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Evacuation under limited visibility

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A multiplicity of situations can trigger off an evacuation of a room under panic conditions. For "normal" (with "normal" meaning absence of obstacles, perfect visibility, etc.) environmental conditions, the "faster is slower" effect dominates the dynamics of this process. It states that as the pedestrians desire to reach the exit increases, the clogging phenomena delays the time to get out of the room. But, environmental conditions are usually far from "normal." In this work, we consider that pedestrians have to find their way out under low visibility conditions. Some of them might switch to a herding-like behavior if they do not remember where the exit was. Others will just trust on their memory. Our investigation handles the herding and memory effects on the evacuation of a single exit room with no obstacles. We also include a section on how signaling devices affect the evacuation process. Unexpectedly, some low visibility situations may enhance the evacuation performance. This can be resumed as a second paradoxical result, since we demonstrated in an earlier investigation that "clever is not always better" G. A. Frank and C. O. Dorso, *Physica A* **390**, 2135 (2011).

Keywords: Evacuation; clogging; visibility; memory; herding.

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1. Introduction

The problem on how to enhance the evacuation process of pedestrians under panic has called the attention of many researchers during the last decades. We can observe a growing interest in building physical models that can handle (at least) the most typical ingredients of a real escaping situation. Remarkable progress has been done on the understanding of the pedestrians behavior in a dangerous situation,[1,2] or the role of obstacles during the evacuation process,[3–5] or the effects of agents that can affect visibility and conscious status of the escaping individuals.[6,7]

Our work focuses on the effects of low visibility during the evacuation of people from a single exit room. But, in order to give a precise description of the environmental conditions considered in our investigation, we will express explicitly our working assumptions as follows:

(a) *No sources of danger will be considered inside the room*
The fatality statistics in building fires point out that more than 50% of the fatalities occur in rooms away from the ignition location.[8] Moreover, excluding fire barriers, the most important cause of fatalities is "not enough time to escape."[8] Therefore, we can assume that the complex clogging processes and time delays during the evacuation take place away from the sources of danger. Our attention will be placed on low visibility environments *with no obstacles or danger points*. Thus, no movement restrictions are included in the analysis, out of the limiting walls of the room.

(b) *There is enough time to escape before pedestrians lose steadiness*
Laboratory experiments and real life data show that smoke and heat not only affect visibility, but provoke lose of steadiness, hypoxia and respiratory tract damage.[9–11] Table 1 resumes some piece of data on the "time available" until environmental conditions become untenable.[12]
The second column in Table 1 represents, in some way, the time available for the pedestrians to escape (see caption in Table 1). Thus, it is the time in which the evacuation mainly depends on the pedestrians dynamic (crowd flow and "queuing," according to Ref. 15) and the room visibility conditions. It is, indeed, the time period where we have been working in the last years and where we will focus this investigation.[3,16,17]

(c) *The visibility distances are consistent with emotional stability*
The actual visibility distance depends on many factors (light sources, individuals visual acuity, etc.), but tests show a fair correlation to the loss of light intensity

Table 1. Mean time until pedestrians lose steadiness and become unable to escape from smoke (second column) for different carbon monoxide (CO) concentrations.[12] Figures in the third column represent the amount of newspapers (cellulose) needed to produce the same CO concentration in a $1000\,\mathrm{m}^3$ room, according to data in Ref. 13. The fourth column is a rough estimation of the visibility distance (lower and upper limits), assuming that smoke conversion factor ϵ is 0.01–0.12, and the mass specific extinction coefficient K_m (extinction coefficient per mass density) is between 4.4 and $7.6\,\mathrm{m}^2/\mathrm{g}$. For details, see Sec. 1 and Ref. 14.

CO (ppm)	Time (min)	m (kg)	d (m)
1600	20	4.70–5.52	0.60–14.5
3200	7.5	9.41–11.03	0.30–7.24
6400	1.5	18.82–22.07	0.15–3.62
12,800	< 1.5	37.65–44.14	0.07–1.81

through a path length L, as stated in Beer–Lambert–Bouguer's law[14]

$$\frac{I}{I_0} = e^{-KL} \tag{1}$$

for I_0 and I meaning the light intensity at the beginning and at the end of the path, respectively. K is defined as the extinction coefficient, measured in m^{-1}. It is also known as the "smoke density."

Experiments on the visibility captured by light reflecting objects (such as human bodies) show that the actual visibility distance is[14]

$$d \simeq \frac{3}{K}. \tag{2}$$

Table 1 resumes the lower and upper limits for the distance d, according to data given in Ref. 14. We can see that the expected visibility distances for fire evacuation ranges from less than 1 m to 14 m.

However, complementary tests on people emotional instability in smoky environments show that the allowable "smoke density" for a safe escape lies between $0.5\,\mathrm{m}^{-1}$ and $3.5\,\mathrm{m}^{-1}$.[18] Both limits correspond to visibility distances between 0.85 m and 6 m, according to Eq. (2).

In Sec. 4, we will show the results for the evacuation of individuals when the visibility distances are 1, 2, 4 and 6 m. For each visibility condition, we analyzed three kinds of pedestrian behavioral patterns:

- The pedestrians were allowed to wander around alone (individualistic behavior).
- The pedestrians were able to follow other pedestrians, like a "herd" (herding-like behavior, as explained in Sec. 2.2).
- The pedestrians were able to "follow the walls" instead of leaving contact after they find one (see Ref. 7 for details).

In Sec. 4.1, we show the corresponding results for the individualistic and the herding-like behaviors, while in Sec. 4.2, we show the results for the "following the wall" behavior.

In Sec. 4.3, we examined the possibility of at least a fraction of the pedestrians keeping memory of the exit location. Specifically, we allowed 50% of the pedestrians to move toward the door, trusting on their own memory. No "following the walls" tendency was included in this section, since it only applies to memoryless individuals.

In Sec. 5, we resume all the conclusions from our research.

2. Background

2.1. *Social force model for perfect visibility*

The "social force model" exploits the idea that human motion depends on the people's own desire to reach a certain destination, as well as other environmental factors.[2,3] The own desire of a pedestrian is modeled by a force called the "desire force" ($\mathbf{f}_d$). The reaction of pedestrians to environmental agents is represented by a "social force" ($\mathbf{f}_s$). Additionally, sliding friction due to contact (i.e. body–body or body-wall contact) is also included in the model as a "granular force" ($\mathbf{f}_g$).

The three kind of forces are described in detail throughout the literature.[2,3] We are going to resume the main expressions for each of them

$$\begin{cases} \mathbf{f}_d^{(i)} = m_i \dfrac{v_d^{(i)}(t)\hat{\mathbf{e}}_d^{(i)}(t) - \mathbf{v}_i(t)}{\tau}, \\ \mathbf{f}_s^{(ij)} = A_i e^{(r_{ij}-d_{ij})/B_i}\mathbf{n}_{ij}, \\ \mathbf{f}_g^{(ij)} = \kappa g(r_{ij} - d_{ij})\Delta v_{ij}\mathbf{t}_{ij}, \end{cases} \tag{3}$$

where the indices i and j stand for two different individuals. d_{ij} is the distance between the central axis of individuals. The distance $r_{ij} = r_i + r_j$ is the sum of the pedestrians radius i and j. The unit vectors $\mathbf{n}_{ij}$ and $\mathbf{t}_{ij}$ are the normal (that is, pointing in the direction $\overrightarrow{ji}$) and tangential directions, respectively. The function $g(\cdot)$ is zero when its argument is negative (that is, $r_{ij} < d_{ij}$) and equals the argument for any other case (see Sec. 2.3 for details). Further details can be found in Refs. 1–3, 16 and 17. Table 2 summarizes the most usual values for the experimental parameters appearing in Eqs. (3).

The desired velocity magnitude v_d in Eq. (3) represents the speed at which the pedestrian is willing to move. For increasing anxiety levels, he (she) will desire to move faster (although he actually is moving at another velocity $\mathbf{v}_i(t)$). The pointing direction is expressed by the unit vector $\hat{\mathbf{e}}_d$. It indicates the target position where the pedestrian is willing to go to. The acceleration time τ is the time needed to reach his (her) desired velocity.

The tendency of the pedestrians to keep some space between each other, or from the walls, is represented by the "social force" $\mathbf{f}_s^{(ij)}$ in Eq. (3). These repulsive feelings become stronger as people get closer to each other (or to the walls). Thus, $\mathbf{f}_s^{(ij)}$ is modeled as an exponentially decaying function (see Eq. (3) and Table 2).

The sliding friction, or "granular force" ($\mathbf{f}_g^{(ij)}$), is assumed to be a linear function of the relative (tangential) velocities of the sliding bodies $\Delta v_{ij} = (\mathbf{v}_j - \mathbf{v}_i) \cdot \mathbf{t}_{ij}$. The function $g(\cdot)$ acts as an "on–off" switch for contacting bodies.

Table 2. Most relevant parameters used for simulating the escaping process from a crowded room.

Parameter	Symbol	Value	Units
Force at $d_{ij} = r_{ij}$	A_i	2000	N
Characteristic length	B_i	0.08	m
Pedestrian mass	m_i	70	kg
Contact distance	r_{ij}	0.6 ± 0.1	m
Acceleration time	τ	0.5	s
Friction coefficient	κ	2.4×10^5	$\mathrm{kg\,m^{-1}s^{-1}}$

The above forces operate on the pedestrians dynamic by changing his (her) actual velocity. The equation of motion for pedestrian i then reads

$$m_i \frac{d\mathbf{v}_i}{dt}(t) = \mathbf{f}_d^{(i)}(t) + \sum_j \mathbf{f}_s^{(ij)}(t) + \sum_j \mathbf{f}_g^{(ij)}(t), \tag{4}$$

where m_i is the mass of pedestrian i. The subscript j represents all other pedestrians (excluding i) and the walls.

2.2. *Social force model for imperfect visibility*

Smoke and other eye-irritating agents may change the pedestrians dynamic. As mentioned above, those pedestrians that are out of the visibility range can no longer point to a target position (i.e. the exit), unless he (she) blindly trust on his (her) memory. But, in those cases, where they cannot figure out the way to leave the room, the "desire force" in the social force model needs to be determined according to some behavioral prescription.

Pedestrians who cannot remember the position of the exit, may try to find its own way out, or, follow the others within their sight. The former is a purely "individualistic" behavior, while the latter is the socio-psychological tendency to do what other people do, and it is sometimes referred to as "mass" behavior or "herding" behavior.[2] Actually, people behave somehow in between these two patterns.

We assume that the modulus of the desired velocity v_d is only affected by the pedestrians anxiety level. Thus, any behavioral pattern may change the desired direction $\hat{\mathbf{e}}_d$, but not the modulus v_d. It has been suggested in Ref. 2 the following general expression for $\hat{\mathbf{e}}_d$

$$\hat{\mathbf{e}}_d(t) = \frac{\alpha(\hat{\mathbf{e}}_1 + \cdots + \hat{\mathbf{e}}_j)_{i\not\subseteq j} + (1-\alpha)\hat{\mathbf{e}}_i}{\|\alpha(\hat{\mathbf{e}}_1 + \cdots + \hat{\mathbf{e}}_j)_{i\not\subseteq j} + (1-\alpha)\hat{\mathbf{e}}_i\|}, \tag{5}$$

where the parameter $0 < \alpha < 0.5$ resembles the degree of the herding-like tendency of the individual. Our "individualistic" pattern corresponds to $\alpha = 0$ in Eq. (5). On the contrary, by setting $\alpha = 0.5$, we get a pointing direction $\hat{\mathbf{e}}_d$ that equally depends on the nearby pedestrians desire and his (her) own desire, representing a completely "herding-like" behavioral pattern. The corresponding expression reads

$$\hat{\mathbf{e}}_h(t) = \frac{\hat{\mathbf{e}}_1 + \cdots + \hat{\mathbf{e}}_i + \cdots + \hat{\mathbf{e}}_j}{\|\hat{\mathbf{e}}_1 + \cdots + \hat{\mathbf{e}}_i + \cdots + \hat{\mathbf{e}}_j\|} = \left(\frac{\langle\hat{\mathbf{e}}_j\rangle}{\|\langle\hat{\mathbf{e}}_j\rangle\|}\right)_{i\subseteq j}, \tag{6}$$

where the subscript $i \subseteq j$ expresses that the pedestrians own velocity is included in Eq. (6). This is for the obvious reason that he (she) will keep moving even when he (she) cannot see other pedestrians from time to time.

Completely "individualistic" ($\alpha = 0$) and completely "herding-like" pedestrians ($\alpha = 0.5$) are the only two situations to be considered in our investigation.

2.3. *Human clusters*

Human clustering arises when pedestrians get in contact between each other. Our definition of human granular cluster C_g is the set of pedestrians that for every member of the cluster (say, i) there exists at least another member of the cluster (j) for whom the following condition is true

$$g(r_{ij} - d_{ij}) > 0, \tag{7}$$

where, as defined in Sec. 2.1, $r_{ij} = r_i + r_j$ is the pedestrian radii sum, d_{ij} is the inter-pedestrian distance and g is a nonvanishing function only for $r_{ij} > d_{ij}$. From all granular clusters, the *blocking clusters* are those that are in contact with enough walls in order to stop the passage of other pedestrians to the exit. Blocking clusters play an important role in the "faster is slower" effect, as shown in Refs. 16 and 17.

3. Numerical Simulations

We studied the evacuation process of 200 pedestrians escaping from a $20\,\text{m} \times 20\,\text{m}$ room with a single exit door. A $40\,\text{m} \times 40\,\text{m}$ room was also examined for some special situations. The door width was always set to $L = 1.2\,\text{m}$, enough to allow up to two pedestrians to escape simultaneously.[16] The occupation density never exceeded $0.5\,\text{persons/m}^2$, as suggested by healthy indoor environmental regulations.[19]

The pedestrians dynamic was computed following the Verlet approximation of Eq. (4) (time-step of $10^{-4}\,\text{s}$). The forces were evaluated from Eqs. (3). The corresponding parameter values were those exhibited in Table 2. However, we introduced some randomness in the pedestrians radius, as occurs in real life situations. We assumed a uniform distribution ($0.3\,\text{m} \pm 0.05\,\text{m}$), as suggested in Ref. 2.

The process started with the pedestrians placed in a homogeneously distributed arrangement throughout the room and each one having a desired velocity pointing to the door, plus a random velocity vector of fixed magnitude $1.5\,\text{m/s}$. At each time step the pedestrians desired direction was updated according to Eq. (5), for the cases $\alpha = 0$ (individualistic) or $\alpha = 0.5$ (herding-like). In those simulations that included memory effects (see Sec. 4.3), the set of pedestrian that remembered the exit location always pointed toward the door.

The individuals reaction to the walls was computed from the social and granular forces expressed in Eqs. (3) (i.e. perfect elastic collisions). But, for those simulations including the alternative "following the wall" behavior, we added the following rule to all the individuals:

"If an individual contacts a wall, his (her) actual velocity direction switches to the wall line direction. In the case that the individual is moving along the wall, as he (she) approaches a corner, he (she) crosses along the shortest possible path to the next wall as soon as he (she) sees it."

All the pedestrians were allowed to follow this new behavior (or rule) until one of the two things happens: the pedestrian loses contact with the wall or he (she) reaches the exit. An individual can lose contact with the wall because other pedestrian pushed him away, or he is a herding-like pedestrian (moving in the same direction of other nearby pedestrians, as described in Sec. 2.2). We implemented three possible behavioral situations when "following the wall":

(a) We assume that all the pedestrians have the tendency to turn in the same direction (indicated, for example, as a big arrow in Fig. 6). That is, they all follow the wall to the right (clockwise in Fig. 6) or to the left. This situation may occur in the presence of signals when all the "exit arrows" point in the same direction.
(b) We assume that all the pedestrians turn toward the shortest possible path (parallel to the wall) in the direction to the exit. This case may occur when emergency signals point to the nearest exit. That is, the "emergency arrows" point right or left depending on its specific place in the room (see the two big arrows in Fig. 6, as an example).
(c) We assume that there is no signaling at all, and individuals who come into contact with the wall (and also when encountering another pedestrian) decide whether to turn right or left by consensus. The consensus is simply asserted by the majority of the pedestrians in contact with the wall and with other pedestrians. For example, if two pedestrians moving to the left encounter three pedestrians moving to the right, the hole cluster of five pedestrians will choose to move to the right.

These three situations were placed either in an environment of individualistic-like or herding-like pedestrians. Full loss of memory was assumed to be compatible with the psychological behavior of "following the wall."

In all the numerical experiments, the evacuation process ran for 1000 s or until 90% of the occupants left the room, whatever occurred first. All positions and velocities were sampled at time intervals of $0.1\,\tau$. No re-entering mechanism was allowed.

The anxiety interval explored in this work covered the range between a relaxed motion ($v_d = 0.5\,\mathrm{m/s}$) and a panicking rush ($v_d = 6\,\mathrm{m/s}$). For any impatience situation (fixed v_d value), 20 evacuation processes were recorded. In order to keep the analysis as simple as possible, we assumed that all the individuals had the same anxiety level in each process.

4. Results

In what follows we show the evacuation results for the following conditions

- Low visibility with full memory loss (without "following the wall") in Sec. 4.1.
- Low visibility including the "following the wall" behavior in Sec. 4.2.
- Low visibility with memory effects (and no "following the wall") in Sec. 4.3.

4.1. *Low visibility effects with full memory loss*

As a first step we measured the mean evacuation time $\langle t \rangle$ (MET) of 20 evacuation processes when no one of the pedestrians remembered the exit position. In Fig. 1, we show a snapshot of a single realization for pedestrians moving like a "herd" (see Sec. 2.2). The color grouping was performed by classifying neighboring pedestrians into sets of almost the same desired direction $\hat{\mathbf{e}}_d$ (tolerance of 10%).

Figures 2(a) and 2(b) exhibit the mean evacuation time of 20 realizations as a function of the desired velocity v_d for herding-like pedestrians. Only the 2 m visibility condition shows a monotonically decreasing behavior for increasing anxiety levels. For the 4 m, 6 m and perfect visibility conditions, the *faster is slower* effect appears (see Fig. 2). These results also hold for individualistic pedestrians (not shown here).

Figure 3 shows the MET as a function of the visibility distance. The steepest increase in the evacuation time occurs along the visibility range between 2 m and 4 m. We will focus on this range for a detailed clogging analysis. For visibility levels between 1 m and 2 m, an increase in the evacuation time can also be captured (see Fig. 3). However, an inspection of the animations shows that no relevant clogging occurs near the door. Instead, the pedestrians remain wandering around, although they may pass very close to the exit. Smoke is so dense that they become almost blind. It seems to be an unlikely scenario, if we realize that individuals have a tendency to "follow the wall" for very low visibilities, as mentioned in Ref. 7. For this

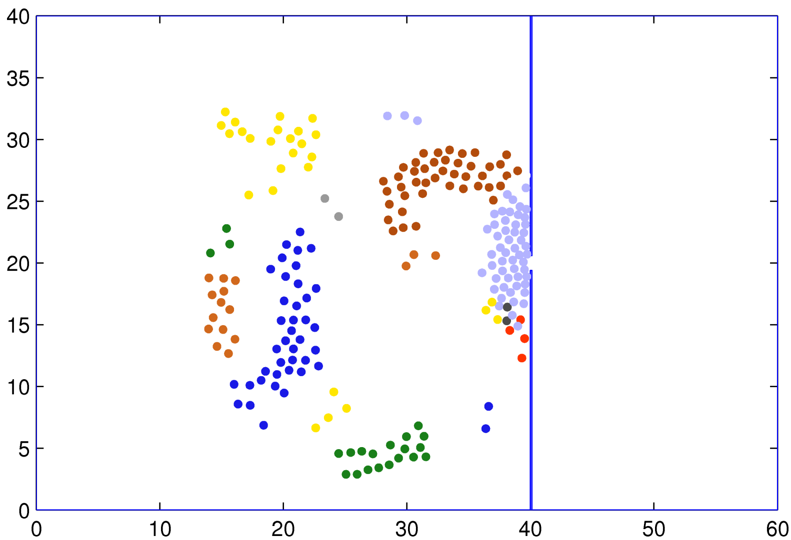


Fig. 1. (Color online) Snapshot of the evacuation process from a $40\,\mathrm{m} \times 40\,\mathrm{m}$ room. Pedestrians are represented by circles. The circles color (on-line version only) means that pedestrians within the same color group are moving like a "herd," pointing to almost the same desired direction $\hat{\mathbf{e}}_d$ within a 10% tolerance and very close to each other (no one remembers the exit position). The desired velocity is $v_d = 4\,\mathrm{m/s}$. The color group close to the door is the blocking cluster. The visibility distance is 2 m, while the door width is $L = 1.2\,\mathrm{m}$.

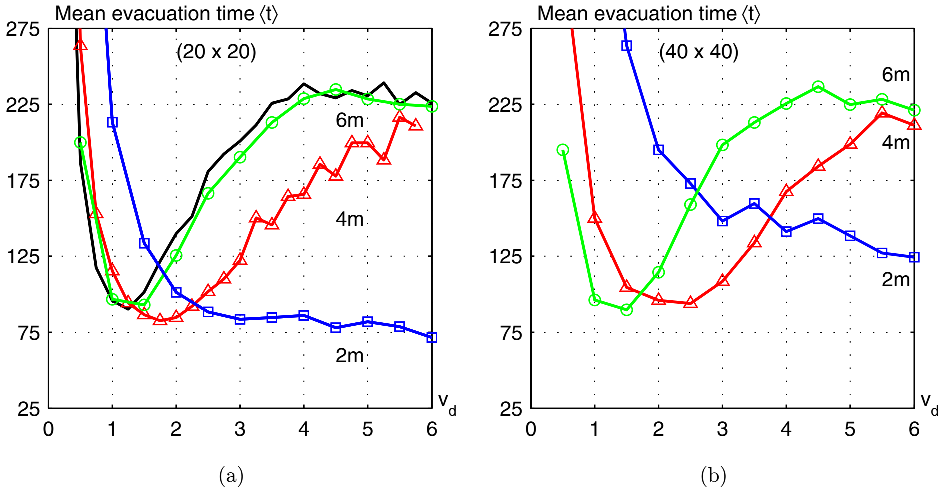


Fig. 2. (Color online) Mean evacuation time $\langle t \rangle$ (in seconds) as a function of the desired velocity v_d (m/s) for the first 160 pedestrians and a door width $L = 1.2\,\text{m}$. (a) The plot on the left represents a room of size $20\,\text{m} \times 20\,\text{m}$. (b) The plot on the right represents a room of size $40\,\text{m} \times 40\,\text{m}$. The blue (squared) data corresponds to a visibility distance of 2 m, the red (triangular) data represents a visibility distance of 4 m and the green (rounded) one corresponds to a visibility distance of 6 m. These three situations assume that the *herding* behavior is present. The mean evacuation time for perfect visibility (and no *herding*) has been included as a black continuous line in plot (a).

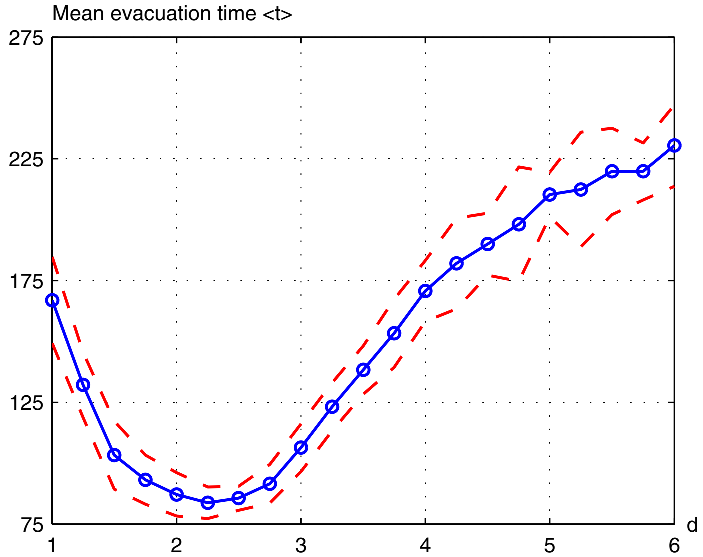


Fig. 3. (Color online) Mean evacuation time $\langle t \rangle$ (in seconds) as a function of the visibility distance (in meters), for the first 160 pedestrians and a door width of $L = 1.2\,\text{m}$. Mean values were computed from 20 realizations. The desired velocity was $v_d = 4\,(\text{m/s})$. The room size was $20\,\text{m} \times 20\,\text{m}$. The blue (circles) represent the mean evacuation time, while the dashed lines correspond to the $\pm\sigma$ (standard deviation) bound. It was assumed a *herding-like* behavior.

reason, we will leave the analysis of this situation to Sec. 4.2, in order to include a change in the pedestrians behavior.

4.1.1. *The blocking dynamics*

In Fig. 4, we show the size of the blocking cluster as a function of time for a single evolution (2 m and 4 m distances, and herding-like pedestrians). It represents the number of individuals belonging to the blocking cluster along time (see Sec. 2.3). Only the time period after the red dashed line is of our interest (see Fig. 4). For the 2 m visibility distance, the landscape exhibits only a few large blocking clusters (approximately eight in Fig. 4(a)). They "live" for a very short time period, while in between, only small blockings or even unclogged periods can be observed. For the 4 m visibility distance, instead, the big blocking clusters are present almost all the time.

An inspection of the movies generated by the processes in Figs. 4(a) and Fig. 4(b), actually confirms the differences between both regimes. Pedestrians can "go" ahead toward the exit pretty easily in the 2 m visibility situation, although they might get stuck (or "stopped") from time to time. This claims to be recognized as a "stop and go" process. On the contrary, the 4 m visibility situation, shows a persistent *bulk* of pedestrians close to the exit, while others wander about the room. Wandering pedestrians arrive to the *bulk* surroundings from time to time. They might join the *bulk* if they see the exit, or they might continue wandering around. Thus, *bulk*

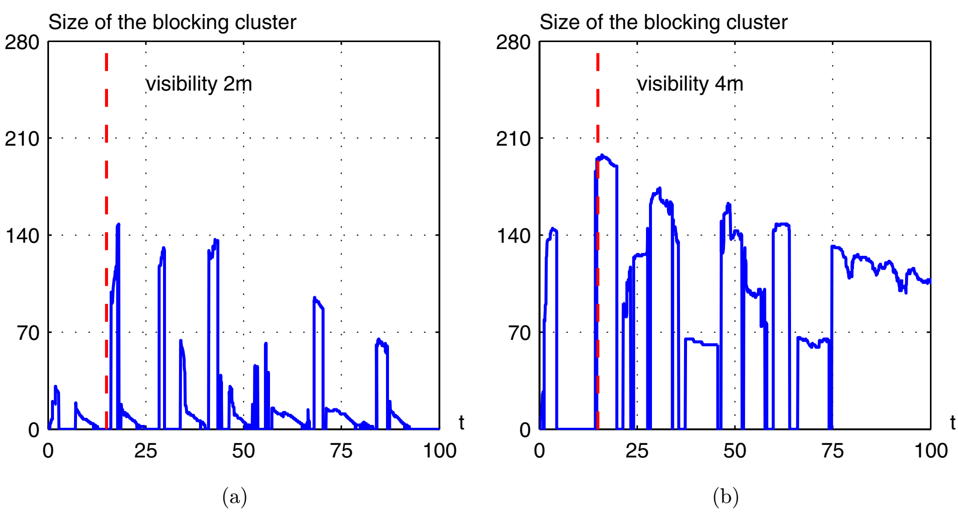


Fig. 4. (Color online) Number of individuals belonging to the blocking cluster along time (in seconds) for a single evacuation process. The red dashed line at $t = 15$ s represents the approximate starting time of the "stop and go" regime (time before that is not of our interest, since it represents the very beginning of the simulation, from uniformly distributed pedestrians to a well established panic situation). (a) On the left plot, the pedestrians visibility is 2 m, while (b) on the right plot, is 4 m. In both cases, the pedestrians follow a herding-like behavioral pattern. The desired velocity (anxiety level) is $v_d = 4$ m/s. The size of the room was $20\,\text{m} \times 20\,\text{m}$, and the door width was $L = 1.2$ m.

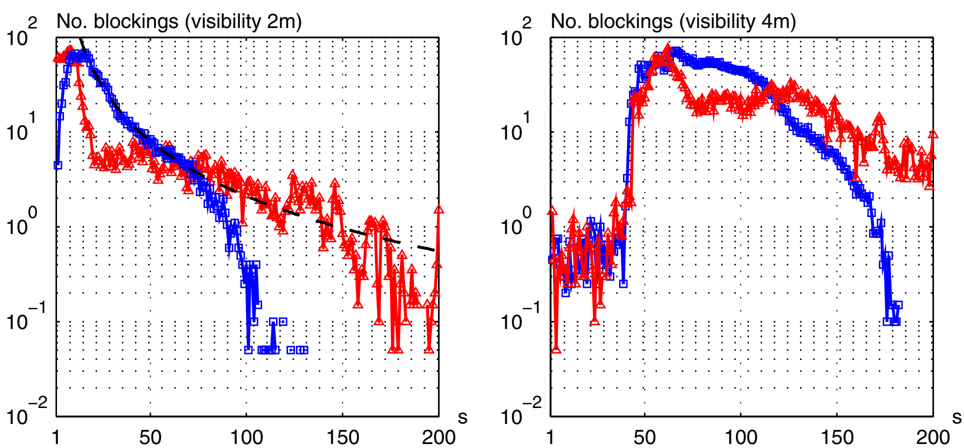
(clogging) dynamics persist as long as wandering pedestrians continue "feeding" the *bulk*.

4.1.2. *The blocking cluster size distribution*

To further explore the effect of the visibility conditions on the blocking formation, we examined the probability of occurrence of these blockings as a function of its size for the 2 m and 4 m visibility situation. Figure 5 shows the corresponding histogram for 20 evacuation processes.

Figure 5(b) (4 m visibility) exhibits a remarkable jump in the number of blocking clusters for those ones exceeding 50 pedestrians. The maximum occurrence is around 60 pedestrians. We can show that this cluster size corresponds to a semi-circular *bulk* of radius close to 4 m as follows.

Let us assume that the *bulk* is compact, and thus, its area density occupied by pedestrians is close to the optimal packing density $\pi/\sqrt{12}$ (corresponding to a hexagonal packing arrangement). The *bulk* may have an effective half circular area $\pi R^2/2$ with effective radius R. If each pedestrian occupies an area πr_i^2 ($r_i \simeq 0.3\,\mathrm{m}$), then the effective (optimal) radius is just about $R \simeq 1.485 \times r_i \times \sqrt{s}$. For the most probable cluster size $s = 60$, the effective radius gives $R \simeq 3.45\,\mathrm{m}$. This is, indeed, pretty close to the visibility distance of 4 m.



(a) (b)

Fig. 5. (Color online) Mean number of blocking clusters of size s (people belonging to the cluster). The vertical axis represents the total number of blocking clusters (as a function of the size s), divided by 20 evacuation processes. The desired velocity v_d was 4 m/s and the room size was 20 m × 20 m. The red (triangular) data corresponds to a herding-like behavior while the blue (squared) data points correspond to an individualistic behavior. The pedestrians were not able to remember the exit location. (a) The plot on the left shows the results for the visibility distance of 2 m. The dashed black line was included to show the matching with a power-law of exponent −1.92. (b) The plot on the right shows the results for the visibility distance of 4 m.

The same analysis can be done for the 6 m visibility situation. For an effective *bulk* radius of 6 m we get a cluster size of $s = 181$. Almost all of the pedestrians might belong to the *bulk*, and thus, this situation does not differentiate much from the perfect visibility one (see Fig. 2).

If we now set the effective radius to $R = 2$ m and repeat the computation for the corresponding cluster size s as above, we find that it should be $s = 20$ pedestrians. Thus, the probability of occurrence of blockings should hold for $s \geq 20$ pedestrians to achieve a *faster is slower* effect, as occurs for the 4 m visibility situation. Instead, Fig. 5(a) exhibits a transition to a power-law regime for the "individualistic" behavior, while the blocking occurrence for "herding-like" pedestrians jumps down above $s \geq 10$. Both downward tendencies for $s \geq 20$ indicate that the *faster is slower* effect is somehow not possible.

4.1.3. *Concluding remarks from the blocking analysis*

From the inspection of Figs. 2–5, we conclude that the visibility conditions work as *blocking cluster size controllers*, and consequently, as *clogging controllers*. For low visibility conditions (say, 2 m), blocking clusters are small, short lived, at low pressure and clogging is not dominant. Thus, no *faster is slower* effect is allowed to happen. But, as the visibility conditions clear up, the visibility area increases, and consequently, more pedestrians are able to join the *bulk* (see Fig. 5). The clogging dynamics dominate the evacuation process, allowing the *faster is slower* effect.

4.2. *Low visibility effects for "following the walls" behavior*

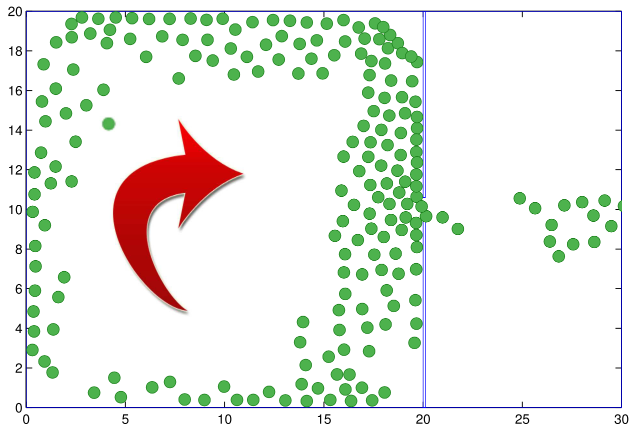
In the previous section, all pedestrians were expected to be repelled by the walls as dictated by the social force model Eq. (3). However, as already mentioned at the end of Sec. 1, pedestrians might suddenly switch to a "following the wall" behavior. We implemented this alternative behavior in three possible ways: (a) all the pedestrians move in the same direction (clockwise in Fig. 6), (b) the pedestrians move toward the shortest path to the exit and (c) they choose a direction by consensus (see Sec. 3 for details).

4.2.1. *Visibility of 1 m and 2 m*

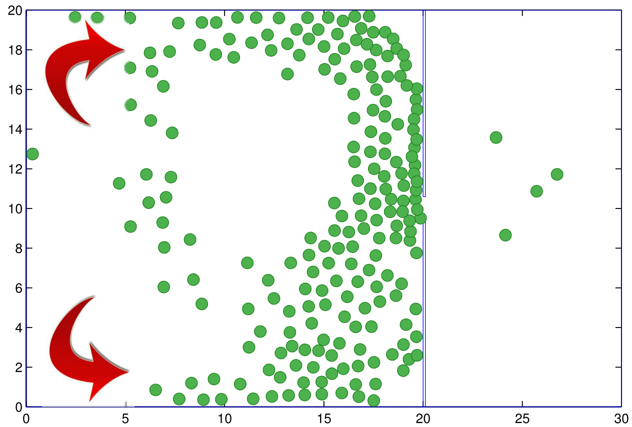
Figure 7 shows the MET for 160 pedestrians in a very heavy smoke situation (visibility of 1 m and 2 m).

For the (a) (clockwise) situation we observe that the *faster is slower* effect never occurs, although a small increase of the MET can appear for herding-like pedestrians with high anxiety levels. We traced this effect on the animations, and found that the "herd" moving around the room "dragged" a few pedestrians that were close to the door inside the room, leaving the exit free. Thus, any *faster is slower* effect can be rejected when "following the wall" in a given direction.

For the (b) (shortest path) situation, the results obtained were completely unexpected. We get a *faster is slower* effect, even though indicating the shortest path



(a)

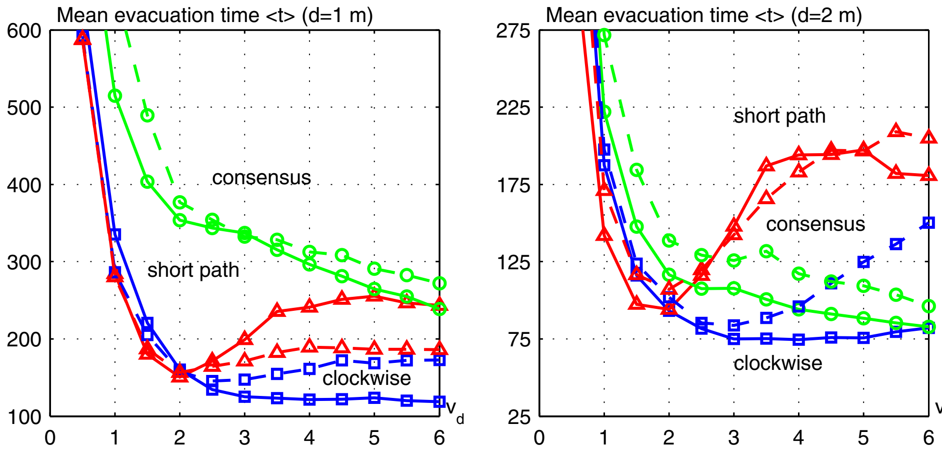


(b)

Fig. 6. (Color online) Snapshots of the evacuation process from a $20\,\mathrm{m} \times 20\,\mathrm{m}$ room. Pedestrians are represented by circles. The desired velocity is $v_d = 4\,\mathrm{m/s}$. The visibility distance is $2\,\mathrm{m}$, while the door width is $L = 1.2\,\mathrm{m}$. In both situations, the pedestrians have a "herding-like" behavior (unless they contact the wall) and neither of them remember the exit position. (a) On top, we see that those individuals who are following the wall move in the clockwise direction. It is assumed that there exists an "emergency arrow" on each wall that points to the right. (b) On the bottom, we can see two behavioral groups. The first group are those pedestrians who follow the walls toward the exit (presuming that the "emergency arrows" point to the shortest path to the exit). The second group, in the middle of the room, are those pedestrians moving like a herd that are still wandering for the exit.

along the wall to the pedestrians was supposed to enhance the evacuation. But, pedestrians following the wall from both sides of the exit, build blocking clusters when they meet at the door, raising up the time delays.

For the (c) (consensus) situation, no *faster is slower* can be observed at all. However, it is clear that the evacuation time is now higher than in the case when the pedestrians were "repelled" by the walls. We found in our movies (not plotted in this



(a)

(b)

Fig. 7. (Color online) Mean evacuation time $\langle t \rangle$ (in seconds) as a function of the desired velocity v_d (m/s) for the first 160 pedestrians and a door width $L = 1.2$ m. The room size was 20 m × 20 m. Continuous lines represent an "individualistic" behavior, while dashed lines represent a "herding-like" behavior. The blue lines (squares) correspond to the situation of the pedestrian turning right (i.e. clockwise or (a) situation). The red lines (triangles) correspond to the situation when the pedestrians take the shortest path to the exit while following the walls (i.e. shortest path or (b) situation). The green lines (circles) correspond to the consensus situation (i.e. (c) situation). On the left, the visibility distance was 1 m. (b) On the right, the visibility distance was 2 m.

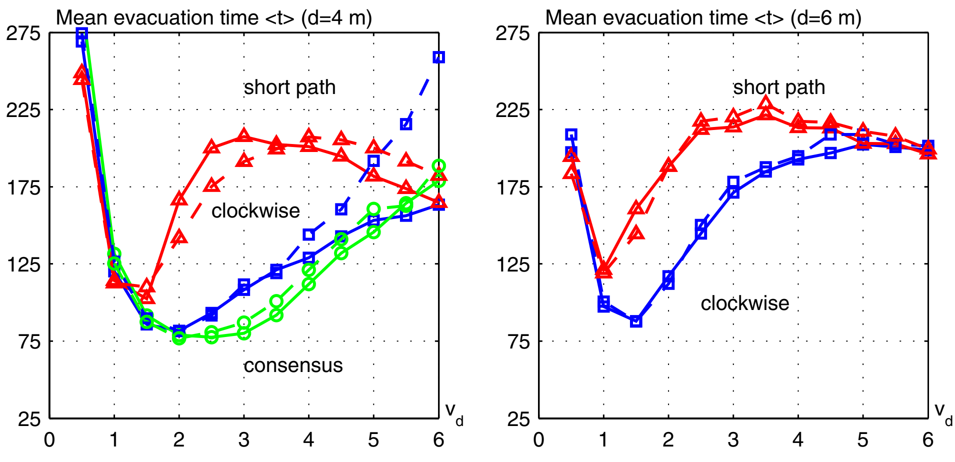
article) some kind of "hesitation" of some small human clusters in contact with the walls. As people get in contact or lose contact with other pedestrians, the consensus decision changes, and thus, the group may go back for some time in the opposite direction. Additionally, we noted that for very low visibilities (say, 1 m visibility) the pedestrians did not see the corners until they are almost there, and thus, they were not able to shorten the path to the next wall. This is another source of time delay.

4.2.2. *Visibility of 4 m and 6 m*

Figure 8 shows the mean evacuation time for visibilities of 4 m and 6 m, respectively.

For the (a) and (c) situations (clockwise and consensus, respectively), the *faster is slower* effect is present. We did not include in Fig. 8 the consensus case for 6 m visibility since the pedestrians were able to shorten their way across the corners, and the effects of consensus could not be seen clearly enough. Despite of that, we can observe no qualitative differences for the MET between "following the wall" or been "repelled" by the wall (compare Figs. 2 and 8).

For the (b) (short path) situation, only the 4 m visibility condition shows a significant (qualitative) change with respect to the results obtained in the previous section (see, for example, Fig. 2). In this case, the *faster is slower* effect is more significant than in Fig. 2 since now the clogging near the door is powered by the pedestrians arrival from the right and left walls.



(a) (b)

Fig. 8. (Color online) Mean evacuation time $\langle t \rangle$ (in seconds) as a function of the desired velocity v_d (m/s) for the first 160 pedestrians and a door width $L = 1.2$ m. The room size was 20 m × 20 m. Continuous lines represent an "individualistic" behavior, while dashed lines represent a "herding-like" behavior. The blue lines (squares) correspond to the situation of the pedestrian turning right (i.e. clockwise or (a) situation). The red lines (triangles) correspond to the situation when the pedestrians take the shortest path to the exit while following the walls (i.e. shortest path or (b) situation). The green lines (circles) correspond to the consensus situation (i.e. (c) situation). On the left, the visibility distance was 4 m. (b) On the right, the visibility distance was 6 m

4.3. *Low visibility with memory effects*

It may happen that some of the pedestrians do remember the exit position and, although they cannot see it, they rush toward this direction. We examined this situation by allowing 50% of the pedestrians, chosen at random, to point $\hat{\mathbf{e}}_d$ toward the door. The evacuation times for visibility distances of 2 m and 4 m are shown in Fig. 9.

The *faster is slower* effect is always present when 50% of the pedestrians remember the exit position, either for the "individualistic" or the "herding-like" behavior (see Fig. 9). If the *faster is slower* effect was already present, as shown for the memoryless pedestrians in Fig. 2(b), adding memory to some of the pedestrians enhances the effect (see Fig. 9(b)).

Our working hypothesis is now that allowing half of the crowd to point to the door causes the same effect as increasing the visibility distance, regardless of the "herding-like" tendency. In order to check this hypothesis, we examined the blocking cluster size for 20 evacuation processes. Figures 10(a) and 10(b) show the results for memoryless pedestrians (on the left) and 50% of remembering pedestrians (on the right).

When memory is added to 50% of the pedestrians, we observe that the blocking cluster becomes bigger with respect to the memoryless situation. More than 100 individuals belong to the blocking cluster, regardless of the visibility condition (2 m or 4 m). Thus, the visibility distance no longer regulates the *bulk* size.

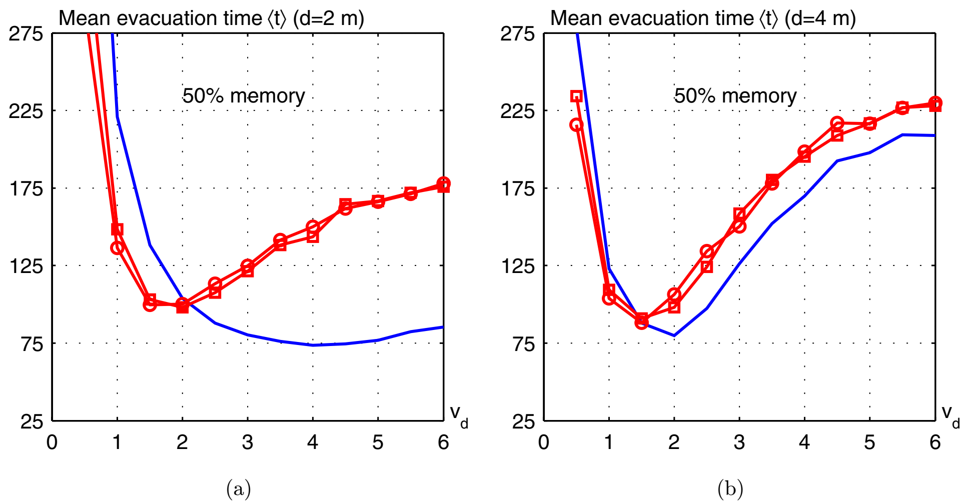


Fig. 9. (Color online) Mean evacuation time $\langle t \rangle$ (in seconds) as a function of the desired velocity v_d (m/s) for the first 160 pedestrians and a door width $L = 1.2$ m. The room size was $20\,\mathrm{m} \times 20\,\mathrm{m}$. Circles represent a "herding-like" behavior, while squares represent an "individualistic" behavior. The red lines correspond to the evacuation when 50% of the pedestrians remember where the exit was. The blue lines correspond to "individualistic" memoryless pedestrians (included for comparison reasons). (a) On the left, the visibility distance was 2 m. (b) On the right, the visibility distance was 4 m.

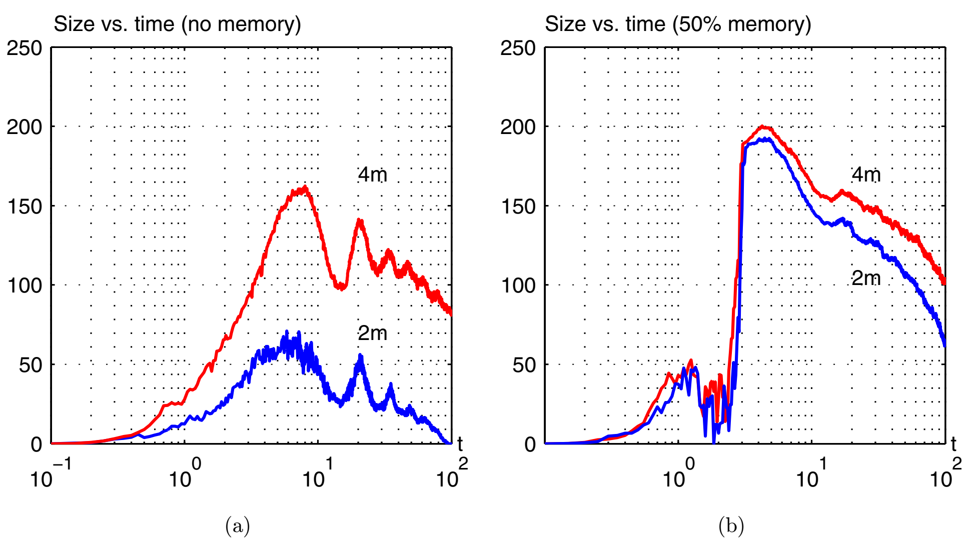


Fig. 10. (Color online) Mean size of the blocking cluster versus time (in seconds). The mean size was computed over 20 evacuation processes (room size of $20\,\mathrm{m} \times 20\,\mathrm{m}$). The pedestrians desired velocity v_d was 4 m/s, moving individualistically. (a) The left plot corresponds to pedestrians with no memory on the exit location. (b) The plot on the right shows the same results but for 50% of the pedestrians remembering the exit location. On both plots, the visibility distance was 2 m for the data in blue, and 4 m for the data in red.

Recalling our computation of the effective radius $R \simeq 1.485 \times r_i \times \sqrt{s}$ from Sec. 4.1.2, we realize that more than 100 individuals will ensure a compact *bulk* of effective radius $R > 4.45$ m. Thus, for the 50% remembering simulation, the blocking cluster will be bigger than the visibility distance almost all the time (until enough pedestrians leave the room).

On the contrary, suppose that the effective radius resembles the visibility distance for the 2 m condition. The corresponding size of the blocking cluster would be around 20 pedestrians. But, since 50% of them (100 pedestrians in our simulation) wish to go to the door, this effective radius will not be tenable.

5. Conclusions

We modeled three pedestrian behavioral patterns in the context of the "social force model" under low visibility conditions: individualistic, herding-like and the "following the wall" pattern. We also allowed half of the pedestrians to remember the exit location.

We first analyzed the evacuation process for memoryless individuals in an environment of 2 m, 4 m and 6 m visibility distances. We found that the 2 m visibility situation has the best evacuation performance, since most blocking clusters become suppressed by this short visibility distance. This is a paradoxical result because heavy smoke is not expected to be an evacuation enhancer.

The 4 m and 6 m visibility conditions allowed larger blocking clusters, since now pedestrians from larger distances are able to reach the exit. The whole clogging dynamics resemble that of the perfect visibility situation (in the context of the "social force model").

These results showed no difference in the evacuation performance if the pedestrians were more "individualistic" or, on the contrary, they moved like a "herd." We found that the way the pedestrians "arrived" to the exit surroundings was really not important. Only the visibility condition was able to control the clogging dynamics, and consequently, the existence of long lasting delays.

As a second step in the investigation, we allowed the pedestrians to "follow the walls" instead of "bouncing the walls." We worked out three possibilities (see Sec. 4.2): (a) all the pedestrians turn right (clockwise) as they contact the walls, or (b) the pedestrians took the shortest direction to the exit, or (c) they move to the right or to the left only by consensus between nearby pedestrians. Four visibility conditions were examined: 1, 2, 4 and 6 m.

We found that, under the tested conditions, "following the wall" in a single direction (i.e. (a), clockwise) turned to be the best strategy, except for "herding-like" pedestrians in a 2 m visibility environment. In this case, we found that the herd "dragged inside the room" the few pedestrians that were about to leave, causing delays in the evacuation process.

The (b) strategy (i.e. following the walls toward the shortest distance to the exit) was the worst one. We observed that the clogging dynamics became powered by the pedestrians who "follow the walls" on both sides of the exit. Pedestrians push from both sides of the door, increasing pressure near the exit. Consequently, the *faster is slower* effect appeared.

The (c) strategy (i.e. consensus) showed the same qualitative evacuation performance as if "bouncing the walls".

When 50% of the pedestrians were allowed to remember the exit location, clogging immediately arose as the dominant effect. The situation resembled the nearly perfect visibility scenario due to the increase in the blocking cluster size. In the end, we realized that memory effects have very similar consequences as increasing the visibility distance.

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