

A counterintuitive way to speed up pedestrian and granular bottleneck flows prone to clogging: *Can ‘more’ escape faster?*

Alexandre NICOLAS¹, Santiago IBÁÑEZ^{2,3}, Marcelo N. KUPERMAN^{2,3}, Sebastián BOUZAT^{2,3}

¹ LPTMS, CNRS, Univ. Paris-Sud, Université Paris-Saclay, 91405 Orsay, France

² Consejo Nacional de Investigaciones Científicas y Técnicas

³ Centro Atómico Bariloche (CNEA) and Instituto Balseiro, R8400AGP Bariloche, Argentina.

Abstract. Dense granular flows through constrictions, as well as competitive pedestrian evacuations, are hindered by a propensity to form clogs. We use simulations of model pedestrians and experiments with granular disks to explore an original strategy to speed up these flows, which consists in including contact-averse entities in the assembly. On the basis of a minimal cellular automaton and a continuous agent-based model for pedestrian evacuation dynamics, we find that the inclusion of polite pedestrians amid a given competitive crowd fails to reduce the evacuation time when the constriction (the doorway) is acceptably large. This is not surprising, because adding agents makes the crowd larger. In contrast, when the door is so narrow that it can accommodate at most one or two agents at a time, our strategy succeeds in substantially curbing long-lived clogs and speeding up the evacuation. A similar effect is seen experimentally in a vibrated two-dimensional hopper flow with an opening narrower than 3 disk diameters. Indeed, by adding to the initial collection of neutral disks a large fraction of magnetic ones, interacting repulsively, we observe a shortening of the time intervals between successive egresses of neutral disks, as reflected by the study of their probability distribution. On a more qualitative note, our study suggests that the much discussed analogy between pedestrian flows and granular flows could be extended to some behavioural traits of individual pedestrians.

1. Introduction

Clogs rank high on the list of nightmares of grain silo managers and crowd managers alike. Every year, grain entrapment still claims the lives of dozens of workers who crawled inside bins or silos to knock down clogs and speed up the outpour. For instance, in the United States, it was at the origin of 11 fatalities and 18 non-fatal injuries in 2016 [1], while in France [2] and in Argentina [3] fatal accidents occur every few years. Concurrently, crowd disasters due to massive rushes towards an exit in situations of emergency hit the headlines on a yearly basis.

From a fundamental perspective, recent works have shed light on similarities in the clogging and unclogging dynamics across a wide variety of systems, from vibrated granular flows to pedestrian flows through a bottleneck [4]. In the study of granular flows through a silo or a hopper, different strategies have been investigated to avoid or destroy clogs. On account of the sensitivity of the flow to the size of the outlet, enlarging the latter is an intuitive and efficient strategy, but researchers have also studied the effect of vibrating the setup vertically [5, 6] or making the exit oscillate in the horizontal plane [7]. Placing an obstacle in front of the exit was also found to enhance the flow in specific conditions [8, 9]. The latter strategy may also be efficient to facilitate the evacuation of living beings, such as sheep and mice, but the results seem to strongly depend on the position of the obstacle [10] and the geometry of the setup [11], and it has not been demonstrated yet that this method also applies to real pedestrian crowds [12]. In contrast, an aspect that is known to considerably affect pedestrian flow rates is the motivation or eagerness to escape. In a first regime, a crowd that is more eager to escape will effectively evacuate faster [13]. However, beyond a certain level of competitiveness, further increasing the eagerness to egress results in the build-up of higher pressure at the bottleneck, due to physical contacts, which stabilises clogs and thus delays the evacuation [14, 15]. This is the well-known ‘faster-is-slower’ effect, first evidenced in numerical simulations [16] (note that similar effects are observed when increasing the effective gravity in granular hopper flows [4]). Pedestrian flow is thus enhanced by maintaining the crowd’s competitiveness in-between these two regimes, where the exit capacity reaches its peak value. Previous numerical studies of evacuation dynamics have also considered crowds with heterogeneous behaviours [17, 18, 19]. These behaviours are split into two categories: cooperative *vs* non-cooperative‡. Non-cooperative behaviour was found to limit the evacuation efficiency owing to the formation of clogs and jams, but purely cooperative behaviour was also suboptimal, because of the placidity of the agents. The fastest evacuations were achieved by mixed crowds, with an optimal mixture of agents.

In this contribution, we examine a somehow counter-intuitive way to accelerate bottleneck flows of highly competitive crowds and grains prone to clogging: Instead of varying the fraction of cooperators within a crowd, we consider a given homogeneous non-cooperative population and bring in *more* entities. Naïvely, one might expect that the evacuation will then always take longer, because the assembly is larger. However, given that clogs are due to force-bearing contacts at the bottleneck, the injection of entities (pedestrians or grains) that shun contacts may actually limit these clogs. We

‡ The behaviours are called ‘patient’ and ‘impatient’ in [17], while ant-like *vs* human-like strategies are considered in [18].

show that such dilution among contact-averse entities can effectively lead to a quicker evacuation of the original system, even though overall more entities need to escape. We start by exposing some theoretical arguments to support the possible occurrence of this paradoxical effect in Sec. 2. Then, we test it in a cellular automaton model for pedestrian evacuation through a bottleneck in Sec. 3 and a related agent-based model (operating in continuous space) in Sec. 4. Finally, in Sec. 5, we report on granular hopper flow experiments with a mix of magnetic and neutral (non magnetic) disks, in which the magnetic disks play the role of contact-averse entities.

2. Theoretical principle

The theoretical idea underlying the method proposed is easy to grasp. Consider an assembly of N discrete bodies (*e.g.*, pedestrians), n of which are prone to contact (that is, highly competitive in the case of pedestrians) while the remaining $m = N - n$ are not. Let $T(n, m)$ be the total time needed for evacuation through a bottleneck of width w . For a large crowd ($N \gg 1$), in the absence of macroscopic segregation, it is fair to approximate T as

$$T(n, m) \approx \frac{n + m}{J\left(\frac{m}{m+n}\right)},$$

where $J(c_m)$ is the steady-state flow rate for a well-mixed assembly made of a fraction $c_m = \frac{m}{m+n} \in [0, 1]$ of contact-averse bodies.

For crowds, the experimentally observed ‘faster-is-slower’ effect [15] suggests that J may increase with rising c_m near $c_m = 0$ §. Therefore, the minimum evacuation time T at fixed n will not necessarily be reached for $m = 0$. Taking the continuous limit $m \in \mathbb{R}$, one can write

$$\left. \frac{\partial T}{\partial m} \right|_n = \frac{J(c_m) - (1 - c_m) J'(c_m)}{J^2(c_m)}.$$

Any extremum of T reached for $c_m \in (0, 1)$ should obey

$$\begin{aligned} J(c_m) - (1 - c_m) J'(c_m) &= 0. \\ \frac{d}{dc_m} [(1 - c_m) J(c_m)] &= 0 \end{aligned}$$

It follows that the evacuation time of the contact-prone entities will be extremised at $c_m > 0$, *i.e.*, in the presence of other people, if the partial flow rate $(1 - c_m) J(c_m)$ is non-monotonic. For instance, should $J(c_m)$ be strongly reduced due to clogs when $c_m \rightarrow 0$, this condition will be met.

This raises two questions. First, beyond its theoretical possibility, can such reduction of delays at bottlenecks through ‘dilution’ actually occur in *realistic* settings? Secondly, can the proposed mechanism be implemented concretely for practical applications? The following sections address the first question, while the second issue will be touched upon in the conclusion.

§ Videos of the clogs obtained in this limit can be found on the internet, *e.g.* at <https://www.youtube.com/watch?v=OCKO0c6lihU>

To address the problem quantitatively, in addition to the *global* evacuation time T and flow rate J , we will inspect the series of exit times t_i , with $i \in [1, N]$, and compute the time gaps $\tau_i = t_i - t_{i-1}$ between successive egresses, where $i \in [2, N]$, as well as the time gaps $\theta_j = t_{\sigma(j+1)} - t_{\sigma(j)}$ between egresses of contact-prone entities, where $\sigma(j)$ is the egress rank of the j -th such entity and $j \in [2, n]$. Note that the global evacuation time is given by

$$T(n, m) = t_1 + \sum_{i=2}^N \tau_i = t_{\sigma(1)} + \sum_{j=2}^n \theta_j,$$

so, for large n , the mean evacuation time per *contact-prone* (competitive) entity is given by $\langle \theta \rangle \simeq \frac{T(n, m)}{n}$.

3. Cellular automaton model for pedestrian evacuation through a bottleneck

We start by exploring the validity of the idea exposed in the previous section with a cellular automaton developed by some of us [19]. The model was shown to semi-quantitatively reproduce the experimental pedestrian-scale dynamics [15] of pedestrian flows through a narrow door, notably the statistics of time gaps between escapes. Here, we consider a crowd of n highly competitive (impatient) pedestrians and m patient agents, all of whom wish to evacuate through a door of width L_d . Patient and impatient agents are characterised by a propensity to cooperate Π that is uniformly distributed in the intervals $(0.8, 1)$ and $(0, 0.2)$, respectively.

3.1. Brief description of the cellular automaton model

To make the paper self-contained, we briefly recall the main features of the model. Space is discretised into a square lattice with at most one agent per site. At each time step,

- (1) each agent behaves either cooperatively (with probability Π) or competitively (with probability $1 - \Pi$);
- (2) all agents select a target site among the four adjacent sites (von Neumann neighbourhood) plus the current one, with probabilities that depend on the proximity of the sites to the exit and a strong preference for empty sites. The probability to select the current site, i.e., to choose to stay on site, is strongly reduced if the agent behaves competitively.
- (3a) if the target site is occupied, the agent just waits;
- (3b) otherwise, he/she moves to it, unless other agents are competing for it (in which case no one moves).
- (4) Following this first round of motion, some sites have been freshly vacated, which may allow waiting pedestrians to move to their target site. Steps (3) are iterated until all possibilities of motion have been exhausted.

The iterative rule (3) allows the formation of files of moving pedestrians, without voids. Note that agents cannot move more than once during a time step and that rule (3b) corresponds to the limit of strong friction, where any competition for a site is counterproductive.

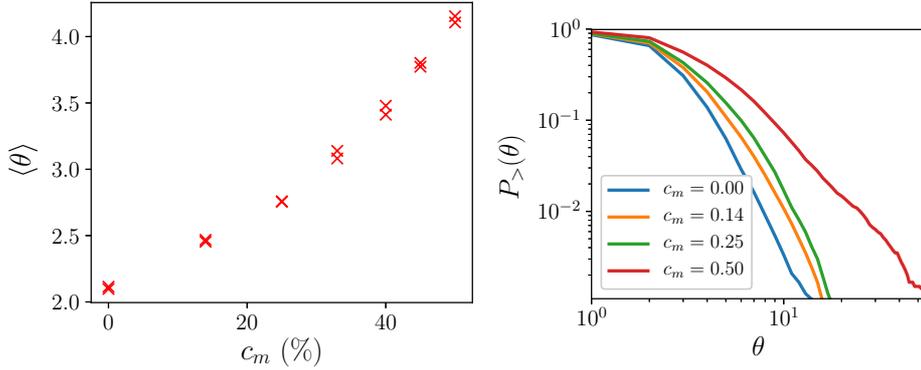


Figure 1. (Colour online) Pedestrian bottleneck flow through a door of size $L_d = 2$ simulated with a cellular automaton. (a) Variation of the mean escape time $\langle \theta \rangle = T/n$ per competitive agent with the fraction of c_m . Each cross corresponds to one realisation of an evacuation of $n = 6,000$ competitive agents. (b) Survival function (CCDF) $P_{>}(\theta)$ of time intervals θ between *competitive* agents for different fractions c_m .

3.2. Results

We consider a crowd of $N = n + m$ agents, where $n = 6,000$ will be kept fixed while m will be varied, and simulate its evacuation through a door of the width of two agents, i.e., $L_d = 2$.

Figure 1(a) shows that the mean evacuation time per competitive agent $\langle \theta \rangle$ increases with m for $L_d = 2$. This implies that the simulated evacuation lasts longer as more patient agents are inserted. Thus, the dilution strategy fails to substantially fluidise the flow. It may be worth mentioning that we had come to a similar conclusion in previously published controlled experiments in which a mixed crowd made of polite and selfish agents evacuated through a narrow door. Indeed, the outflow was found to slow down as the fraction c_m of polite participants in the crowd increased [13]. This observation should be put in parallel with the absence of long-lasting clogs in the evacuation of the purely selfish crowd ($c_m = 0$): For the chosen door width, as a result of the safety prescriptions, the participants did not behave competitively enough to make the evacuation dynamics strongly intermittent.

In our simulations, the delay induced by the addition of m patient agents in the crowd is confirmed by plotting the complementary cumulative distribution function (CCDF) $P_{>}(\theta) = \int_{\theta}^{\infty} p(\theta') d\theta'$, where $p(\theta)$ is the probability density function of time gaps between *competitive* agents. Note that $\langle \theta \rangle$ can be deduced from the CCDF via $\langle \theta \rangle = \int_0^{\infty} P_{>}(\theta') d\theta'$. As can be seen in Fig. 1(b), larger time gaps θ become more frequent as the fraction of patient agents $c_m = \frac{m}{N}$ increases.

In light of the failure of the fluidisation strategy for $L_d = 2$, we consider an even narrower door, $L_d = 1$, which should lead to even more clogging. This narrowing considerably affects the results. The evacuation time $\langle \theta \rangle$ per competitive agent then seems to be reduced as patient agents are introduced in the crowd and reaches its minimal value for a fraction $c_m > 0$ [Fig. 2(a)]. However, despite the large crowd ($N > 6,000$), very large fluctuations occur between realisations under the same

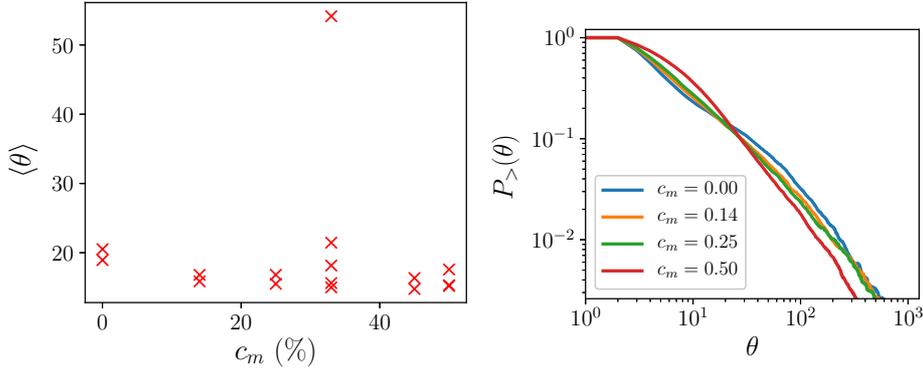


Figure 2. (Colour online) Pedestrian bottleneck flow through a door of size $L_d = 1$ simulated with a cellular automaton. **(a)** Variation of $\langle \theta \rangle$ with c_m . Each cross corresponds to one realisation of an evacuation of $n = 6,000$ competitive agents. **(b)** Survival function $P_{>}(\theta)$ for different fractions c_m .

conditions, typical of clogged flows, which hampers a clear appraisal of the evolution of $\langle \theta \rangle$ with c_m . Here, the seemingly erratic outliers at surprisingly large values of $\langle \theta \rangle$ originate in the fortuitous encounter of extremely competitive agents ($\Pi \rightarrow 0$) at the door. Therefore, we turn to an inspection of the CCDF $P_{>}(\theta)$ in Fig. 2(b). While the addition of patient agents (larger c_m) still increases the overall frequency of moderate to long time gaps θ between competitors ($\theta > 10$), it results in rarer very long clogs (leading to $\theta > 30$), as the doorway is less likely to be blocked by an encounter between extremely competitive agents. Even though such clogs are rare events, they are so long that they significantly reduce the flow rate. The strategy of introduction of patient agents thus succeeds in fluidising the competitors' flow via the alleviation of these long clogs.

4. Agent-based model for pedestrian dynamics

4.1. Brief description of the model

In the previous section, flow enhancement through the incorporation of polite agents was proven possible within a lattice-based model, which had been calibrated for the evacuation of *homogeneous* crowds. To test the robustness of these predictions, we now investigate a second model for pedestrian evacuation dynamics. This model, introduced in [20], operates in discrete time and continuous space, and it also considers the influence of different individual attitudes. Agents are modelled as hard disks of diameter $d = 1$ and continuously make decisions about how to move in a changing environment. When possible, they step into free space but, if little space is available, they adopt a behaviour that is either patient (cooperative strategy) or impatient (competitive strategy). Patient agents will only attempt a move if some distance $\mu = \mu_m$, with $0 < \mu_m < 1$ is available in the desired direction, whereas their impatient counterparts will try to move as soon as they see a distance $\mu = \mu_n$ in this direction, with $0 < \mu_n \ll \mu_m$. We will vary μ_n while keeping $\mu_m = 0.6$ fixed. The desired

direction is drawn randomly within a window of angular width η around the direction towards the exit or, if it is obstructed, one of the two perpendicular directions.

More precisely, at the beginning of the evacuation, N pedestrians are randomly distributed (without overlaps) in a square room of size L , with an exit in the middle of one of the walls. At each time step,

- (1) every agent *considers* a move towards the exit, with a small random angular fluctuation of standard deviation $\eta = \pi/8$ around the direction of the exit;
 - (2a) if the gap distance D_{\parallel} to the nearest obstacle (e.g., another agent) along the desired direction is larger than μ (which depends on the strategy), the agent *attempts* a forward step of size $\min(1, D_{\parallel})$;
 - (2b) otherwise, the agent *considers* a lateral move to the right or to the left, within η of the perpendicular to the exit direction;
 - (2c) if the gap distance D_{\perp} to the nearest obstacle along that direction is larger than μ , the agent *attempts* a lateral step of size $\min(1, D_{\perp})$;
 - (3) Once all individuals have defined their desired moves, conflicts may arise if these moves lead to collisions; they are settled by randomly selecting a winner among the rivals and letting her move.
 - (4) all agents move to their new positions.
- The update dynamics are synchronous.

4.2. Results

Let us first consider a purely competitive population with $N = n = 1000$ agents (while $m = 0$), and on the other hand a purely cooperative population with $N = m = 1000$ ($n = 0$). Figure 3(a) shows that, as expected, the addition of x agents of the same type as the original ones to either of these populations lengthens the evacuation: $T(1000 + x, 0)$ and $T(0, 1000 + x)$ grow monotonically with x . In contrast, when x *cooperative* agents are inserted amidst the *competitive* population, the evacuation time $T(1000, x)$ is found to decrease for small x and reaches a minimum close to $x = m^* \approx 50$. For $x > m^*$, the delay associated with the egress of the cooperators is no longer compensated by the higher flow rate, and the evacuation time increases with x . The effect is better shown in Fig. 3(b), where we plot the evacuation time per competitive agent $\langle \theta \rangle \equiv T(n, m)/n$ as a function of m for fixed $n = 1000$. The effect holds for the three different values of the minimal distance μ_n that we have tested.

Figure 4 shows how the fluidising effect of cooperators depends on the door width L_d . The effect disappears for a door wider than 3 agents, which is rather similar to our findings with the cellular automaton (where the effect disappeared for a door width $L_d = 2$). Conversely, the peak reduction in evacuation time, relative to the situation without cooperators, is enhanced from 1% to 2% (approximately) when the door is reduced from $L_d = 2$ to 1.75. The main reason for this trend is the strong increase in the propensity for clogs when the door narrows down [note, in particular, the related increase for $m = 0$].

Finally, the dependence of $\langle \theta \rangle \simeq T(n, m)/n$ on the number n of competitive agents to be evacuated is studied in Fig. 5. The relative reduction in evacuation time seems to be enhanced for larger crowds (larger n).

All in all, the agent-based model corroborates the results obtained with the cellular automaton.

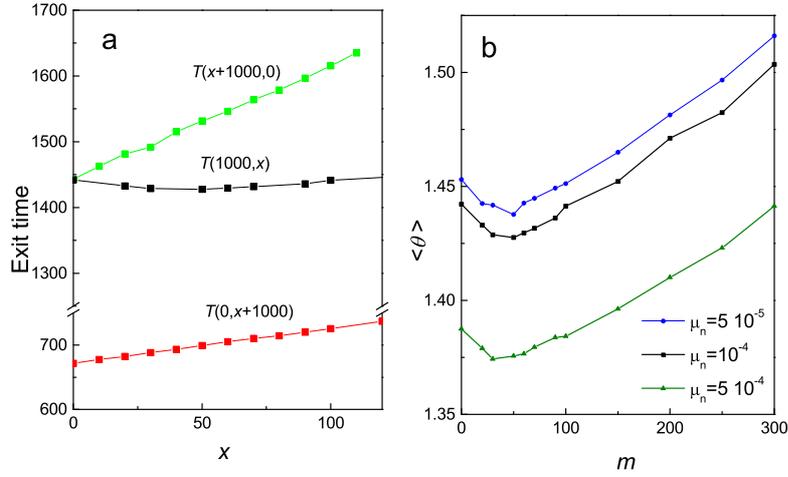


Figure 3. Evacuations of N pedestrians through a door of size $L_d = 2d$ in the agent-based model. (a) Global evacuation times for a purely competitive crowd ($N = n = 1000 + x$), a purely cooperative one ($N = m = 1000 + x$) and a mixed one, ($N = n + m$, $n = 1000$ and $m = x$). Here $\mu_n = 10^{-4}$ and $\mu_m = 0.6$ (b) Evacuation times per competitive agent for a mixed crowd composed of 1,000 competitive agents and m cooperative ones, as a function of m , for distinct minimal distances μ_n .

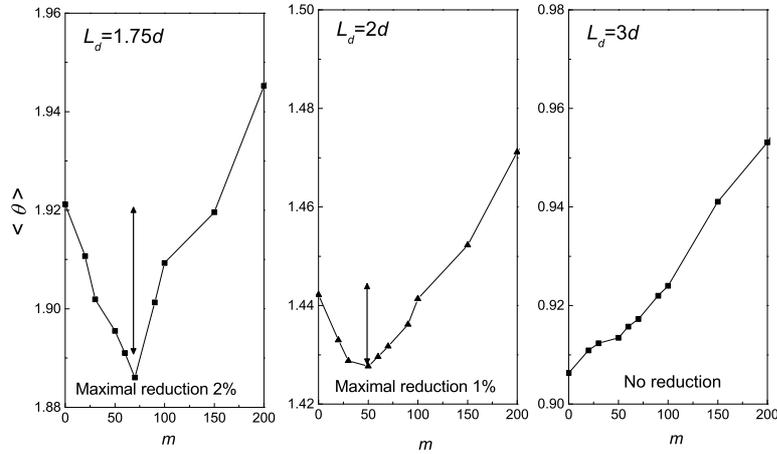


Figure 4. Dependence on the door width L_d of the evacuation times per competitive agent ($\theta \simeq T/n$) for a crowd composed of 1,000 competitive agents ($\mu_n = 10^{-4}$) and m cooperative ones, as a function of m , in the agent-based model.

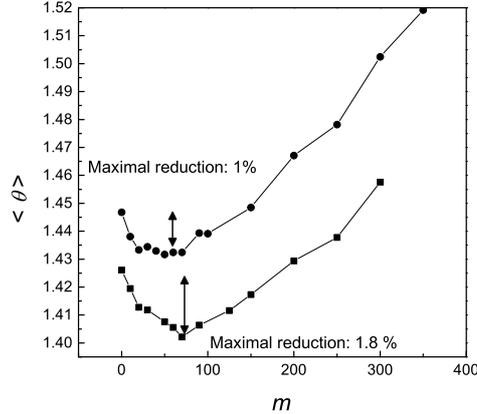


Figure 5. Influence of the number of competitive agents n ($\mu_n = 10^{-4}$) on the evacuation time per competitive agent (θ) $\simeq T/n$, shown as a function of m for $n = 1,000$ (circles) and $n = 1,200$ (squares). The door width is $L_d = 2d$.

5. Hopper flow experiments with magnetic and non-magnetic disks

Having validated the proposed speeding-up method in two distinct models for pedestrian dynamics, we now test it in a granular hopper flow experiment.

We studied the flow of mixed magnetic and neutral (non magnetic) disks through a two dimensional (2D) vibrated hopper, sketched in Fig. 6. The setup was previously used in [21]. The magnetic disks have parallel magnetic moments so that they repel each other and thus act as contact-averse entities; their magnetic interactions become very small (compared to friction) for distances larger than 1 disk diameter and practically negligible beyond 3 or 4 diameters. In contrast, neutral disks interact purely mechanically and have a stronger tendency to clogging.

As a matter of fact, the study of the hopper flow of magnetic and non-magnetic disks is a topic worthy of interest *per se*. Surprisingly, these systems have never been investigated. Some pioneering studies bore on magnetic grains in a silo [22], or the hopper flow of only magnetic disks [23, 24]. In the latter case, however, no vibrations were applied to the setup and permanent clogs were observed.

Beyond the intrinsic relevance of the granular system, it is interesting to recall the analogy that has been pointed out between granular hopper flows and pedestrian evacuations [4, 21]. In fact, in our experiment, magnetic disks mimic patient or polite pedestrians (due to their tendency to avoid frictional contacts), while neutral disks resemble competitive pedestrians. A subtle difference between the granular and pedestrian systems is that magnetic disks will not be repelled by neutral ones. Therefore, in some sense, they are less cooperative than polite pedestrians. Apart from this subtlety, the analogy between pedestrian and granular flows gains practical relevance if one calls to mind the risk associated with conducting pedestrian experiments under conditions that favour large delays at bottlenecks such as those

observed in highly competitive crowds \parallel .

Experimental setup and data analysis

We start by describing the setup in detail. Magnetic disks are about 1 mm-thick and consist of a circular plastic cap of 13 mm of diameter, mounted on a commercial Neodyme magnet of smaller diameter; they weigh $0.55\text{g} \pm 0.01\text{g}$. For the neutral disks, the magnet is replaced by a bronze washer and the total weight is $0.58\text{g} \pm 0.01\text{g}$ ¶.

During the experiments, disks are confined between a tilted chipwood panel (at the bottom) and a transparent plastic sheet. Thin plastic bars between the panel and the sheet define a hopper geometry by delimiting a 2D funnel-like region, with an aperture of width $w = 3$ cm (i.e., 2.3 disk diameters) and an opening angle of 58° (see Fig. 6).

The setup is subjected to (in-plane) vibrations, with an amplitude of about 3-6 mm and a frequency of around 10 Hz. To this end, a motor equipped with an unbalanced helix was tied underneath the panel. The latter was carefully polished and varnished to reduce the friction coefficient and make it as homogeneous as possible. The static friction coefficient between disks and panel was about $\mu_s \simeq 0.32$, which corresponds to an angle of friction $\psi = \tan^{-1}(\mu_s) \simeq 18^\circ$; the plane of the hopper is tilted by an angle roughly equal to (but slightly smaller) than, μ_s . Still, since vibrations tend to suppress friction, sliding is possible. At the beginning of each experiment, n neutral (non-magnetic) disks and m magnetic ones (with typically $N \equiv m + n$ of order 300) are inserted from the top of the funnel, in random order, and the setup is vibrated for ten seconds before the start. The error in the number of inserted disks is generally lower than 2%, i.e., 1-6 disks out of 300.

Experiments are filmed with a 60 Hz camera placed above the aperture ⁺. Egresses of disks through the aperture are detected manually with the help of a computer-aided routine (similar to that used in [21, 13], following [26, 15]), which constructs time frames of escapes by extracting a line of pixels just past the exit from every frame of the video and stitching these lines together (an example of such a time frame is shown in Fig. 6(c)). The analysis gives access to the series of exit times t_i , $i \in [1, N]$, and to the time gaps τ_i and time gaps θ_i between the egresses of neutral disks.

The granular flows observed experimentally display highly intermittent dynamics, as shown in Fig. 7, with broadly distributed time gaps τ . In particular, long halts due to clogs are observed. To avoid excessive delays, we artificially destroy clogs of duration $\tau > 15$ s, by introducing a plastic bar in the setup. This procedure does not affect the distribution of time gaps $p(\tau)$, nor the CCDF $P_{>}(\tau) = \int_{\tau}^{\infty} p(\tau') d\tau'$, for $\tau < 15$ s, but it has an impact on the global flow rate $J = (\int_0^{\infty} P_{>}(\tau) d\tau)^{-1}$. Accordingly, we define the *capped* time gaps between egresses of disks, $\bar{\tau}_i = \min(15 \text{ s}, \tau_i)$, or neutral

\parallel Examples include some emergency evacuations [25] as well as the huge clog formed at the gate of a stadium in the 2013 running of the bulls in Pamplona.

¶ The slightly smaller weight of the magnetic disks may be thought of as an additional sign of cooperativeness, as it results in a slightly smaller sliding speed (on average) than that of the neutral disks, in the absence of collective interactions.

⁺ Videos are provided as Supplemental Material; in particular, they show how magnetic interactions can help to break the clogging arches.

disks only, $\overline{\theta}_j = \min(15 \text{ s}, \theta_j)$. The corresponding *capped* global and neutral flow rates read

$$\overline{J} = \frac{N-1}{\sum_{i=2}^n \overline{\tau}_i} \text{ and } \overline{J}_n = \frac{n-1}{\sum_{j=2}^n \theta_j}. \quad (1)$$

These capped flow rates are unaffected by our manual destructions of clogs and, were there no clogs that last longer than 15 s, they would match their *bona fide* counterparts, i.e., $\overline{J} = J$.

Stationarity of the flow

To examine the stationarity of the flow, we compare the CCDF $P_{>}(\tau)$ computed for subparts of each experiment, namely, for the first, second, and third $N/4$ grains, where $N = n + m$ is the total number of grains. For experiments with $c_m < 0.5$, no significant difference is seen between these moving averages. If one discards the last 15% of grains, the flow can be regarded as stationary, even though the number of grains in the hopper varies during the experiment. Consistently with Beverloo's law for non-vibrated systems [27], the flow rate is indeed independent of the column height (as long as it is a couple of times larger than the width). In contrast, for $c_m = 1$, the flow is smoother (less intermittent); it is strongly non-stationary and monotonically decreases with time, as the height of the granular layer declines. Indeed, (frictional) force chains are absent in this purely magnetic case, and the pressure at the bottom thus continuously decreases during the experiment. In the following, we restrict our attention to situations with $c_m < 0.5$, in which quasi-stationarity is achieved. For the same reason, the last 50-52 disks of each realisation will be discarded.

Analysis of the results

Figure 8(a) presents CCDFs $P_{>}(\tau)$ of all time gaps τ (irrespective of the nature of the disks) for the 3 realisations performed for each fraction of magnetic disks: $c_m = 0$, $c_m = 0.2$, and $c_m = 0.4$. The experimental data are noisy, but what clearly appears above the noise level is that the CCDFs for $c_m = 0.4$ decay faster than those for $c_m = 0.2$, which decay faster than those at $c_m = 0$. The difference appears more clearly if data from realisations under the same conditions are aggregated [Fig. 8(b)].

However, we are not interested in the total flow rate, but only in enhancing the flow of the neutral disks. Therefore, we now discard the magnetic disks and consider the time gaps θ_n between consecutive neutral disks; the CCDFs of the corresponding aggregated data are plotted in Fig. 9(a) with envelopes containing all values of $P_{>}$ found in the different realizations (from the lowest one to the largest one). One can see that the neutral CCDFs decay faster for $c_m = 0.4$ than for $c_m = 0$; results for $c_m = 0.2$ (*not shown*) are virtually indistinguishable from those obtained for $c_m = 0$, within the experimental error bars. Thus, introducing 40% of magnetic grains reduces the time gaps between egresses of the neutral grains and, as a consequence, speeds up the outflow of the latter. This confirms the validity of our fluidisation strategy in granular hopper flows. It is interesting to note that the fraction c_m of magnetic ('polite') particles leading to neutral flow enhancement is larger than what we found

Experiments at constant $N = 300$

c_m	0	0.2	0.4
\overline{J}	0.67	0.86	1.46
\overline{J}_n	0.67	0.70	0.98
$\langle \overline{\tau} \rangle$	1.49	1.16	0.68
$\langle \overline{\theta} \rangle$	1.49	1.42	1.02

Experiments at constant $n = 180$

c_m	0	0.2	0.4
\overline{J}	0.69	0.80	1.46
\overline{J}_n	0.69	0.67	0.98
$\langle \overline{\tau} \rangle$	1.45	1.25	0.68
$\langle \overline{\theta} \rangle$	1.45	1.49	1.02

Table 1. Capped total and neutral flow rates, \overline{J} and \overline{J}_n , for different fractions c_m . For the sake of exhaustiveness, we also report the associated mean (capped) time intervals between egresses of disks ($\langle \overline{\tau} \rangle$) or neutral disks ($\langle \overline{\theta} \rangle$).

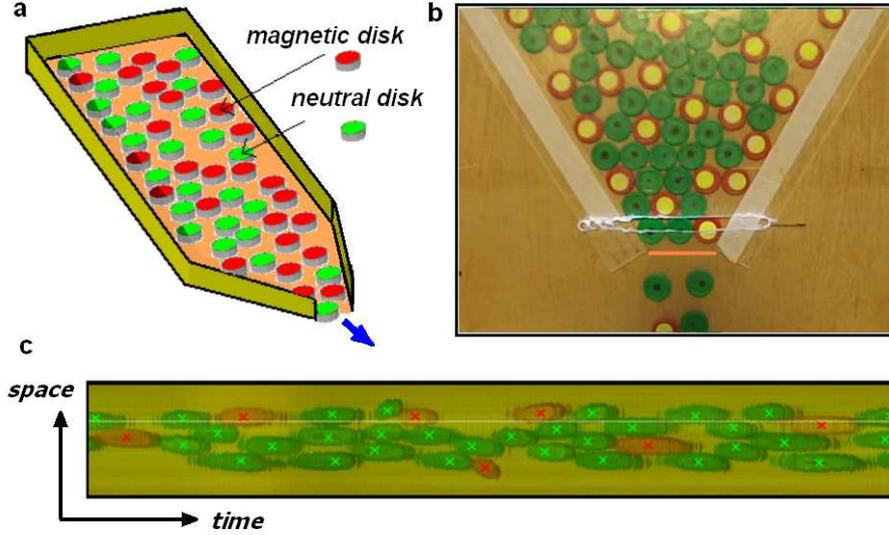


Figure 6. (Color online) Experimental setup and video analysis. (a) Sketch of the setup. (b) Snapshot taken during the discharge of the hopper, close to the aperture. (c) Time frame obtained by stitching lines of pixels extracted from successive video frames (this line is marked in orange in panel b), as described in the main text, and manual tagging of the image.

in our pedestrian crowd models (see previous sections). This observation may be associated with our remark that magnetic disks are ‘less polite’ than their pedestrian counterparts, because they do not spontaneously avoid contact with neutral disks.

These results were obtained by comparing experiments at different fractions c_m in which the same total number of disks, N , is discharged. Similar conclusions are reached if one chooses to compare segments of the experiments corresponding to the discharge of a given number of neutral disks n (while discarding the initial and final transients, i.e., the first 70 grains and the last 50 ones, approximately). The neutral CCDFs thus obtained are plotted in Fig. 9(b).

The capped neutral flow rates \overline{J}_n shown in Table 1 confirm the significant speed-up of the neutral flow $\overline{J}_n(c_m)$ for $c_m = 0.4$, viz., $\overline{J}_n(0.4) > \overline{J}_n(0.2) \approx \overline{J}_n(0)$, both at fixed N and at fixed n .

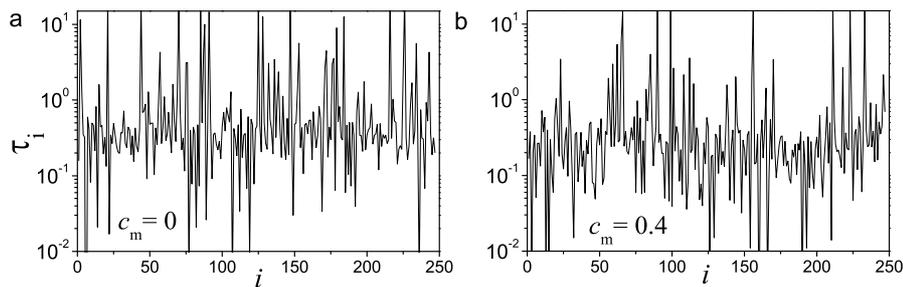


Figure 7. Time series of the time gaps τ_i between successive egresses, labelled by their order of egress i , for (a) $c_m = 0$ and (b) $c_m = 0.4$. Note that the time gaps τ_i which reach the upper bound of the window (15 s) correspond to long-lived clogs that were eventually destroyed manually.

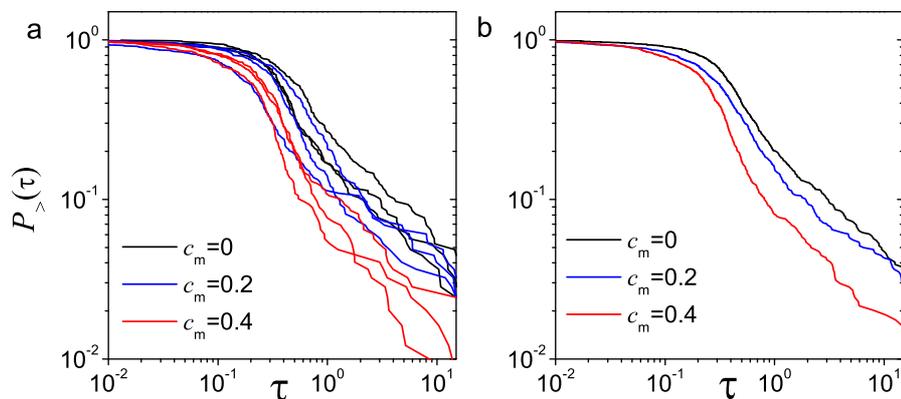


Figure 8. (Colour online) Survival functions of the time gaps τ between successive egresses **(a)** for every independent realisation. **(b)** for the aggregated data, grouped according to the fraction c_m .

6. Summary and outlook

In summary, we have studied a strategy to enhance the efficiency of pedestrian evacuations through a narrow door, prone to clogging, by introducing contact-averse particles in the system. This strategy is somewhat counterintuitive insofar as more agents then need to escape to complete the evacuation of the original system. Still, using two distinct models for the evacuation dynamics of pedestrian crowds, one based on a lattice and the other one operating in continuous space, we found that the positive effect of the reduction of long clogs (caused by the encounter of competitive agents) could prevail over the negative effect due to the increase of the crowd size, when the door is very narrow. Moderate reductions in the evacuation times were then observed. On the other hand, for wider doors, the strategy is not operational: It heavily relies on the propensity to clogging displayed by the original system.

On the basis of the established similarities between competitive pedestrian evacuations and granular hopper flows, we then turned to an experimental test of the proposed strategy. The role of contact-averse agents was played by magnetic disks, which interact repulsively with each other, while the original system was made of neutral

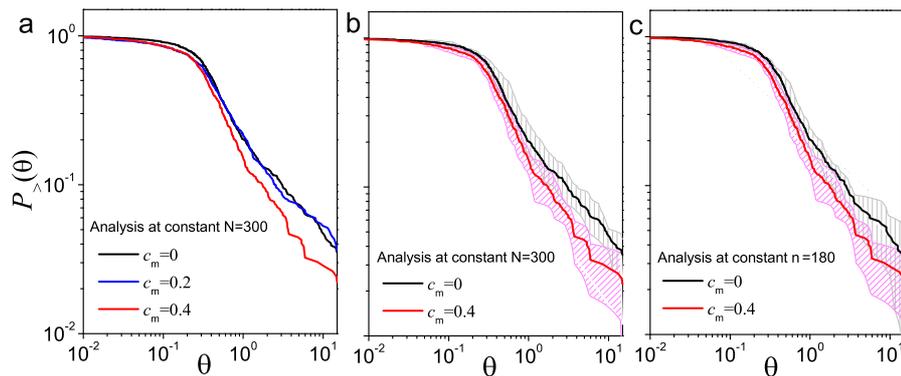


Figure 9. (Colour online) Survival functions of time gaps θ between the egresses of consecutive *neutral* disks. (Data corresponding to realisations under the same conditions have been aggregated.) (a) For the 3 fractions c_m of magnetic disks under study. (b) For $c_m = 0$ and $c_m = 0.4$, with envelopes (hatched regions) stretching from the lowest value of $P_{>}(\theta)$ obtained over the set of realisations to the largest one, for every θ (three realisations for each condition). (c) Same as panel (b), but this time the analysis is performed over the time window associated with the discharge of a fixed number of neutral disks, $n = 180$, instead of a fixed total number of disks, $N = 300$.

disks flowing through a two-dimensional hopper subjected to vibrations. When a fraction of around 40% of magnetic disks was introduced, we observed a faster decay of the distribution of time gaps between consecutive egresses of neutral disks, hinting at an effective enhancement of the flow of the original system. This effect was above the level of experimental noise and robust to variations in the total number of disks.

Having summarised our findings and shown the technical validity of the proposed strategy, we now wonder about their practical relevance. Regarding granular systems, one of the drawbacks of the method is that it cannot directly be transposed to three dimensions, where magnetic interactions would not be only repulsive. But one could contemplate the incorporation of soft frictionless particles, which are much less prone to clogging than their hard frictional counterparts [28], instead of magnetic disks. Turning to crowds, it should be borne in mind that our study is based on simplistic models: Any extrapolation to real crowds, though sensible, is speculative. Besides, in practice it is not possible to introduce polite pedestrians at the last moment, should an emergency occur. Nonetheless, our findings tentatively suggest that the presence of a small number of attendants trained to keep calm during emergencies (such as safety officers), despite making the crowd slightly larger, might be beneficial in terms of evacuation efficiency *even if* these agents do not modify the behaviour of the rest of the attendants.

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