# Beyond the "faster is slower" effect

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The "faster is slower" effect raises when crowded people push each other to escape through an exit during a panic situation. As individuals push harder, a statistical slowing down in the evacuation time can be achieved. The slowing down is caused by the presence of small groups of pedestrians (say, a small human cluster) that temporary block the way out when trying to leave the room. The pressure on the pedestrians belonging to this blocking cluster raises for increasing anxiety levels and/or larger number of individuals trying to leave the room through the same door. Our investigation shows, however, that very high pressures alters the dynamics in the blocking cluster, and thus, changes the statistics of the time delays along the escaping process. It can be acknowledged a reduction in the long lasting delays, while the overall evacuation performance improves. We present results on this novel phenomenon taking place beyond the "faster is slower" regime.

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## I. BACKGROUND

### A. The Social Force Model

### B. Clustering structures

The time delays during an evacuation process are related to clustering people as explained in Refs. [1, 2]. Groups of pedestrians can be defined as the set of individuals that for any member of the group (say, $i$) there exists at least another member belonging to the same group ($j$). in contact with the former. That is, the distance between them $d_{ij}$ is less than the sum of their radius ($d_{ij} < r_i + r_j$). This kind of structure is called a *human cluster*.

From all human clusters appearing during the evacuation process, those that are simultaneously in contact with the walls on both sides of the exit are the ones that possibly *block* the way out. Thus, we are interested in the minimum number of contacting pedestrians belonging to this *blocking cluster* that are able to link both sides of the exit. We call this minimalistic group as a *blocking structure*. Any blocking structure is supposed to work as a barrier for the pedestrians in behind.

## II. NUMERICAL SIMULATIONS

The simulation processes were performed on a 20 m × 20 m room with 225 pedestrians inside. The occupancy density was close to 0.6 individuals/m$^2$ in order to meet current health regulations [3]. The room had a single exit on one side, as shown in Fig. 1. The door was placed in the middle of the side wall to avoid corner effects. Only door widths of 1.2 m and 2.4 m were examined throughout the investigation.

The pedestrians were initially placed in a regular square arrangement with random velocities, resembling a Gaussian distribution with null mean value. All the pedestrians were willing to go to the exit with the same desired velocity $v_d$. No changes in $v_d$ (modulus) was allowed in order to keep the process as simple as possible. The desired velocity pointing direction $\mathbf{e}_d$, however, was updated at every time-step to keep the pedestrians trying to escape from the room.

Two different boundary conditions were examined. The first one included a re-entering mechanism for the outgoing pedestrians. That is, those individuals who were able to leave the room were moved back inside the

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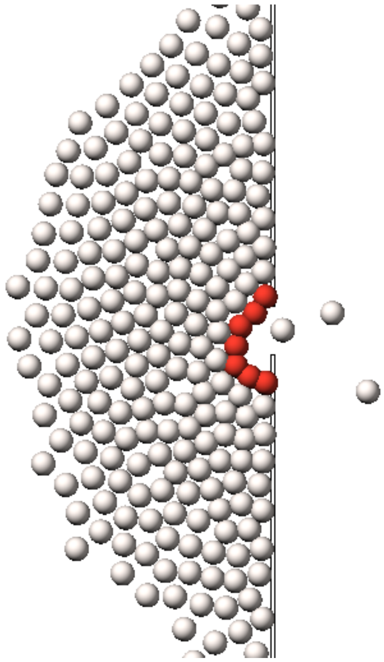

FIG. 1. Snapshot of an evacuation process from a $20\,\mathrm{m} \times 20\,\mathrm{m}$ room, with a single door of 1.2 m width. The blocking structure is identified in red color. The rest of the crowd is represented by white circles. It can be seen three individuals that have already left the room. The desired velosity for the individuals inside the room was $v_d = 6\,\mathrm{m/s}$.

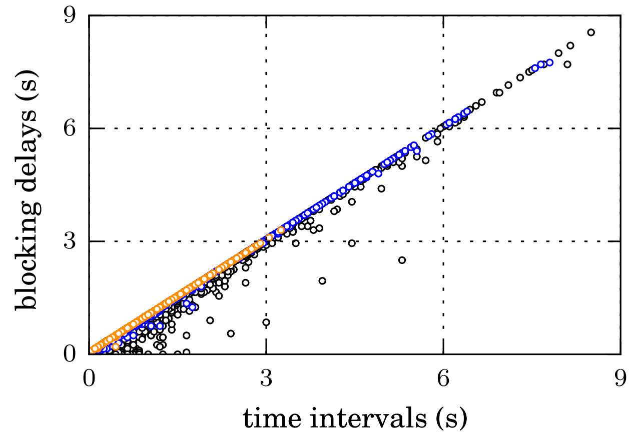


FIG. 2. Blocking delays vs. the time interval between consecutive outgoing pedestrians (colors can be seen in the on-line version only). The data points correspond to a single evacuation process from a 20×20 m roon with a single door of 1.2 m width. A re-entering mechanism was allowed for keeping a regular number of pedestrians inside de room (approximately 225). The measurement period lasted 2000 s. The circles in black correspond to $v_d = 3\,\mathrm{m/s}$. The circles in blue correspond to $v_d = 6\,\mathrm{m/s}$. The circles in orange correspond to $v_d = 17\,\mathrm{m/s}$.

room. They were placed at the very back of the bulk with velocity $v = 0.1\,\mathrm{m/s}$, in order to cause a minimal bulk perturbation. This mechanism was carried out for keeping the crowd size unchanged.

The second boundary condition was the open one. That is, the individuals who left the room were not allowed to enter again. This condition approaches to real situations, and thus, it is useful for comparison purposes.

The simulating process lasted for approximately 2000 s whenever the re-entering mechanism was implemented. If no re-entering was allowed, each evacuation process lasted until 160 individuals left the room. If this condition could not be fulfilled, the process was stopped after 1000 s.

We explored a wide range of anxiety situations, ranging from relaxed evacuation processes ($v_d < 2\,\mathrm{m/s}$) to the extremely axious situation of $v_d = 20\,\mathrm{m/s}$. Whenever the re-entering mechanism was not allowed, at least 30 evacuation processes were run for each desired velocity $v_d$, so as to attain enough statistical information.

The simulations were supported by LAMMPS molecular dynamics simultator with parallel computing capabilities [4]. The time integration algorithm followed the velocity Verlet scheme with a time step of $10^{-4}\,\mathrm{s}$. All the necessary parameters were set to the same values as in previous works (see Refs. [5–7]).

We implemented special modules in C++ for upgrading the LAMMPS capabilities to attain "social force model" simulations. We also checked over the LAMMPS output with previous computations (see Refs. [5, 6]).

Data recording was done at time intervals of $0.05\tau$, that is, at intervals as short as 10% of the perdestrian's relaxation time (see Section I A). The recorded magnitudes were the pedestrian's positions and velocities for each evacuation process. We also recorded the corresponding social force $f_s$ and granular force $f_g$ actuating on each individual.

## III. RESULTS

As a first step, we measured the time intervals between consecutive leaving pedestrians at the door position. We also accounted for the blocking structures close to the door. Fig, 2 shows the relatiionship between the life time of the blocking structures (that is, the time delays taking place due to the blocking structure) and the time intervals for consecutive leaving pedestrians.

As can be seen in Fig, 2, the blocking structures are responsible for the evacuation delays. Only a few data

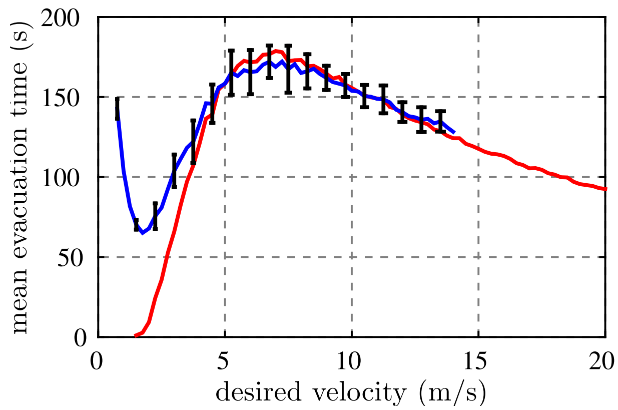


FIG. 3. Evacuation time and total blocking delays as a function of the desired velocity $v_d$ (colors can be seen in the online version only). Data in blue corresponds to the evacuation time. Data in red corresponds to the total blocking delays. Both data sets represent the mean values from 30 evacuation processes. The simulated room was 20×20 m with a single door of 1.2 m width on one side. The number of individuals inside the room was 225 (no re-entering mechanism was allowed).

points can not be explained by the blockings for the desired velocity as low as $v_d = 3\,\mathrm{m/s}$. The higher the desired velocities $v_d$, the tighter the data points to the line of unit slope. The $v_d = 17\,\mathrm{m/s}$ situation, however, does not spread along the whole line, but upon shorter time intervals.

Fig. 3 plots the total blocking time and the evacuation time for a wide range of desired velocities. Notice that both curves come close to each other beyond $v_d = 4\,\mathrm{m/s}$. thus, the blocking delays become relevant above this threshold. We will focus our investigation on this range of desired velocities (*i.e* anxiety levels).

## IV. CONCLUSIONS

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## Appendix A: A simple blocking model

### 1. The dynamic

This Appendix examines in detail a very simple model for the time delays in the blocking cluster. We consider a single moving pedestrian stuck in the blocking cluster, as shown in Fig. 4. The moving pedestrian tries to release from two neighboring individuals that are supposed to remain still during the process. The three pedestrians belong to the same blocking structure, according to the definition given in Section I B. The movement equation for the pedestrian in the middle of Fig. 4a reads

$$m\,\frac{dv}{dt} = f_s + f_d - 2f_g \tag{A1}$$

where $f_s$ represents the force due to other pedestrians pushing from behind, $f_d$ represents the moving pedestrian own desire, and $f_g$ represents the corresponding tangential friction due to contact between the neighboring pedestrians. $m$ and $v$ are the mass and velocity of the moving pedestrian (see caption in Fig. 4), respectively. The expressions for $f_d$ and $f_g$ are as follows

$$\begin{cases} f_d = \dfrac{m}{\tau}(v_d - v) \\[2ex] f_g = \kappa\,(2r-d)\,v \ \text{ if } \ 2r-d>0 \end{cases} \tag{A2}$$

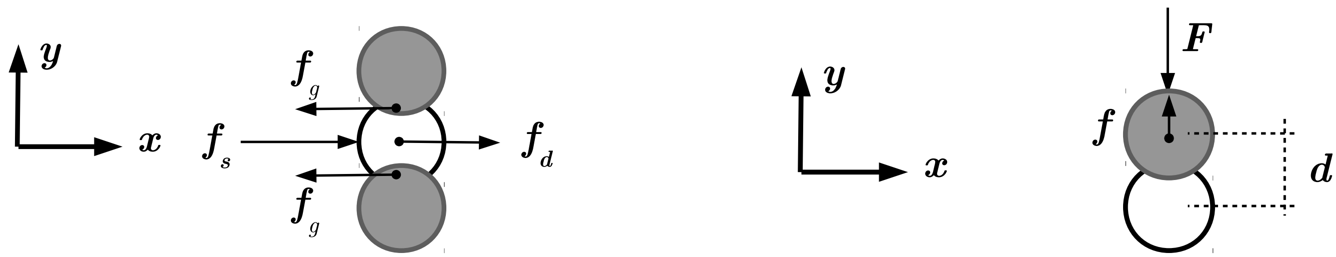
The granular force $f_g$ expressed in (A2) depends only on the velocity $v$ since the other pedestrians are supposed to remain still. The magnitude $2r - d$ is the difference between the pedestrian's diameter $2r$ and the inter-pedestrian distance $d$. It represents the compression between two contacting individuals. The other parameters correspond to usual literature values (see Refs. [1, 2]).

The movement equation (A1) expresses the dynamic for the passing through pedestrian. The characteristic time needed for the pedestrian to reach the stationary state is

$$t_c = \frac{\tau}{1+\dfrac{2\kappa\tau}{m}\,(2r-d)} \tag{A3}$$

and therefore we expect the pedestrian movement to become stationary after this time. It can be easily checked that $t_c$ drops to less than 0.1 s for compression distances as small as 1 mm. This means that the moving pedestrian's velocity will be close to the stationary velocity if the passing through process scales to $t \gg t_c$.

The stationary velocity $v_\infty$ can be obtained from Eq. (A1) and the condition $\dot{v} = 0$. Thus,




(a) force balance for the $x$-axis.

(b) force balance for the $y$-axis.

FIG. 4. Force balance for a moving pedestrian between two still individuals. The moving pedestrian is represented by the white circle, while the gray circles correspond to the still individuals. The movement is in the $+x$ direction. $f_s$ represents the (mean) force due to other pedestrians pushing from behind. $f_d$ is the moving pedestrian's own desire. $f_g$ corresponds to the tangential friction (*i.e.* granular) between the moving pedestrian and his (her) neighbors. $\mathcal{F}$ and $f$ are the forces actuating on the upper (still) pedestrian. $f$ corresponds to the social repulsive force due to the moving pedestrian, while $\mathcal{F}$ represents the counter force for keeping the pedestrian still.

$$v_\infty = t_c \left[\frac{f_s}{m} + \frac{v_d}{\tau}\right] \tag{A4}$$

This is (approximately) the velocity that the moving pedestrian will hold most of the time while trying to get released from the other individuals. Thus, the time delay $t_d$ while passing across the still pedestrians will scale as $v_\infty^{-1}$.

Notice from Eqs. (A3) and (A4) that $v_\infty$ decreases for increasing compression values. Also, an increase in the values of $f_s$ or $v_d$ will cause the corresponding increase in $v_\infty$. The resulting value for $v_\infty$ is a balance between the distance $2r-d$ and the forces $f_s$ or $v_d$. The distance $2r-d$, however, resembles the compression between members of the same blocking cluster, while the force $f_s$ corresponds to individuals out of the blocking cluster.

#### 2. The force balance

Fig. 4b shows a schematic diagram for the forces applied to one of the still individuals. The force $f$ in Fig. 4b represents the repulsive feeling actuating on the still individual due to the moving pedestrian. The force $\mathcal{F}$ is the required counter force necessary to keep the individual still. That is, $\mathcal{F}$ balances the repulsive feeling $f$ for a specific compression distance $2r-d$ (and fix values of $f_s$ and $v_d$). According to Section I A, the relationship between the compression distance and $\mathcal{F}$ (or $f$) is as follows

$$2r - d = B\,\ln(\mathcal{F}/A) \tag{A5}$$

for the known values $A$ and $B$.

The relation (A5) can be applied to the expression (A3) for computing the characteristic time $t_c$. This means that $t_c$ may be controlled by $\mathcal{F}$, and consequently, it controls the stationary velocity $v_\infty$, according to (A4). Actually, the value of $v_\infty$ results from the balance between $\mathcal{F}$ and $f_s$ (and $v_d$).

#### 3. The crowd context

The above relations for a single moving pedestrian sliding between two still individuals should be put in the context of an evacuation process. These three pedestrian may belong to a "blocking structure", as defined in Section I B. The blocking structure may be surrounded by a large number of pedestrians that do not belong to this structure, but continuously pushes the structure towards the exit. Therefore, the forces $f_s$ and $\mathcal{F}$ are similar in nature and somehow represent the pressure actuating on the blocking structure from the surrounding crowd.

The pressure from the crowd depends on the anxiety level of the pedestrians. It has been shown that, at equilibrium, the crowd pressure grows linearly with the desired velocity $v_d$ and the number of individuals pushing from behind (see Ref. [7]). It seems reasonable, as a first approach, that $f_s$ and $\mathcal{F}$ varies as $\beta v_d$ for any fixed coefficient $\beta$.

The forces $f_s$ and $\mathcal{F}$ may be replaced by $\beta v_d$ in Eq. (A4) for the evacuation process scenario. Thus, the stationary velocity $v_\infty$ only depends on the desired velocity of the pedestrians (and the total number of individuals). Fig. 5 shows the behavior of the time delay ($v_\infty^{-1}$) for a wide range of desired velocities $v_d$.

The continuous line in Fig. 5 exhibits a local minimum and a maximum at $v_d = 1\,\mathrm{m/s}$ and $v_d = 3.7\,\mathrm{m/s}$, respectively. The behavioural pattern for $v_d < 1\,\mathrm{m/s}$

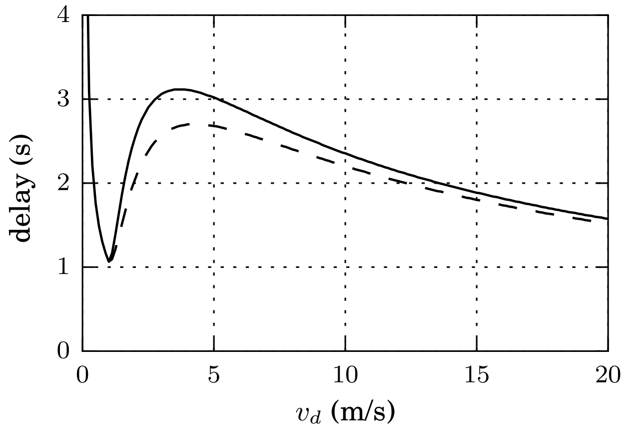



FIG. 5. Time delay ($v_\infty^{-1}$) for a moving individual passing between two still pedestrians, as shown in Fig. 4. The time interval was measured along 10 m across the still pedestrians. The initial velocity was $v_d$. The continuous line corresponds to the measured delay for $\beta v_d = 2000\, v_d$ and $f = A\, \exp[(2r-d)/B]$ (see text for details). The dashed line corresponds to the measured delay for $\beta v_d = 2000\, v_d$ and $f = A\, \exp[(2r-d)/B] + k\,(2r-d)$ (see text for details). The minimum time delay for both lines takes place at $v_d = 1\,\mathrm{m/s}$. The maximum time delay for the continuous line takes place at $v_d = 3.7\,\mathrm{m/s}$, while for the dashed line takes place at $v_d = 4.2\,\mathrm{m/s}$.

corresponds to non-contacting situations (that is, $2r-d<0$). The characteristic time for this regime is $t_c = \tau$, and thus, the time delay decreases for increasing values of $v_d$, according to Eq. (A4).

The regime for $v_d > 1\,\mathrm{m/s}$ corresponds to those situations where the moving pedestrian gets in contact with the two still individuals. Since the compression distance $2r-d$ becomes positive, there is a reduction in the characteristic time $t_c$, according to Eq. (A3). This reduction actually changes the value of the stationary velocity $v_\infty$, as expressed in (A4). It is not immediate whether the $t_c$ reduction increases or decreases the velocity $v_\infty$. A closer inspection of the $v_\infty$ behavioural pattern is required.

The computation of the slope for $v_\infty$ with respect to $v_d$ gives the following expression

$$\frac{dv_\infty}{dv_d} = \left[1 - \frac{2\kappa B}{m}\, t_c\right] \frac{v_\infty}{v_d} \qquad \text{(A6)}$$

This expression shows a change of sign in the slope of $v_\infty$ for increasing values of $v_d$. It can be checked over that the expression enclosed in brackets is negative for small compressions, but as $t_c$ decreases (due to $v_d$ increments), it becomes positive. The vanishing condition for (A6) is

$$B \ln\left(\frac{\beta v_d}{A}\right) = B - \frac{m}{2\kappa\tau} \qquad \text{(A7)}$$

The last term on the right becomes neglectable with respect to $B$ for the current literature values. Thus, the maximum time delay ($v_\infty^{-1}$) takes place close to $v_d = 2.7\, A/\beta$. The corresponding compression distance for this desired velocity is $2r-d=B$.

## 4. Remarks

The above computations show two relevant $v_d$ values: the one where a minimum time delay takes place and the one where the maximum time delay happens. The former corresponds to $v_d = A/\beta$, or equivalently, $2r-d=0$. The latter corresponds to $v_d = 2.7\, A/\beta$ or $2r-d=B$ (approximately).

The forces $f_s$ and $\mathcal{F}$ are similar in nature for the evacuation scenario. Therefore, $\mathcal{F}$ can be replaced by $f_s$ in the Eq. (A5) for the stationary passing through process shown in Fig. 4. The stationary balance for Eq. (A1) then reads

$$A\, e^{(2r-d)/B} + \frac{m v_d}{\tau} = \left[2\,\kappa\,(2r-d) + \frac{m}{\tau}\right] v_\infty \qquad \text{(A8)}$$

Accordingly, the time delay reads

$$v_\infty^{-1} = \frac{1 + \dfrac{2\kappa\tau}{m}\,(2r-d)}{\dfrac{A\tau}{m}\, e^{(2r-d)/B} + v_d} \qquad \text{(A9)}$$

Notice from this expression that small increments of $2r-d$ produce increasing values of the time delay $v_\infty^{-1}$ if $2r-d<B$. But, further compression increments (that is, increments beyond $2r-d>B$) reduce the time delay, since the exponential function grows increasingly fast.

The above observations give a better understanding for the local maximum exhibited in Fig. 5. The positive slope range for $v_\infty^{-1}$ corresponds to small values of $f_s$ (that is, small values for the exponential function in (A9)), while the negative slope range (beyond the local maximum) corresponds to high $f_s$ values.

Although Fig. 5 is in correspondence, the local maximum does not actually take place at $v_d = 2.7\,\mathrm{m/s}$ but at $v_d = 3.7\,\mathrm{m/s}$. This is right since Fig. 5 represents a complete simulation of the moving pedestrian instead of the stationary model for the pedestrian at the crossing point between the still individuals, as expressed in Eq. (A1) and shown in Fig. 4.

Fig. 5 also shows in dashed line the time delay for individuals with non-neglectable elastic compressions (see caption for details). The local maximum also appears but for lower time delay values.

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