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Flow of pedestrians through narrow doors with different competitiveness

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Abstract. We report a thorough analysis of the intermittent flow of pedestrians through a narrow door. The observations include five different sets of evacuation drills with which we have investigated the effect of door size and competitiveness on the flow dynamics. Although the outcomes are in general compatible with the existence of the faster-is-slower effect, the temporal evolution of the instantaneous flow rate provides evidence of new features. These stress the crucial role of the number of people performing the tests, which has an influence on the obtained results. Once the transients at the beginning and end of the evacuation are removed, we have found that the time lapses between the passage of two consecutive pedestrians display heavy-tailed distributions in all the scenarios studied. Meanwhile, the distribution of burst sizes decays exponentially; this can be linked to a constant probability of finding a long-lasting clog during the evacuation process. Based on these results, a discussion is presented on the caution that should be exercised when measuring or describing the intermittent flow of pedestrians through narrow doors.

Keywords: jamming and packing, self-propelled particles, traffic and crowd dynamics, granular matter

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1. Introduction

A key issue in the management of pedestrian motion is the actual capacity of emergency exits during an evacuation process. Design of safe facilities relies heavily on the dimensions of such exits. If a precinct has a capacity N, safety requirements usually require that complete evacuation should take place before a given time. It is therefore natural to quantify the flow rate J, defined as the number of persons ΔN going out during a certain time lapse Δt. If J is assumed to depend linearly on the exit width, then another useful quantity is the specific flow rate J_s, defined as the flow per unit length of the perpendicular cross section of the way out, namely, $J_s = J/b = \frac{\Delta N}{b \cdot \Delta t}$. While in an open system the section b could be arbitrarily chosen, in a door or in a bottleneck its width must be used. In this way, a time limit can be directly translated into the required number of doors and their sizes. The measurement of the specific flow rate is therefore essential for building design [1].

Of course, the flow rate depends on the density of pedestrians near the door and other conditions under which the evacuation takes place. It is well known that there is a strong dependence of the average speed v on the density of pedestrians ρ. The plot representing these two variables has been termed the fundamental diagram (FD) of pedestrian flow, and shows a monotonic decrease of the average velocity as the density increases. Instead of v, the specific flow can be alternatively used since $J_s = \rho \cdot v$. This representation has the benefit of manifesting a maximum for J_s (known as the capacity of the way out) at an optimal or critical density ρ_{cr}. The characterization of this FD has been the subject of many investigations (as reported for instance by Seyfried and coworkers [2]).

The specific flow rate is a key magnitude for architectural engineers. Indeed, legal codes and engineering tables provide values for the specific flow rate, usually ranging between $J_s = 1.1\ (m \cdot s)^{-1}$ and $J_s = 1.8\ (m \cdot s)^{-1}$ (see, for instance, [3–7]). In many cases, fundamental diagrams are measured to estimate the maximum value of J_s in available premises or in laboratory tests. Conditions there can be assimilated to open spaces or hallways and corridors of constant width, without impediments in the form of obstacles and bottlenecks, so that density is the only limitation to movement. Measured maximum values of J_s are of the same order as the figures cited above: between 1.2 and 1.9 $(m \cdot s)^{-1}$ ([8–11], available at [12]). The corresponding critical densities range from 1.2 [11] to 2.1 m^{-2}[10] (the maximum values of the densities considered were 2.3 [8] and 5.5 m^{-2} [11]). Measurements have been also carried out for systems where the maximum density reached much higher values, and the maximum specific flow rate was similar: for instance, $J_s = 1.8\ (m \cdot s)^{-1}$ [13] (at $\rho_{cr} = 4\ m^{-2}$; the maximum density reached $\rho = 10\ m^{-2}$), and $J_s = 1.5\ (m \cdot s)^{-1}$ [14] (at $\rho_{cr} = 6.6\ m^{-2}$; the maximum density was $\rho = 8\ m^{-2}$). Slightly higher values of the flow were reported for commuters at Osaka, Japan [15], where $J_s = 2.3\ (m \cdot s)^{-1}$ was found at $\rho_{cr} = 3.6\ m^{-2}$. These figures tell us that design codes implicitly assume that the door capacity can be calculated from the fundamental diagram, taking the maximum value for J_s and multiplying it by the door width b (see for instance chapter 14 of the SFPE Handbook [3]).

It is not at all clear that these measurements can be directly applied to a door or a bottleneck, independently of b. This intuition is supported by experiments looking at evacuations through doors and bottlenecks in normal conditions, i.e. without pushing or shoving, and trying to avoid physical contact. In these cases, the total evacuation time is usually measured, with some exceptions where the evacuation time of a given number of people in the room is taken as a representative quantity. In any case, the average flow is $J = \frac{N-1}{t_N - t_1}$ and the mean specific flow is easily calculated as J/b. Kretz et al [16] report specific flows between 1.5 and 1.9 $(m \cdot s)^{-1}$ for $N = 100$ persons exiting through doors of widths between 0.6 and 1.40 m. Surprisingly, a higher specific flow is found ($J_s = 2.2\ (m \cdot s)^{-1}$) for a smaller door ($b = 0.4$ m). In this study, a small decreasing trend is found for J_s as the door is widened. In another experiment [17] the same decreasing tendency was observed; specific flows between 2.5 and 2.1 $(m \cdot s)^{-1}$ can be calculated for doors between 0.6 and 1.8 m. But when performing experiments in bottlenecks instead of doors, the opposite variation has been described. Seyfried and collaborators [18] found $J_s = 1.6\ (m \cdot s)^{-1}$ for $b = 0.8$ m and $J_s = 1.97\ (m \cdot s)^{-1}$ for $b = 1.2$ m, both of them for $N = 60$ pedestrians. Hoogendoorn and Daamen [19] report $J_s = 0.8\ (m \cdot s)^{-1}$ for $b = 1$ m but $J_s = 1.4\ (m \cdot s)^{-1}$ for $b = 2.25$ m. It is fitting to remark that while doors do not impose any restriction on movement once the door is crossed, allowing for a reduction of density after the door, in bottlenecks this freedom is lost. This difference could result in some limitations to the flow upstream of the constriction. Moreover, it has been claimed [19] that the flow rate in a bottleneck can only increase in a step-wise manner with the door size. The reasoning is that the flow rate should depend on the integer number of pedestrian lanes that are allowed to pass through the door. Newer experimental evidence, however, demonstrates how the flow continuously varies with the bottleneck width [16–18, 20]. It is welcome that in all these scenarios, the reference values offered by the codes and handbooks cited above are compatible with fundamental diagrams found in open systems and in doors and bottlenecks under normal conditions.

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The situation is completely different if the evacuation is performed under competitive conditions, allowing for physical contact while in the presence of a geometrical constriction—a narrowing, for instance. This scenario can give rise to all kind of effects typically found in granular systems, such as the formation of arches and clogging, caused by friction and intimately related to the existence of downright pressure in the system. Few experiments are available concerning this case. One of them was performed by Nagai and coworkers [21], where $N = 75$ persons evacuated a room through a door adjacent to a corner. The flow displays a continuous variation with the door width, and the specific flow is $J_s = 4.3\ (m \cdot s)^{-1}$, $J_s = 3.3\ (m \cdot s)^{-1}$ and $J_s = 2.4\ (m \cdot s)^{-1}$ for doors of 0.4, 0.8 and 1.6 m respectively (data are available at [22]). Note the decreasing trend of the specific flow as the door width increases. Another competitive evacuation was presented by Müller et al [17], in which 150 to 195 people took part. Four different door widths were analyzed, ranging from $b = 0.9$ m to $b = 1.8$ m (in this case, the door was centered). The corresponding flows are $J_s = 3.2\ (m \cdot s)^{-1}$ for the smallest door and $J_s = 4.9\ (m \cdot s)^{-1}$ for the bigger one, showing a robust increase of J_s with the door size. It is worth noting that the biggest specific flows reported in these two evacuation drills carried out in competitive conditions (namely, $J_s = 4.3\ (m \cdot s)^{-1}$ and $J_s = 4.9\ (m \cdot s)^{-1}$) are nearly three times greater than the average value measured in normal conditions ($J_s = 1.5\ (m \cdot s)^{-1}$).

If this is confirmed, it means that competitive conditions would increase the exit capacity of the doors. Taken at face value, this could seem worthwhile. However, increased competitiveness can also lead to undesired events, such as clogging and bad falls, which may block the way out. Besides, increasing the competitiveness will quite likely reach a point from which the flow will drop. This is known as the 'faster-is-slower' effect, and it was first described by Helbing and coworkers [23] in computer simulations. This expression conveys the meaning that, in some cases, increasing the competitiveness can be detrimental for the total evacuation time; hence trying to exit faster and faster can result in slower evacuations. In the last years faster-is-slower has been experimentally evidenced for granular matter [24] and humans [25], and definitively proved and generalized for several different many-particle systems [26]. It is worth mentioning that in terms of the social force model [23], a higher desired velocity ('faster') produces a higher driving force. But in fact a higher driving force can be attained by pushing, independently of the velocity. Even though in [26] the increasing levels of pushing were correlated with higher desired velocities, it remains an open question whether the cause of a worsened evacuation performance is a 'faster' free velocity or 'pushing harder'. An aspect that has been shown to be relevant is the increase in contact forces between particles [27], which leads to longer clogs [26].

In this manuscript we extend and thoroughly analyze the outcomes of two previous sets of experiments [25, 26] dealing with pedestrian evacuation through a narrow door under different conditions of competitiveness. The egress is carried out with different motivation levels, and two door widths are used. Our goal is to characterize the flow rate of people through the door, as well as the temporal evolution of the specific flow during every single test. In this way, we will hopefully contribute to a better understanding of the evacuation processes, which—as can be gathered from the above paragraphs—is still plagued with riddles. The data we will present can also be useful for designing blueprints, and for validating microscopic models and simulation software [28], at least in a qualitative way.

2. Methodology

Two sets of evacuation drills were carried out at the indoor gym of the University of Navarra. The participants were volunteer students in the fourth year of the School of Architecture: young men and women aged about 22 years old. They gathered on two different days for around 4 h (a complete Saturday morning); on the first day there were 85 ± 2 persons and on the second day there were 95 ± 3 persons. The slight variation of these figures was caused by different reasons: a couple of students were delayed, and a few had to leave in advance. The students wore dark clothes and each one was given a red hat to speed up the subsequent image processing. The participants were instructed to exit the gym through a door at the side of the room that leads to a corridor much wider than the door (about 3 m wide). At the end of the corridor there is a hall that was used as the assembly point. As the existing door was too large for our purposes, we built a frame so that the effective door width was 75 cm on the first day. On the second day, we also installed pressure sensors at the door jambs and covered them with protective foam, leaving an effective section of 69 cm. These two doors will be referred to in the following as LD (large door, 75 cm width) and SD (small door, 69 cm width). Before starting the evacuation, the volunteers assembled in a rectangular area of about 6.6×3.7 m^2 which was marked on the floor, the door being at the centre of the longer side of this rectangle. Therefore, the average initial density was close to 4 persons m^{-2}. They were also instructed not to be closer than 1 m from the door at the start.

In order to control and handle the proceedings, ten managing staff (professors, technicians and postdoctoral students) were also present. The managing staff carried wearable radio devices allowing two-way communication. A control center was established at the grandstand, from where the head supervisor monitored the live feed of surveillance video cameras and radioed orders to the managing staff. Other managers were conveniently placed at the side just after the door, inside the gym and along the corridor. They were identifiable by high visibility clothing. Audible signals were arranged for starting and stopping the evacuation drills. An emergency stop was also planned that could be issued whenever asked for by any participant or manager. For instance, an inconsequential fall of a volunteer resulted in a halt and the cancellation of a test. Several blank tests were carried out until all the participants were familiar with the practice. All the evacuation drills took place safely and uneventfully.

The volunteers were instructed to exit the room as far as they could following some rules that were intended to change the competitiveness. On the first day (LD runs), we carried out two sets of runs. In one set, students were told to avoid pushing or elbowing one another (on the understanding that unintended physical contact was allowed). In another set, they were allowed to reasonably push and jostle for the exit (using common sense). In fact after a couple of blank tests the drills were performed in a safe and repetitive way. On the second day (SD runs), we carried out three sets of runs, with the following directions: (i) intentional physical contact was to be avoided;

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Table 1. Number of runs and passage times for each experimental situation.

	LD HC	LD LC	SD HC	SD MC	SD LC
Number of runs	8	5	13	10	10
Total number of passage times	682	420	1241	970	920

Note: On the first day the LD was used, and on the second day the SD was used. Conditions are referred to as high competitiveness (HC), moderate competitiveness (MC) and low competitiveness (LC).

(ii) soft physical contact (touching) was allowed; and (iii) moderate pushing and elbowing was allowed (of course, violent shoving was excluded). These directions effectively resulted in different levels of competitiveness (low, middle and high) as already proved by two independent measurements: the initial group velocity, and the pressure at the door jamb [26]. In table 1 we summarize the number of runs performed in each day, the specific door size, the competitiveness level and the total number of passage times that were recorded.

In order to record the evacuations, two cameras were placed above the door, one inside the room and another outside. The cameras pointed downwards, so that the recordings were taken from the zenithal position and the red hats were clearly visible. The film of the evacuation recorded just after the door had a resolution of 704×576 pixels registered at 25 frames per second. From this, we performed a procedure akin to the photo-finish used in track and field competitions. It basically involves sampling a given line of pixels from every frame and stacking it vertically. We have sampled a line at about 1 m after the door. In this way, an image is obtained where one dimension (vertical) is the space along the line and the other dimension (horizontal) is time; and this is why this representation is often called a spatio-temporal diagram. In figure 1 we illustrate this method for three cases corresponding to the three competitiveness levels of the second day (small door). Let us note that in order to improve the time resolution, we have sampled a five-pixel-thick line. The spatio-temporal diagrams of the evacuations are processed to detect the centroid of the red hats. Thus, the passage time of every individual is obtained with a precision of $\pm$ 0.1 s.

3. Instantaneous flow

As explained above, from the spatiotemporal diagrams, it is straightforward to plot the exit time for each individual as in figures 2(a) and (b). An alternative that is also widely used in the literature is plotting these graphs with the axis interchanged; i.e. the number of pedestrians who evacuate the room in a given amount of time as in figures 2(c) and (d). The first conspicuous feature that is evidenced in any of these graphs is that the statistical variations are large; for instance, one particular evacuation drill at high competitiveness (HC) can be either faster or slower than another in the low competitiveness (LC) scenario (see figure 2(a) or (c)). Therefore, it is only on average that one can state whether these two protocols give different results. Second, as expected, a wider door results in a shorter evacuation time (figure 2(b) or (d)).

Figure 1. Evacuation drills: on the top row, snapshots taken from the camera located inside the gym. Middle row: snapshots from the camera outside the door; the pixels sampled to obtain the spatiotemporal diagrams are marked with a green line. Bottom row: spatiotemporal diagrams, in which red hats are marked with a white dot. Low, middle and high competitiveness correspond to left, middle and right columns respectively.

From the results of all the evacuations, we obtain the averages for each experimental condition (large and small door, different levels of competitiveness) as shown in figure 3. These averages could be calculated in two different ways: (1) averaging over the individual numeral (by calculating the mean exit time of the nth individual at each drill) as in figure 3(a); (2) averaging over time (by calculating the mean number of individuals who have gone out at different times) as in figure 3(b). Both representations lead to similar outcomes. As expected, increasing the door size leads to a reduction of the evacuation time. Moreover, for the large door ‘faster-is-slower’ seems to be obvious as increasing the competitiveness leads to an increase of the evacuation time. For a small door, however, ‘faster-is-slower’ is only seen in a certain lapse of the evacuation duration (measured in either time or in number of evacuated persons). Apparently, there is a transient (the first dozen persons, say) where competitiveness plays a very small role. Then ‘faster-is-slower’ is observed for a while. For the last few individuals, on the other hand, we can say that ‘faster is faster’.

With the aim of investigating in more depth the dynamics of the evacuation process, we look at the temporal evolution of the instantaneous flow rate. This is related to the slopes of the plots displayed in figures 2 and 3, so the calculation involves the derivative which gives rise to noisy data series. Therefore, we need to perform the average over as many tests as possible. As a consequence only the experiments of the second day will be used, because there are more available series than in the first day (see table 1). Moreover, in order to further reduce noise, we calculate the flow rate (number of individuals per unit time) for a window comprising 15 persons. All the results are summarized in figure 4. In the top row, we represent the passage time for the three levels of motivation implemented with the small door. Each realization is plotted with a different color. In the bottom row, the instantaneous flow rate (calculated as explained above) is represented. The thick black lines are the mean instantaneous flow rates averaging over all the drills (the averages are performed over the individual numeral,

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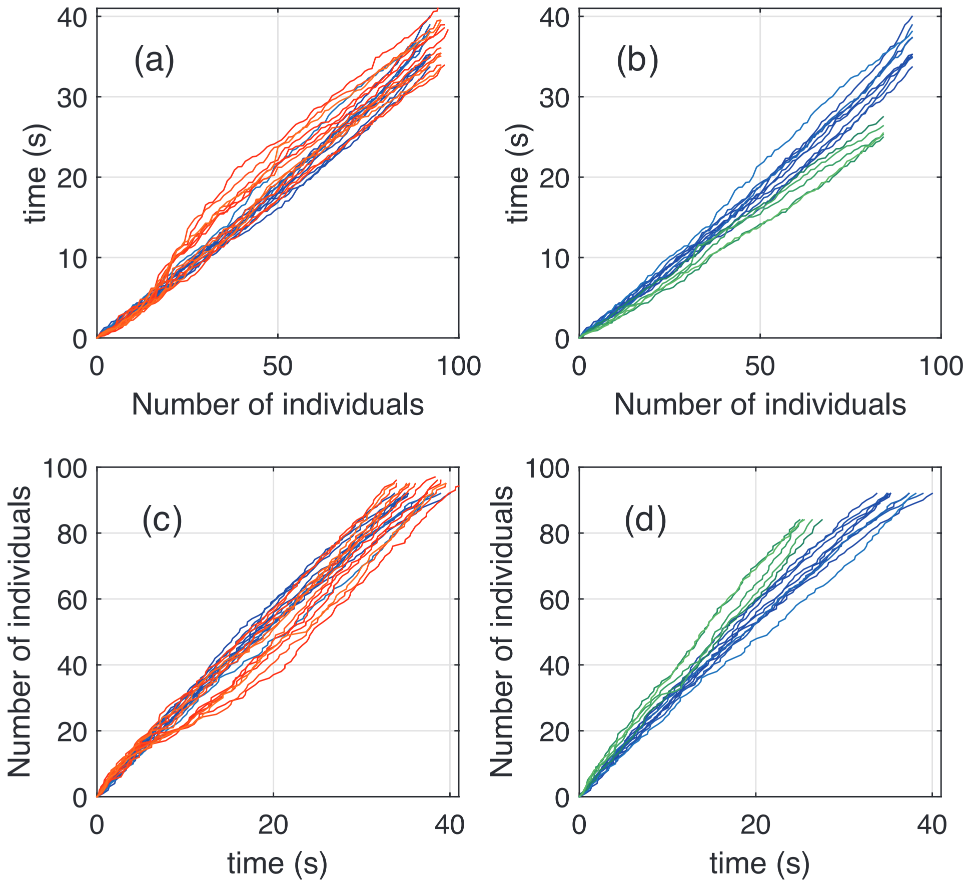

Figure 2. Passage times for individuals. (a) For the 69 cm wide door, low competitiveness (blue/dark shades) and high competitiveness (orange/light shades) are shown. (b) Low competitiveness egress for the 69 cm wide door (blue/dark shades) and for the 75 cm wide door (green/light shades). The same runs are displayed with the same color codes inverting the horizontal and vertical axes in (c) for the 69 cm wide door, low and high competitiveness, and in (d) for the low competitiveness in both doors.

as explained before). Note that, independently of the scenario, the specific flow rates are very high (around $J_s = 4.0\ (m \cdot s)^{-1}$, which corresponds to $J = 2.8\ s^{-1}$) as compared to the figures given in the section 1.

The differences in the temporal evolution of the instantaneous flow rate for the three competitiveness levels are clear. For the low motivation case, the instantaneous flow rate decreases as the number of people in the room diminishes. This behavior could be related to a decrease in the hurry as the room is emptying; on the contrary, in the absence of competitiveness a constant flow rate would be expected. This feature, however, disappears for the medium and high competitiveness cases. In the latter, there is a clear transient at the beginning of the evacuation, where the instantaneous flow rate is very high (3.2 persons per second, so 4.5 persons per second per meter). This can be easily understood by visual inspection of the video recordings. As stated above, the initial conditions were such that the volunteers were distributed randomly in an area close to the door at a density of about 4 persons m^{-2}, but leaving

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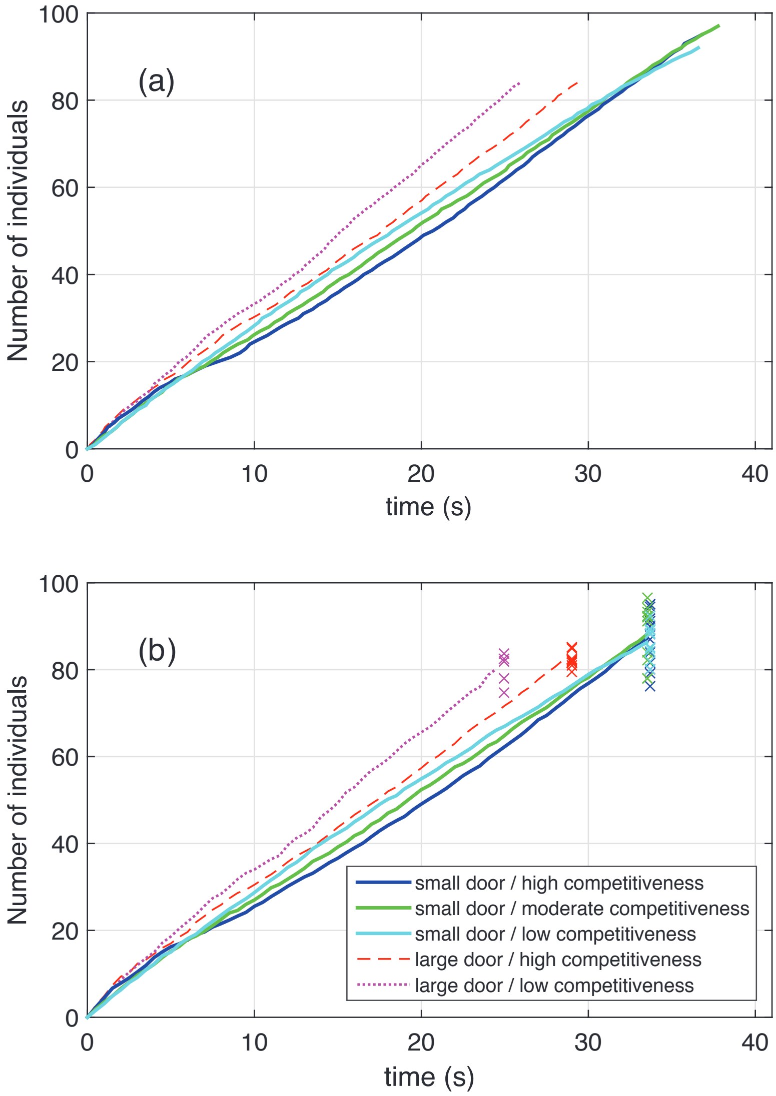

Figure 3. Number of evacuated individuals versus time for the di□erent door size and competitiveness, as indicated in the legend. In (a) the mean evacuation time has been calculated by averaging the exit time for each ordinal of the exiting individuals. In (b) the averages have been performed for the numbers of individuals that egress in temporal intervals of 0.5 s. As these averages must stop after the shorter evacuation, a cross has been marked to indicate the dispersion of all the di□erent cases at that moment.

a gap of at least 1 m to the door. When the evacuation starts, the people nearest to the door go quickly towards the exit and, as the local density is still relatively low, they can proceed almost unimpeded. When the density near the door builds up (in a few seconds), the flow decreases abruptly. Afterwards, the flow rate slowly increases, presumably as the pressure imposed by the people reduces. The same phenomenon can be seen for medium competitiveness but the features are, of course, weaker. A transient for reaching the steady state has also been found in the recent work of Liao and coworkers [20].

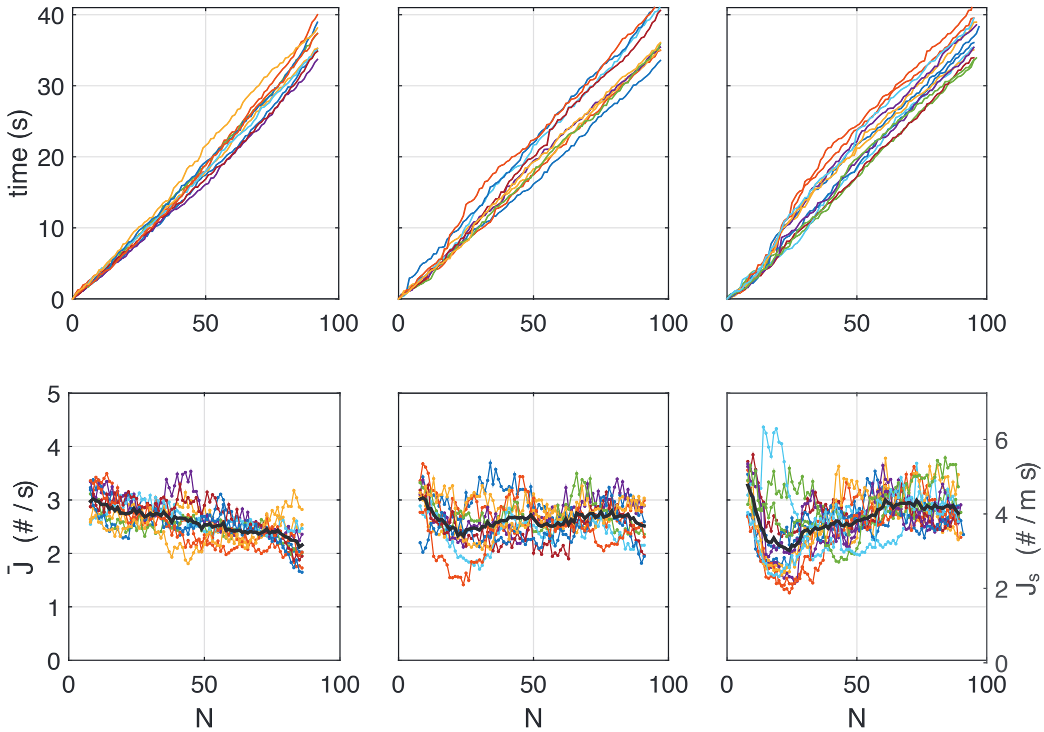

Figure 4. Passage times (top row) and instantaneous flow (bottom row) for low, medium and high competitiveness (left, center and right column respectively), corresponding to the 69 cm wide door. Each color stands for one drill. N is the numeral for individuals. The right axis of the bottom row provides the specific flow J_s. Thick black lines in the bottom row are averages taken for each ordinal of the exiting individual.

4. Bursts and clogs

Considering the evolution of the evacuation process described so far, we have decided to deeply analyze the flow intermittencies. We have recently argued [25, 26, 29, 30] that the total evacuation time leaves out significant information on the exit process. For instance, the total evacuation time is nothing more than the average time per person, multiplied by the number of individuals. It begs the question of whether such a mean is well defined, in the statistical sense. Moreover, investigating the nature of the flow fluctuations may provide information concerning clogs, and understanding the variations from one individual to another may also have deep significance.

In order to do this, we found it suitable to consider the time interval Δt between the passage of two consecutive individuals. Of course, this quantity is not highly relevant in a situation of non-contacting individuals in which the time intervals between two pedestrians are related to a queuing process. Instead, here we are considering a highly congested pedestrian state where friction impedes the movement and hinders the room evacuation. In figure 5 we display a box plot of Δt for all the scenarios studied, evidencing that the median slightly increases when the door size is reduced. More significative than the median seems to be the data dispersion towards high values of Δt characterized by the whiskers and the outliers. Clearly, the dispersion increases as the door size

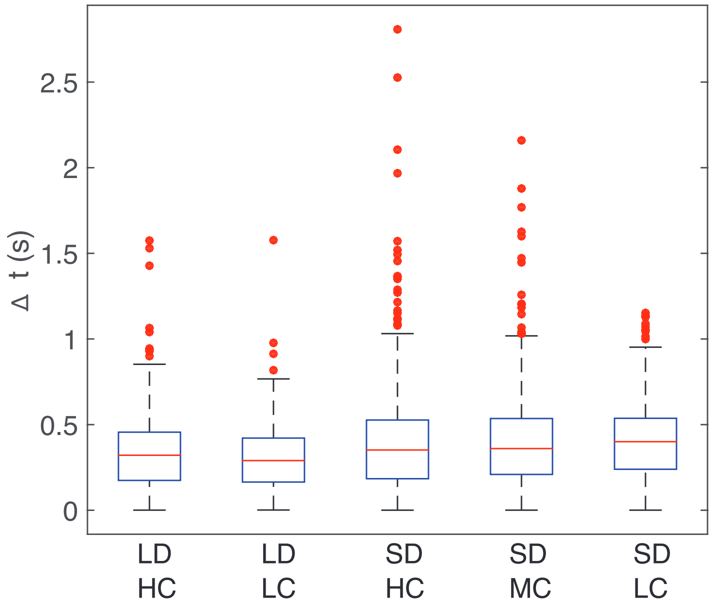

Figure 5. Box-and-whiskers plot of the five cases studied: LD and SD for high competitiveness (HC), moderate competitiveness (MD) and low competitiveness (LC). Outliers are marked with red dots. In order to compare different cases, we have considered the same number of persons for the LD and SD runs, i.e. the lowest number of persons for each case. For the LD, all 420 persons have been represented in the (LD, LC) plot; for the (LD, HC) case, 420 different persons out of the total 682 participants have been randomly chosen to draw the boxplot. In the same way, 920 different persons have been randomly chosen for the (SD, HC) and (SD, MC) boxplots and all the participants are included in the (SD, LC) case. The random selection of data introduces slight variations in the boxplots every time they are calculated, but this is necessary to compare tests with different amounts of data.

is reduced and the competitiveness is increased. The reason for this should be sought in the fact that Δt does not follow a normal distribution. Indeed, a power law tail of this distribution $(\Delta t)^{-\alpha}$ has been reported, both in animals [29], persons [25] and silo clogs in granular materials [31].

In order to look deeply into the nature of these distributions, in figure 6 we display the complementary cumulative distribution function of Δt (also known as the survival function) for the SD in the LC and HC cases. The survival function is nothing more than the probability of finding a time lapse between two consecutive individuals larger than a given value, and can be directly obtained from the passage times. These distributions have been obtained after removing the transient at the beginning and end of the evacuation (we leave out the first 10 people and the last 12 who exit the room). This is an arbitrary choice, but we have tested that a change of several persons above or below these values has very little influence on the figures given (see supplementary material of [26]). From figure 6 it is suggested that the distribution tails can be fitted with the already mentioned power law decays, but also with stretched exponentials $P(\Delta t) = a\, e^{(-b\Delta t^{d})}$. These functions were introduced by Kohlrausch in 1854 [32] when studying the discharge of capacitors and therefore, an analogy could be drawn with the

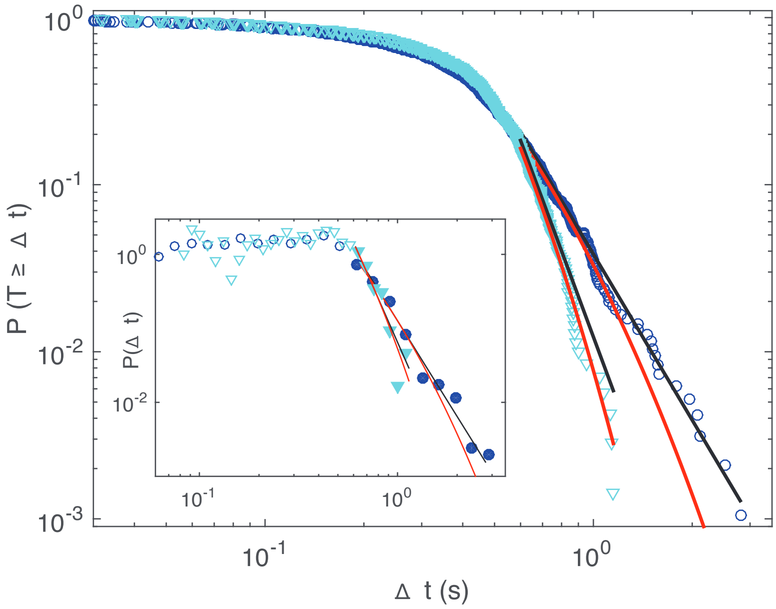

Figure 6. Survival function (i.e. complementary of the cumulative distribution function or CDF) of the passage times obtained for the SD in the low (□) and high (°) competitiveness cases. The tail of the distributions can be fitted by power laws or stretched exponentials. Black lines are power law fits with $\alpha = 4.3$ (HC) and $\alpha = 6.3$ (LC). Red lines are stretched exponentials with parameters (see main text) $b = 10.0$, □ $= 0.434$ (HC) and $b = -13.8$, □ $= 0.533$ (LC). All fits have been performed for the data beyond $\Delta t = 0.6$ s. Inset: the (non-cumulated) normalized histogram for both cases, in logarithmic scale, with the same fits as in the main figure. Solid symbols correspond to points beyond $\Delta t = 0.6$ seconds. The stretched exponential fits have been performed with the Matlab curve fitting toolbox and the goodness of fit is as follows: for the HC, power law fit: SSE = 0.029 29, $R^2 = 0.9677$; stretched exponential: SSE = 0.028 36, $R^2 = 0.9687$. For the LC case, power law fit: SSE = 0.4448, $R^2 = 0.8839$; stretched exponential: SSE = 0.4539, $R^2 = 0.8816$. SSE stands for sum of squared errors.

pedestrian system assuming that clogs and bursts act like discharges. Also, it is rather well known that in many natural processes it can be difficult to distinguish between these stretched exponentials and power laws [33]. This indeterminacy of the best fitting equation becomes more evident in situations, such as that studied here, where the amount of data is not very large. In particular, the R^2 values of the power law and stretched exponential fittings are very similar: $R^2 \approx 0.97$ for HC and $R^2 \approx 0.88$ for LC. Nevertheless, by visual inspection of the survival functions it seems that the steeper the distribution is, the better the stretched exponential fit works. On the contrary, the HC case—which leads to fatter tails—seems to be slightly better fitted by the power law decay.

Despite the fact that both stretched exponentials and power law decays are equally valid to fit the distribution tails, the fact that in previous experiments with silos, power law decays have been observed with exponents below 2, prompts us to use this latter expression to analyze the differences between the scenarios studied. Importantly, as will be observed, such small exponents are never achieved in the present experiments so the exponent α might be considered as a qualitative measure of the steepness of the PDF.

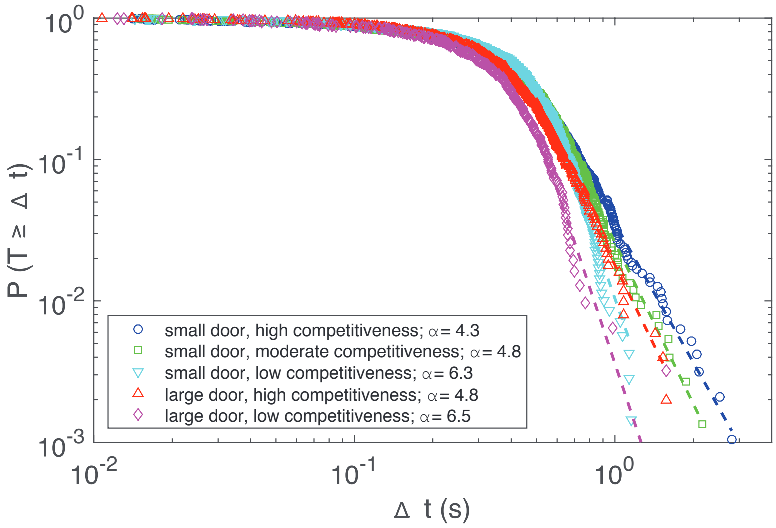

Figure 7. Survival function for the different evacuation scenarios studied in this work as shown in the legend. Note that in this cumulated representation the slope of the power law tail is $\alpha + 1$.

A suitable method to fit the power-law distributions has been proposed by Clauset and coworkers [34]. We follow it, obtaining the results displayed in figure 7. Following the criteria explained in this work we can state that, in all the scenarios studied, the existence of a power law tail is compatible with our data as p-values are never below 0.05 (these p-values, as explained by the authors, arise from a Kolmogorov–Smirnov test performed with synthetic data sets obtained by bootstrapping). As expected, α is very sensitive to the evacuation conditions. In particular, we found that α is lower for the SD (both at HC and LC). Also, α decreases with competitiveness, both for small and large doors. A lower value of α means that large clogs are more probable, so the results are in good agreement with the expected behavior: clogging is favored by reducing the door size and increasing the competitiveness.

Let us remark that we have found $\alpha > 2$ in all the distributions (as this is a cumulated probability, the exponent of the power-law tail in the survival function is $\alpha + 1$). This means that the average Δt is well defined and so is the average flow rate (for a power law distribution, the moment of order m is well defined if $\alpha > m + 1$). However, this may not be the case for other situations, as has already been observed for the case of clogging arches in vibrated silos [30]. In that scenario, the exponent α dropped below 2 in some cases, implying that averages did not make any sense as the process was dominated by the extreme events (long lasting clogs). It can be speculated that in pedestrian evacuations this could happen in an extreme competitiveness scenario. In any case, although $\alpha > 2$ in all our experiments, the fact that the distribution could decay algebraically is a warning about the need to characterize the distribution of passage times before providing an average evacuation time (or an average flow rate).

Another variable that can be easily calculated from the individual passage times is the size of the bursts s: the number of people that egress between two consecutive clogs. Of course, in order to do this we must first define clog (namely, the time interval Δt_c between two consecutive individuals, above which the flow is said to be halted). Let us first analyze the burst size distribution for a particular value of Δt_c (figure 8) and then

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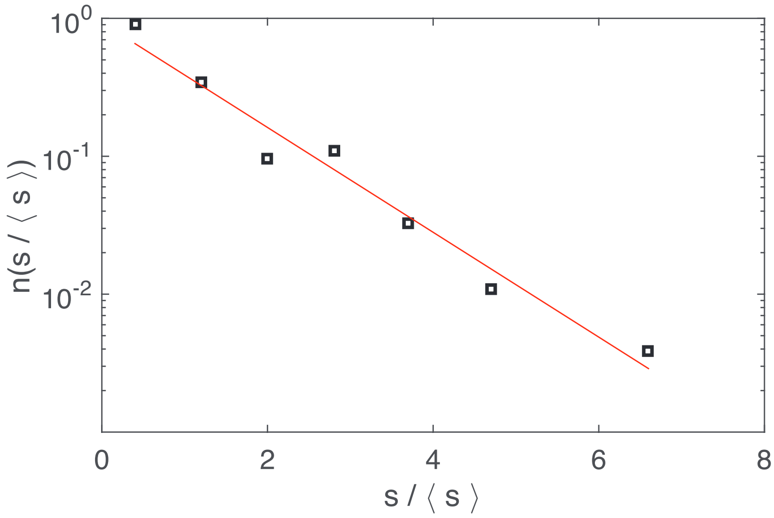

Figure 8. Burst size distribution in semilogarithmic scale for the 69 cm wide door, HC case. The threshold time for defining a clog has been taken as $\Delta t_c = 0.7$ s. The burst size has been rescaled by the average burst size. The solid line is an exponential fit of the data.

we will turn to the effect of changing such a threshold value. In order to calculate burst sizes, we remove some individuals from the beginning and end of each evacuation drill (as in the previous analysis) and we aggregate all the evacuation drills together by linking the last valid person of one evacuation with the first valid person of the next one. This is the reason why, occasionally, a burst bigger than the number of participants in the drill can be found.

In all the scenarios studied, the burst size displays an exponential distribution regardless of the competitiveness, the door size, or the threshold value used to define a clog. This exponential behavior can be easily understood if the probability of clog development is constant during the whole duration of the evacuation [35–37] (omitting the transients that, as stated above, are not included in the analysis). In addition, the exponential decays imply that the average burst sizes $\langle s \rangle$ are always well defined. Therefore, from now on $\langle s \rangle$ is used to compare the effect of door size and competitiveness in the different evacuation scenarios implemented. As the averages will strongly depend on the threshold time Δt_c used to define clogs, before these comparisons are made one should first analyze the effect of this figure. Provided that there is not an a priori preferred value for the threshold time Δt_c above which the system can be unequivocally said to be clogged, we have opted to calculate $\langle s \rangle$ for a range of Δt_c (figure 9). As expected, burst size monotonically increases with Δt_c, as the larger the time lapse needed to define a clog, the more people can egress before one such clog occurs. When comparing the different evacuation conditions we find that, for a given door size, burst size decreases with competitiveness. Besides, for the same competitiveness level, bursts are bigger for the LD than for a SD. Therefore, we can conclude that even though the election of Δt_c does not change the qualitative picture, it is essential to consider it if quantitative comparisons among different experiments are performed.

Another magnitude that is interesting to evaluate is the flow rate within bursts Φ which, in principle, might be thought to provide information about the flowing

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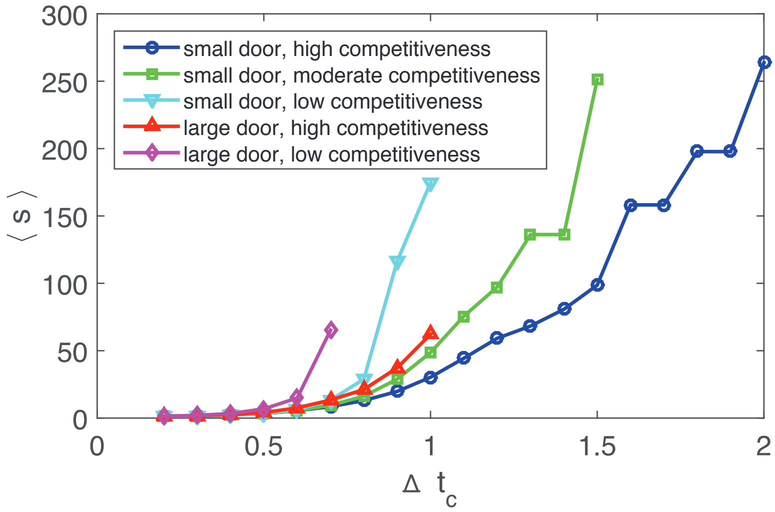

Figure 9. Mean burst size $\langle s \rangle$ as a function of the threshold time Δt_c used to define a clog. The graphs stretch as long as the data availability allows to calculate an average.

regime. Unfortunately, we have to face the same problem that we found when trying to define the mean burst size: Φ is strongly dependent on the arbitrary threshold time Δt_c used to define a clog. Clearly, as the threshold time increases, the bursts include longer lapses during which nobody passes through the door. Therefore, the flow rate within bursts must necessarily decrease with Δt_c as observed in figure 10. Concerning the behavior observed in the different scenarios analyzed, it is clear that for the LD, Φ decreases with competitiveness according to the expected faster-is-slower effect. For the SD, however, the results are rather different. Indeed, only when long Δt_c are considered (above $\Delta t_c = 1.2$ s) does the flow rate of moderate and high competitiveness scenarios slightly fall below the case of low competitiveness. We argue that these outcomes could be reflecting the dual effect of increasing competitiveness: on one hand, it augments the probability of finding long clogs, but on the other hand it increases the desired speed and therefore, the flow rate within bursts. Another conclusion that can be inferred from figure 10 is the lack of a clear meaning of the flow rate within bursts, which is of course caused by the absence of a temporal scale in the Δt distribution that might allow us to unequivocally separate bursts and clogs.

5. Conclusions

We have reported the results of evacuation drills of around 90 volunteers in five different conditions, varying door size and competitiveness. The number of test repetitions in the same conditions allow a thorough statistical analysis that reveals new features of the egress process. The picture that emerges is that of an intermittent flow where the flowing part is characterized by an exponential distribution of burst sizes that implies a constant probability of clogging. In contrast, the distribution of clog duration reveals heavy tails. It is this latter distribution that may eventually give rise to anomalous

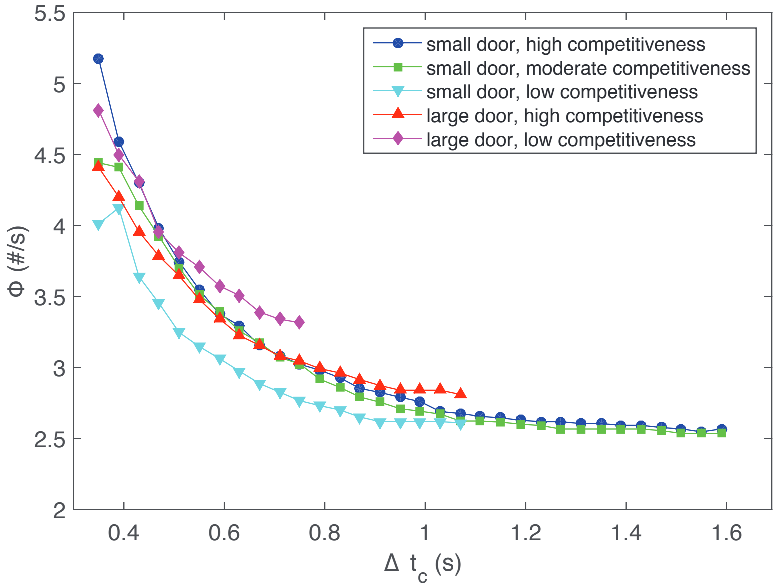

Figure 10. Mean flow rate within bursts Φ as a function of the threshold time Δt_c used to define a clog (and hence, the beginning and end of a burst). The graphs stretch as long as the data availability allows us to calculate an average.

statistics and prevent a clear and neat separation of the bursts and clogs. Accordingly, all the descriptors based in bursts properties lack robustness in the sense that they strongly depend on the threshold value implemented to define the bursts. On the contrary, the exponent of the power law fit of the tail in the clog duration distribution is shown to be a right variable to quantify the fluidity of a crowd passing through a bottleneck: the larger the exponent the less likely that long lasting clogs develop in a given scenario. The goodness of this exponent is supported by the fact that it increases with the door size and reduces with competitiveness. The latter correlates with the faster-is-slower effect expected in an evacuation process when competitiveness increases and pressure and friction forces may cause clogging. Note that the results shown in figure 6 suggest that the exponent of the stretched exponential could be also a nice alternative to quantify the fluidity of multiparticle frictional systems flowing through bottlenecks, but this should be checked in other systems where the amount of accessible data allows better statistical analysis.

We have also characterized the temporal evolution of the instantaneous flow rate. Whereas for the 75 cm wide door, the two competitiveness levels seem to lead to faster-is-slower during the whole evacuation, for the 69 cm wide door a more complex behavior is found. Indeed, faster-is-slower is only observed in the central part of the evacuation: after an initial transient and well before the end of the evacuation where faster-is-faster is obtained. This finding stresses the key relevance of the number of people involved in the drills and alerts about the misinterpretations that can arise from experiments with few individuals. Also, special attention should be paid when comparing experiments with a different number of people. In addition, the results shown here provide evidence for the necessity of performing similar experiments (where contact and moderate pushing is allowed) with a much larger number of people.

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Finally, let us remark on the high values of the average specific flow rates measured in all the scenarios, around $J_s = 4\ (m\cdot s)^{-1}$. These values confirm previous data reported for competitive evacuation, which results in a specific flow several times greater than the capacity as obtained from fundamental diagrams measured in cooperative conditions and usually considered in legal codes for safety and building design. However, this increase in the flow comes along with an increased probability that long clogs will develop, and (quite probably) with a growth of the likelihood of people falling. Both events can cause a blockage at the exit. In a purely theoretical scenario in which the competitiveness level could be tuned at will, this should be also considered when providing optimal values.

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