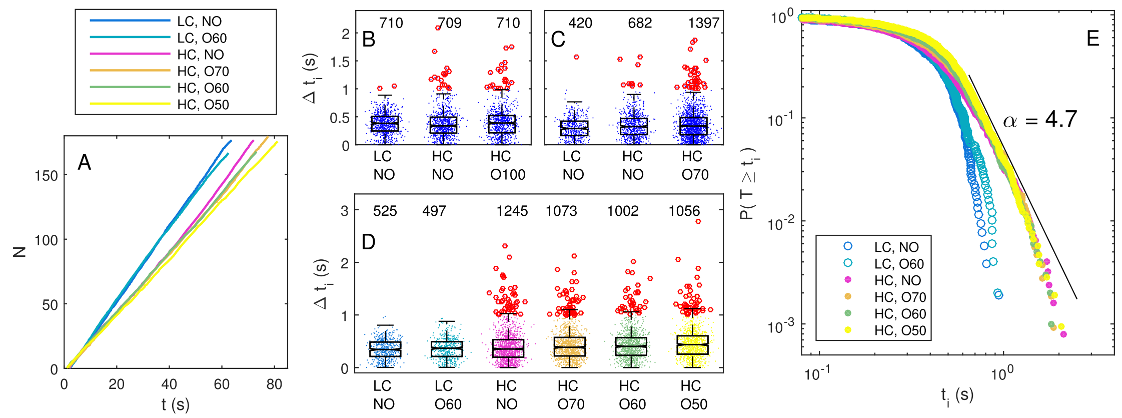

Figure 2. Evacuation times. (A) For the third series of experiments, average number of persons that left the room N as a function of time t, where $t = 0$ is the moment at which the first person crosses the door in each drill. The slope is the flow rate. Colours correspond to different scenarios: LC, low competitiveness; HC, high competitiveness; NO, no obstacle; O70, O60, and O50, obstacle at 70, 60, and 50 cm from the door respectively. (B)–(D) Boxplots of the time laps Δt_i between the passage of consecutive persons through the door. The boxes display the median and the interquartilic range (IQR), and the whiskers reach the closest data point inside 1.5 IQR. Instead of marking outliers, red circles indicate clogs longer than $\Delta t_i = 1$ s to allow better comparison among different cases. The total number of measured Δt_i is shown on top of each boxplot. In (B) we show results of the first set of evacuations (O100 means an obstacle at 100 cm). In (C), we display results of the second series of evacuations. In (D) same set of evacuations than in (A), i.e. third series of evacuations. (E) The complementary cumulated distribution function (or survival function) for the time intervals in the same set of evacuations than in (A) and (D). The survival function fit of the power law for all the highly competitive cases gives the same exponent (−4.7 as displayed in the plot).

negligible. Finally, in order to discard that the obstacle position was still too far from the door, or that the effect was not showing due to the low number of people in the room, we devised the final series of exercises (series 3, table 1). In these, the same obstacle than in the second evacuation series (figure 1) was placed at three different distances from the door. Once more, we observed the same behaviour than in the two first series: decreasing competitiveness reduces evacuation times, but placing an obstacle does not. Nevertheless, an unexpected behaviour became apparent when dealing with such high number of people in competitive conditions: the placement of an obstacle seemed to suppress transversal collective motions that can cause falls (see supplementary material). The danger of these movements can be gauged by the fact that many deaths in emergency evacuations are caused by a mob threading on fallen people. Aiming to quantify all these features we have performed a careful examination of the pedestrian trajectories and velocities behind the bottleneck (figure 1(B)–(D)), as well as a detailed analysis of the passage times through the exit.

In figure 2 we show the outcomes of the evacuation times for all series of experiments. As an example, in figure 2(A) we report the average number of evacuated people versus time for the six different scenarios investigated in the third series of experiments mentioned above. Clearly, non-competitive evacuations display higher slopes than competitive ones, indicating greater flow rates. Additionally, figure 2(A) suggests that the effect of placing an obstacle is negligible in both, competitive and non-competitive evacuations. For a more rigorous verification of this result, we obtained the time lapses Δt_i between consecutive individuals. Remark that this information is not usually provided, but it is suitable to detect temporary door blockages which might become unperceived when computing average magnitudes such as the mean flow rate. The boxplots of Δt_i displayed in figure 2(D) confirm that the statistics of the competitive evacuations are distinct from the non-competitive ones; and this is so irrespective of the presence of the obstacle. As it was already reported [37], pushing and shoving leads to the development of long-lasting clogs which appear as outliers in the distributions and are the consequence of unsolved conflicts among pedestrians coinciding at the exit. Surprisingly, the presence of the obstacle (which in theory should be able to suppress or at least lessen pressure at the exit) is not able to reduce the number of these long-lasting clogs. This result is confirmed by representing the survival function (or CCDF) of the time lapses between consecutive pedestrians (figure 2(E)). All the evacuations performed in highly competitive conditions display broader distributions than those in low competitiveness, independently on the presence of the obstacle. We can therefore conclude that, for all the situations tested in this work, the obstacle has no effect in the passage time distributions. The features of the passage times described for the third series of experiments were also observed in the two previous ones. By way of example, in figures 2(B), (C) we present the boxplots of passage times in the other two series of evacuation drills. From these data, gathered from three different groups of people, we can challenge the notion that placing an obstacle in front of the door leads to an improvement in the evacuation time, at least for the crowd sizes, door widths, symmetrical obstacle positions and competitiveness level tested in this work. Still, it should not be discarded that there exists a specific condition in which the obstacle might offer some benefit concerning the evacuation time, but this

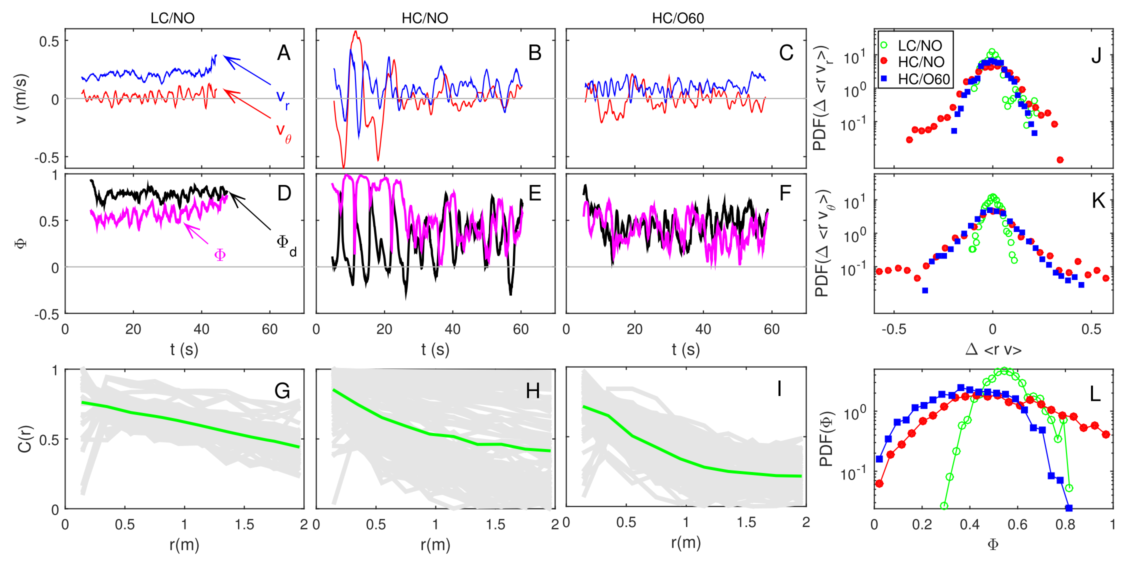

Figure 3. Pedestrian velocities and collective motion. Quantification of pedestrian movements for three cases (LC/NO; HC/NO; and HC/O60) as marked on top of each of the first three columns. In the first row (A)–(C) we show the temporal evolution of the radial (v_r) and azimuthal (v_θ) average velocities for all the persons inside the room in a typical evacuation. The transients at the beginning (during the exit of the first 12 persons) and at the end (the last 40 persons) have been omitted from the averages. Radial velocities are positive towards the door. (J) and (K) show the PDF of the radial and azimuthal velocities fluctuations. In this case, we have rescaled all the velocities by the distance to the door r to account for the radial dependence [22]. (D)–(F) Show the temporal evolution of the polarization ϕ and the 'alignment parameter' ϕ_d (see methods) for the same cases than in (A)–(C). The PDF of ϕ is shown in (L). Panels (G)–(I) show the spatial correlation of the velocity direction of the participants, for every single video frame (*light grey lines*) of a typical evacuation drill for each experimental condition. Green lines represent the time average correlation.

feature must not be taken as a generic hallmark of pedestrian dynamics in any case. Furthermore, our finding contrasts with previous data on the effect of the obstacle in animal flow through bottlenecks [31, 13, 32], exposing a clear instance of the dangers involving direct extrapolation of animal behaviour to humans.

As mentioned, when implementing the third series of experiments we realized that the undesired transversal collective motions appearing in highly competitive evacuations [22] were almost suppressed by the placement of an obstacle (transversal in this context meaning in a direction mostly perpendicular to the door direction). Therefore, aiming to quantify this feature, we extracted the pedestrian trajectories, which were then used to obtain several indicators related with collective movements and, in particular, with the development of transversal rushes. The first one consists on analysing the temporal evolution of the average velocity of the whole group. Accounting for the special geometry of our problem, we consider polar coordinates centred at the exit door, and report, in figures 3(A)–(C), the radial (in the exit direction) and azimuthal (perpendicular to the exit direction) velocities for single evacuations in three different representative cases. When the evacuation proceeds smoothly (figure 3(A)) the average azimuthal velocity is nearly zero over all the exercise and the average radial velocity has a finite, rather constant, value. Increasing competitiveness (figure 3(B)) provokes the emergence of peaks in the azimuthal velocity (a signature of the transversal rushes) that are often associated with high amplitude oscillations of the radial velocity (note that a negative radial velocity means that people are, in average, moving away from the door). Interestingly, we have observed that these transversal waves are more likely to occur in the first half of the evacuation (when there is still a large number of people in the room). This feature should be further studied but points towards the importance of the group size in determining the collective behaviour emerging in these kind of complex systems. For the case of high competitiveness, the presence of the obstacle (figure 3(C)) leads to a remarkable reduction of the peaks in both azimuthal and radial velocities. The generality of this behaviour is manifested in figures 3(J), (K) where we display the distributions of radial and azimuthal velocities for all the evacuations performed in the same conditions. Clearly, increasing competitiveness leads to broader distributions and placing the obstacle minimizes the occurrence of extreme events, especially for the case of radial direction.

In order to further investigate the emergence of collective movements, we have looked at the so-called polarization [39, 40] ϕ (as defined in section 2). This parameter accounts for the degree of global ordering: it is one if all the individual velocities point in the same direction and close to zero when they point in random directions. The low competitiveness evacuations (figure 3(D)) reveal a rather constant value of ϕ around 0.5, caused by the homogeneous movement of pedestrians towards the door. Indeed, the polarization slightly grows at the end of the evacuation when the number of pedestrians within the room reduces and their velocities direction becomes comparable. Increasing competitiveness (figure 3(E)) provokes a dramatic change in the behaviour of ϕ. The most conspicuous characteristic is the existence of time lapses during which all velocities point in the same direction ($\phi = 1$), alternating with very short intervals in which pedestrians move almost randomly (downwards spikes nearly reaching $\phi \approx 0$). Interestingly, the presence of the obstacle prevents these ordered movements (figure 3(F)). Again, the distribution of the instantaneous polarization values obtained for all the evacuations performed in the same conditions (figure 3(L)) reflects the importance of the obstacle in eradicating situations in which all pedestrians move in the same direction.

Also, trying to adapt the measurement of the polarization to the special geometry of our problem, we have calculated what we named the 'alignment parameter' ϕ_d as it accounts for the alignment of each pedestrian velocity with their expected desired direction towards the exit (see methods). In brief, the contribution of each pedestrian to the value of ϕ_d is: $+1$ when its velocity point towards the door; -1 when it points in the opposite direction; and 0 when it points transversally to the exit direction. As expected, in the low competitiveness scenario ϕ_d takes constant values (close to one) all over the evacuation (figure 3(D)). Oppositely, in the high competitiveness case (figure 3(E)) ϕ_d strongly varies with time, reaching zero, and even negative values. Interestingly, the instants of $\phi_d \approx 0$ coincide with values of $\phi \approx 1$, indicating that all the individuals move in the same direction, which is approximately perpendicular to the exit direction (see supplementary material). The presence of the obstacle abates these events (figure 3(F)), yet it is not able to completely repair the effect of introducing competitiveness in the system as reflected by the lower values of ϕ_d obtained in figure 3(F) than in figure 3(D).

Finally, we have looked at the spatial correlation, $C(r)$, of the individual velocities at a given instant. In figure 3(G), the $C(r)$ instantaneous curves (one for each frame of the recorded video) are represented for a given evacuation in non-competitive conditions. The outcomes evidence that: (i) all curves are similar, in agreement with the small temporal variations observed for other magnitudes (figures 3(A) and (G)); and (ii) the velocity correlation decays slowly as expected from the specific geometry of our problem where the velocity direction depends on the position. Increasing competitiveness, however, introduces a high degree of inhomogeneity between the curves for different times (figure 3(H)): in some instants the correlation decays abruptly whereas, in other cases, it keeps a value close to one for distances up to 2 m. The abrupt decays in correlation correspond to situations in which $\phi \approx 0$ and the strongly spatially correlated scenarios happen when $\phi \approx 1$. As it happened with the other variables, placing the obstacle is found to minimize the highly correlated situations (figure 3(I)).

In summary, we have reported genuine experimental results of several series of experiments, demonstrating that the believed reduction of evacuation times caused by an obstacle is not necessarily true for the case of crowds of up to 200 pedestrians. Despite that this phenomenon must be confirmed by further experiments in which other obstacle diameters and shapes as well as more competitiveness levels are implemented, our work challenges the validity of most of the existent models in which there is always a given range of obstacle positions for which the flow rate improves (with more or less efficacy depending on the obstacle properties). This hints about the necessity of revisiting, for the case of highly competitive conditions, some numerical aspects (such as the route choice [41] at spatial scales smaller than one metre) and/or incorporating new ones (such as the individuals shape [42, 43] and the preferred orientation in the displacement [44, 45]). Moreover, we discovered that placing an obstacle in front of the exit reduces the magnitude and number of collective transversal displacements, suggesting that its implementation would be beneficial in preventing falls. Again, this novel feature should be corroborated by performing similar drills varying parameters such as the obstacle geometry, alignment with the centre of the door, or pedestrian competitiveness.

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