

# Room evacuation through two contiguous exits

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## Abstract

Current regulations demand that at least two exits should be available for a safe evacuation during a panic situation. The second exit is expected to reduce the overall clogging, and consequently, improve the evacuation time. However, rooms having contiguous doors not always reduce the leaving time as expected. We investigated the relation between the door's separation and the evacuation performance. We found that there exists a separation distance range that does not really improve the evacuation time, or it can even worsen the process performance. To our knowledge, no attention has been given to this issue in the literature. This work reports how the pedestrian's dynamics differ when the separation distance between two exit doors changes and how this affects the overall performance.

*Keywords:*

Panic evacuation, Social force model, Clogging delay

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## 1. Introduction

The practice of providing two doors for emergency evacuation can be traced back to the last Qing dynasty in China (1644-1911 AD). A mandatory regulation established that large buildings had to provide two fire exits [1]. This kind of regulations upgraded to current standard codes with detailed specifications on the exits position, widths and separations [2, 3].

8 Current regulations claim that the minimum door width should be 0.813 m  
9 while the maximum door-leaf should not exceed 1.219 m [3, 4]. If more than  
10 two doors are required, the distance between two of them must be at least  
11 one-half or one-third of the room diagonal distance. But, no special require-  
12 ments apply to the rest of the doors.

13  
14 The rulings leave some space for placing the extra openings (*i.e.* those  
15 above two exits) at an arbitrary separation distance. Thus, it is possible to  
16 place a couple of doors on the same side of the room at any distance. The  
17 special case of two contiguous doors has been examined throughout the lit-  
18 erature [5, 6, 7, 8].

19  
20 Kirchner and Schadschneider studied the pedestrians evacuation process  
21 through two contiguous doors using a cellular automaton model [5]. The  
22 agents were able to leave the room under increasing panic situations for be-  
23 havioural patterns varying from individualistic pedestrians to strongly cou-  
24 pled pedestrians moving like a *herd*. The evacuation time was found to be  
25 independent of the separation distance between doors for the individualistic  
26 pedestrians in a panic situation. But if the pedestrians were allowed to move  
27 like a herd, an increasing evacuation time for small separation lengths (less  
28 than 10 individuals size) was reported.

29  
30 The above conclusions are not in complete agreement with the investi-  
31 gation acknowledged in Ref. [6]. The authors assert that the total number  
32 of pedestrians leaving the room per unit time slows-down for separation dis-  
33 tances (between doors) smaller than four door widths [6]. This slow-down  
34 is identified as a disruptive interference effect due to pedestrians crossing in  
35 each other's path. For the particular case analyzed in this work, the threshold  
36 of four door widths ( $4d_w$ ) corresponds to the distance separation necessary  
37 to distinguish two independent groups of pedestrians, each one surrounding  
38 the nearest door.

39  
40 Researchers called the attention on the fact that no matter how sepa-  
41 rated the two contiguous doors are placed, the overall performance does not  
42 improve twice with respect to a single exit (of the same total width). This  
43 effect is attributed to some sort of pedestrian interference [6].

44  
45 Although the above results were obtained for very narrow doors (*i.e.* sin-

gle individual width), further investigation showed that they also apply to doors allowing two simultaneous leaving pedestrians. However, this does not hold for a room with a single door [7]. In this case, it is true that the mean flux of evacuating people increases with an increasing door width, but the ratio flux per door width decreases [9].

It was observed in Ref. [5, 7] that the two contiguous doors should not be placed near the wall corners, since the side walls affect negatively the evacuation efficiency. No further explanation was given on this phenomenon, although the authors concluded this may cause a worsening in the evacuation performance for large separation distances between doors.

A recent investigation (Ref. [8]) on evacuation processes of cellular automata suggests that five distances should be taken into account when studying the evacuation performance: the total width of the openings (that is, adding the widths of each door), the doors separation distance, the width difference between the two doors, and the distance to the nearest corner.

From the results shown in Ref. [8], the evacuation time depends on the total width of the openings (if both doors have the same width). But, for a fixed total width of the opening, it appears that the optimal location of the exits depends on the doors separation distance.

Our investigation focuses on symmetric configurations with equally sized doors. At variance to the above mentioned literature, we examine the evacuation dynamics by means of the Social Force Model (SFM). An overview of this model can be found in Section 2.

In Section 3 we describe the specific settings for the evacuation processes. The measurement conditions for the simulations can also be found there.

In Sections 4.1 to 4.2.2 the single door configuration is revisited. Its purpose is to make easier the understanding of the two-doors configuration for very small separation distances  $d_g$ .

In Section 4.3 we examine the case of two separated doors. We explore the effect of increasing the separation distance  $d_g$  until the clogging areas close to each door become almost independent.

Section 5 resumes the pedestrians behavioural patterns, and its consequences on the evacuation performance, for the different door separation scenarios.

## 2. Background

### 2.1. The Social Force Model

The “social force model” (SFM) deals with the pedestrians behavioural pattern in a crowded environment. The basic model states that the pedestrians motion is controlled by three kind of forces: the “desire force”, the “social force” and the “granular force”. The three are very different in nature, but enter into an equation of motion as follows

$$m_i \frac{d\mathbf{v}^{(i)}}{dt}(t) = \mathbf{f}_d^{(i)}(t) + \sum_j \mathbf{f}_s^{(ij)}(t) + \sum_j \mathbf{f}_g^{(ij)}(t) \quad (1)$$

where  $m_i$  is the mass of the pedestrian  $i$ , and  $\mathbf{v}_i$  is its corresponding velocity. The subscript  $j$  represents all other pedestrians (excluding  $i$ ) and the walls.  $\mathbf{f}_d$ ,  $\mathbf{f}_s$  and  $\mathbf{f}_g$  are the desire force, the social force and the granular force, respectively. See Refs. [10, 9, 11, 12, 13] for details.

The desire force reflects the pedestrian’s own desire to go to a specific place [10]. He (she) needs to accelerate (decelerate) from his (her) current velocity, in order to achieve his (her) own willings. As he (she) reaches the velocity that makes him (her) feel comfortable, no further acceleration (deceleration) is required. This velocity is the “desired velocity” of the pedestrian  $\mathbf{v}_d(t)$ . The expression for  $\mathbf{f}_d$  in Eq. (2) handles this issue.

$$\begin{cases} \mathbf{f}_d^{(i)}(t) &= m_i \frac{\mathbf{v}_d^{(i)}(t) - \mathbf{v}_i(t)}{\tau} \\ \mathbf{f}_s^{(ij)} &= A_i e^{(r_{ij}-d_{ij})/B_i} \mathbf{n}_{ij} \\ \mathbf{f}_g^{(ij)} &= \kappa g(r_{ij} - d_{ij}) \Delta \mathbf{v}_{ij} \cdot \mathbf{t}_{ij} \end{cases} \quad (2)$$

109  $\tau$  means a relaxation time. Further details on each parameter can be  
 110 found in Refs. [10, 9, 11, 12, 13].

111

112 Notice that the desired velocity  $\mathbf{v}_d$  has magnitude  $v_d$  and points to the  
 113 desired place at the direction  $\hat{\mathbf{e}}_d$ . Thus,  $v_d$  represents his (her) state of anxi-  
 114 ety, while  $\hat{\mathbf{e}}_d$  indicates the place where he (she) is willing to go. We assume,  
 115 for simplicity, that  $v_d$  remains constant during an evacuation process, but  $\hat{\mathbf{e}}_d$   
 116 changes according to the current position of the pedestrian.

117

118 The social force  $\mathbf{f}_s$  corresponds to the tendency of each individual to keep  
 119 some space between him and other pedestrians, or, between him and the  
 120 walls [14]. The  $\mathbf{f}_s$  expressed in Eq. (2) depends on the inter-pedestrian dis-  
 121 tance  $d_{ij}$ . The magnitude  $r_{ij} = r_i + r_j$  is the sum of the pedestrian's radius,  
 122 while  $A_i$  and  $B_i$  are two fixed parameters ( $r_j = 0$  for the interaction with the  
 123 wall). Thus,  $\mathbf{f}_s$  is a repulsive monotonic force that resembles the pedestrian  
 124 feelings for preserving his (her) *private sphere* [10, 14].

125

126 The granular force  $\mathbf{f}_g$  appearing in Eq. (1) represents the sliding friction  
 127 between contacting people (or between people and walls). Its expression can  
 128 be seen also in Eq. (2). It is assumed to be a linear function of the relative  
 129 (tangential) velocities  $\Delta\mathbf{v}_{ij} \cdot \mathbf{t}_{ij}$  of the contacting individuals. The function  
 130  $g(r_{ij} - d_{ij})$  returns the argument value if  $r_{ij} > d_{ij}$ , while  $\kappa$  is a fixed param-  
 131 eter (see Refs. [10, 9, 11, 12, 13]).

132

133 One of the most remarkable phenomena attained by this model is the  
 134 “faster is slower” effect. It states that the higher the desired velocity, the  
 135 higher the evacuation time [10]. Experimental data has achieved this effect,  
 136 while the pressure of the bulk raises as a relevant magnitude in the worsening  
 137 of the evacuation time. Experiments also show that the bulk pressure is a  
 138 function of the number of people and the maximum group speed. The latter  
 139 is associated to the desired velocity in the Social Force Model (see Ref. [15]).

## 140 2.2. Clustering structures

141 The time delays during an evacuation process are related to clustering  
 142 people as explained in Refs. [9, 11]. Groups of pedestrians can be defined as  
 143 the set of individuals that for any member of the group (say,  $i$ ) there exists  
 144 at least another member belonging to the same group ( $j$ ) in contact with the  
 145 former. That is,

$$i \in \mathcal{G} \Leftrightarrow \exists j \in \mathcal{G} / d_{ij} < r_i + r_j \quad (3)$$

where  $\mathcal{G}$  corresponds to any set of individuals. 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.

### 2.3. The local pressure on the pedestrians

The pressure on a single pedestrian (say,  $i$ ) is defined as [10]

$$P_i = \frac{1}{2\pi r_i} \sum_{j=1}^{N-1} \mathbf{f}_s^{(ij)} \cdot \mathbf{n}_{ij} \quad (4)$$

$\mathbf{f}_s^{(ij)}$  are the forces acting on the individual  $i$  due to the other individuals. Recall that these forces point from any individual  $j$  to the individual  $i$ , and thus, the products  $\mathbf{f}_s^{(ij)} \cdot \mathbf{n}_{ij}$  are always positive.

Notice that Eq. (4) holds either if the pedestrians are in contact or not. The feelings for preserving the *private sphere* actuate as a “social pressure” that makes possible for the individuals to change their behavioural pattern when they come too close to each other or to the walls.

A more formal definition for the “social pressure” is given in Appendix A. We show that the definition (4) is in accordance with the one in Appendix A, if the momentum  $p_i$  of the individuals become neglectable. Thus, the expression (4) is suitable for clogging situations where the pedestrians move slowly.

We further applied the formal definition for the “social pressure” to a simple example in Appendix B. We also checked that both definitions give

176 the same results all through Section 4.

177

### 178 **3. Numerical simulations**

#### 179 *3.1. Geometry and process simulation*

180 We simulated different evacuation processes for room sizes of  $20\text{ m} \times$   
181  $20\text{ m}$ ,  $30\text{ m} \times 30\text{ m}$  and  $40\text{ m} \times 40\text{ m}$ . The rooms had one or two exit doors  
182 on the same wall, as shown in Fig. 1. The doors were placed symmetrically  
183 from the mid position of the wall, in order to avoid corner effects. Both doors  
184 had also the same width.

185

186 At the beginning of the process, the pedestrians were all equally sepa-  
187 rated in a square arrangement. The occupancy density was initially set to  
188  $0.6\text{ people/m}^2$ , close to the allowed limiting values by current regulations [16].  
189 They all had random velocities resembling a Gaussian distribution with null  
190 mean value. The pedestrians were willing to go to the nearest exit. Thus, all  
191 the pedestrians had the desired velocity  $\mathbf{v}_d$  pointing to the same exit door if  
192 only one door was available, or to the nearest door if two exits were available.

193

194 In order to focus on the effects due to dual exits, we only allowed the  
195 pedestrians to move individualistically, that is, neither leaderships nor herd-  
196 ing behaviors were present during the evacuation process. At any time, the  
197 pedestrians knew the doors location and tried to escape by their own.

198

199 The simulations were supported by LAMMPS molecular dynamics simula-  
200 tor with parallel computing capabilities [17]. The time integration algorithm  
201 followed the velocity Verlet scheme with a time step of  $10^{-4}\text{ s}$ . All the nec-  
202 essary parameters were set to the same values as in previous works (see  
203 Refs. [12, 13]). It was assumed that all the individuals had the same radius  
204 ( $r_i = 0.3\text{ m}$ ) and weight ( $m_i = 70\text{ kg}$ ). We ran 30 processes for each panic  
205 situation, in order to get enough data for mean values computation.

206

207 Although the LAMMPS simulator has the most common built-in functions,  
208 neither the social force  $\mathbf{f}_s$  nor the desire force  $\mathbf{f}_d$  were available. We imple-  
209 mented special modules (with parallel computing compatibilities) for the  $\mathbf{f}_s$   
210 and  $\mathbf{f}_d$  computations. These computations were checked over with previous

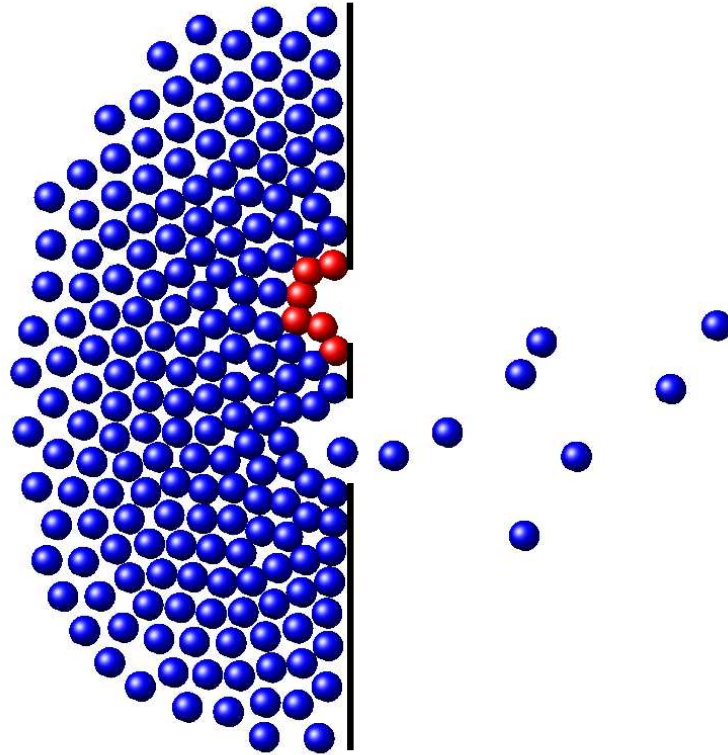


Figure 1: Snapshot of an evacuation process from a  $20\text{ m} \times 20\text{ m}$  room, with two doors. In red we can see a blocking structure around the upper door. The desired velocity was  $v_d = 4\text{ m/s}$ .



211 computations.

212

213 The pedestrian’s desired direction  $\hat{\mathbf{e}}_d$  was updated at each time step. Af-  
214 ter leaving the room, they continued moving away. No re-entering mechanism  
215 was allowed.

216

### 217 3.2. Measurements conditions

218 Simulations were run in the same way as in Refs. [12, 13]. Each process  
219 started with all the individuals inside the room. The measurement period  
220 lasted until 80% of the occupants left the room. If this condition could not be  
221 fulfilled within the first 3000 s, the process was stopped. Data was recorded  
222 at time intervals of 0.05 s (cf. Eq. (2a)).

223

224 The simulations ran from relaxed situations ( $v_d < 2$  m/s) to very stressing  
225 rushes ( $v_d = 8$  m/s). We registered the individuals positions and velocities  
226 for each evacuation process. Thus, we were able to compute the “social  
227 pressure” through out the process and to trace the pedestrians behavioural  
228 pattern.

229

## 230 4. Results

### 231 4.1. The faster is slower effect

232 As a starting point, we checked over the “faster is slower” effect for the  
233 room with two doors on the same wall. Fig. 2 shows the recorded evacuation  
234 time when the doors are separated a distance of  $d_g = 1$  m and when no sep-  
235 aration exists at all ( $d_g = 0$ ). The latter means a single opening with width  
236 equal to two doors. Both cases (with or without separation) exhibit a change  
237 in their corresponding slopes. Thus, the “faster is slower” effect is achieved  
238 following the same qualitative response as the one found in previous works  
239 for rooms with a single exit [10, 9].

240

241 The evacuation time for separated doors in Fig. 2 is always above the  
242 time required to evacuate the pedestrians through the single opening (*i.e.*  
243 null separation). For  $v_d = 6$  m/s, the single opening improves the evacuation  
244 performance in half of the time that demands the  $d_g = 1$  m separation con-  
245 figuration. Other separation distances (not shown) exhibit the same qualitative

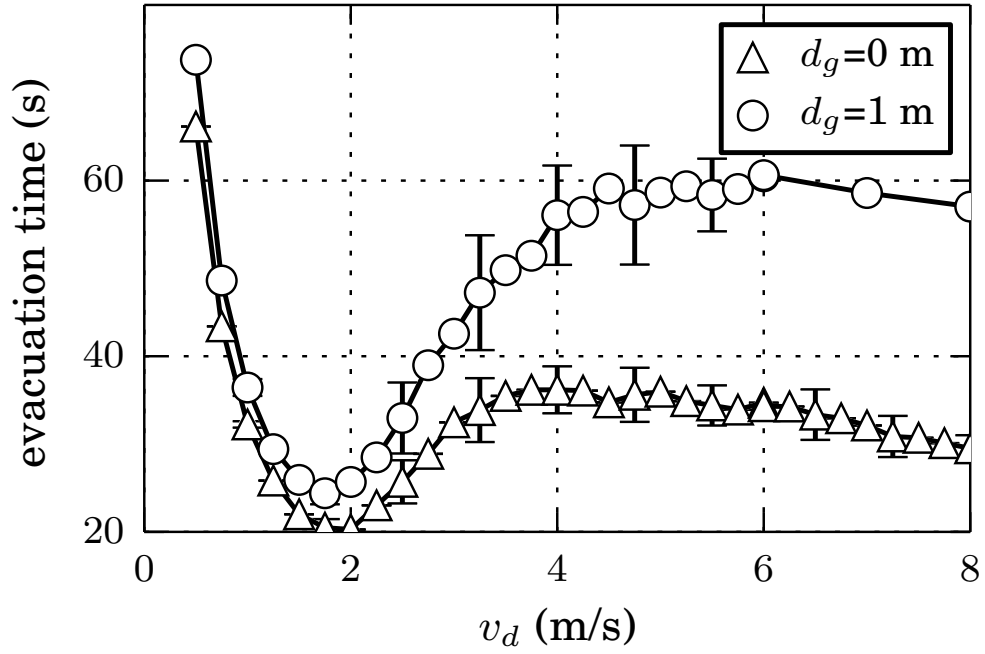


Figure 2: Mean evacuation time for 160 individuals (seconds) vs. the pedestrian's desired velocity (m/s). The room was  $20 \times 20$  m size. Two contiguous doors were placed on one side of the room as shown in Fig. 1 (see text for details). Mean values were computed from 30 evacuation processes. Each door was  $d_w = 1.2$  m width. The desired velocity was  $v_d = 4$  m/s. Two situations are shown:  $\triangle$  corresponds to the null separation distance between doors, meaning a single door of  $2d_w$  width.  $\circ$  corresponds to the 1 m separation distance between doors ( $d_g = 1$  m).

246 pattern as the example presented in Fig. 2. Therefore, it is clear that while  
 247 the total width of the opening remains unchanged, splitting this width into  
 248 two symmetric exits affects significantly the evacuation performance.

249  
 250 Notice that there is a slightly negative slope for velocities higher than  
 251 6 m/s. This behavior will be discussed in Section 4.3.2.

252  
 253 We made further research on the  $d_g = 0$  and  $d_g > 0$  scenarios. The former  
 254 is investigated in Section 4.2, while the latter is left to Section 4.3.

255

#### 256 4.2. The single door vs. the null separation

257 Recall that the  $d_g = 0$  scenario corresponds to a single opening, but the  
 258 total width of the opening is twice the width of a single door (see Section 4.1).  
 259 Actually, it resembles the situation of a double sheet door.

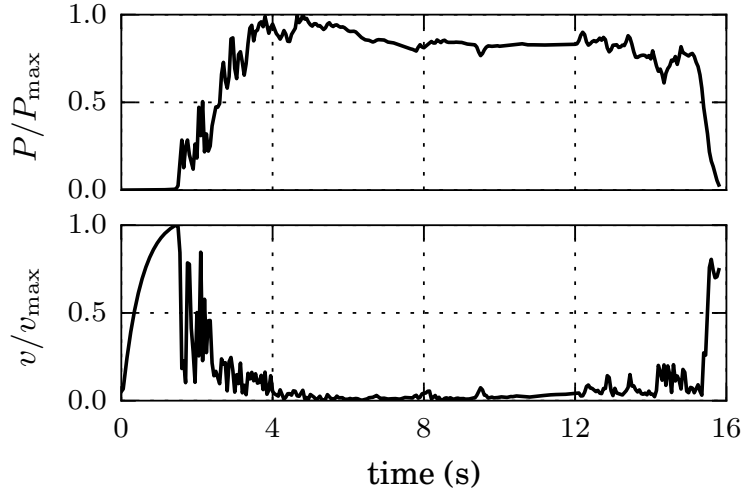
260

##### 261 4.2.1. The stop-and-go process

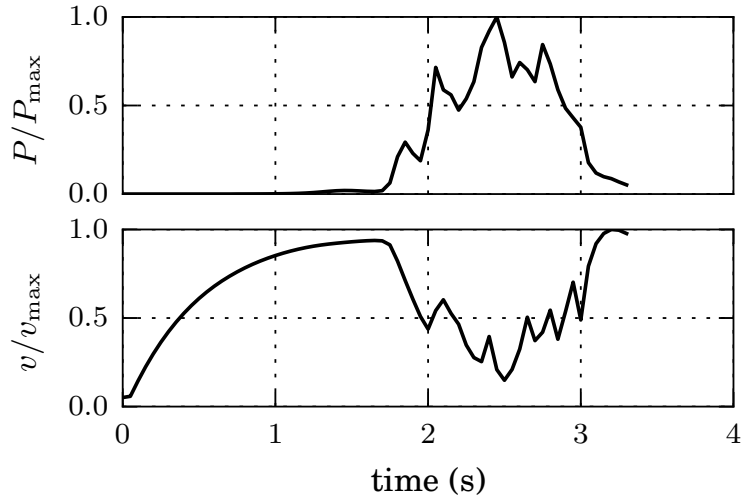
262 Fig. 3 illustrates on how the evacuation performance improves as the  
 263 opening becomes wider. Fig. 3a corresponds to the single door ( $d_w = 1.2$  m),  
 264 while Fig. 3b corresponds to a wider opening ( $3d_w = 3.6$  m), resembling  
 265 a multi-leaf opening. Both figures represent the time evolution of a sin-  
 266 gle pedestrian during an evacuation process. We can see the (normalized)  
 267 pressure acting on the pedestrian and his (her) corresponding velocity. The  
 268 starting point of the pedestrian was  $(x, y) = (12.35 \text{ m}, 8.45 \text{ m})$ . Notice that  
 269 an increase in the opening width from  $d_w$  to  $3d_w$  (Fig. 3a and Fig. 3b, re-  
 270 spectively) reduces the evacuation time by one-fifth approximately.

271

272 The pedestrian represented in Fig. 3 increases his (her) velocity towards  
 273 an asymptotic value at the beginning of the processes. This value corre-  
 274 sponds to the desired velocity  $v_d = 4$  m/s. But close to  $t = 2$  s, the pedes-  
 275 trian suddenly stops because of the clogging around the exit. Clogging is also  
 276 responsible for the pressure increase, as shown in both Fig. 3a and Fig. 3b.  
 277 This can be checked over by means of Eq. (2) because when the velocity of  
 278 the pedestrian vanishes, the desire force  $\mathbf{f}_d$  attains a maximum (in panic sit-  
 279 uations only). Notice, however, that any further fluctuation of the pressure  
 280 acting on the pedestrian corresponds to an inverse fluctuation on the velocity.



(a) Opening of  $d_w = 1.2$  m width.



(b) Opening of  $3d_w = 3.6$  m width.

Figure 3: Normalized pressure and velocity on a single pedestrian during an evacuation process. Data was recorded from the the initial position at  $x = 12.35$  m and  $y = 8.45$  m, until the individual left the room ( $x > 20$  m). The pedestrians desired velocity was  $v_d = 4$  m/s. Two situations are shown: (a) evacuation through a single door of width  $d_w = 1.2$  m. (b) evacuation through an opening of  $3d_w = 3.6$  m.

281 Thus, the pedestrian is able to reach the exit following a stop-and-go process.

282

283 The instantaneous pressure acting on a single pedestrian can be computed  
284 from Eq. (4) for a slow moving pedestrian (that is,  $p_i \simeq 0$ ). The maximum  
285 pressure values  $P_{\max}$  in Fig. 3a and Fig. 3b are  $8550 \text{ N.m}^{-1}$  and  $6475 \text{ N.m}^{-1}$ ,  
286 respectively. The corresponding mean pressure values (after the first 2 s)  
287 are 80% and 55% of the respective maximum values. This means that the  
288 mean pressure value for the  $3d_w$  situation is lower than the corresponding  
289 mean value for the  $d_w$  situation. That is, the wider opening seems to re-  
290 lease pressure from time to time. Consequently, the stop-and-go processes  
291 are somehow different for the single door with respect to the  $d_g = 0$  situation  
292 (the wider opening).

293

294 The above analyses corresponds to a single pedestrian moving along the  
295 middle of the room. It does not hold for the whole crowd. For details on the  
296 pressure patterns of the crowd, see Section 4.2.2.

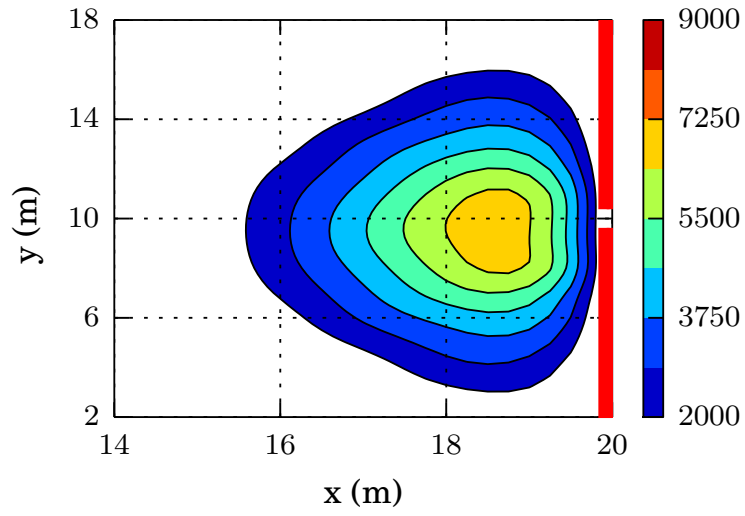
#### 297 4.2.2. The pressure and stream patterns

298 For a better understanding on how the pedestrians are (intermittently)  
299 released from high pressures in the wide opening situation, we pictured the  
300 whole scene into a pressure contour map and a mean stream path map for all  
301 the individuals. Figs. 4a to 4c show the pressure levels ( $P_i$ ) for the clogging  
302 area. The warm colors are associated to high pressure values. These values  
303 are close to the corresponding maximum pressure values (not shown). Thus,  
304 the warm regions define the places where the pedestrians slow down most of  
305 the time. They are expected to get released only for short periods of time.  
306 On the contrary, the regions represented in cold colors (low mean pressure)  
307 are those where the individuals are able to get released for longer time peri-  
308 ods.

309

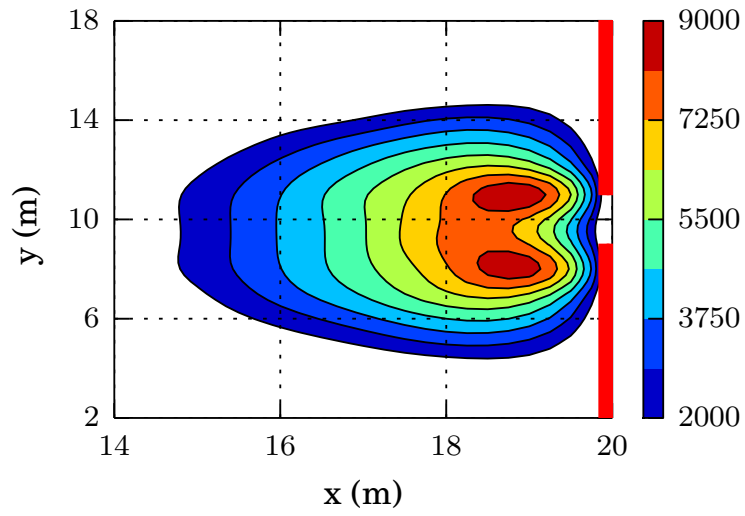
310 Figs. 5a to 5c represent the mean stream lines during the evacuation pro-  
311 cess. The three exhibits the released paths for leaving the room, but Fig. 5c  
312 shows more gathering lines in the central path (higher flow). Notice that  
313 the stream lines pass through the low pressure regions in Fig. 5c. That is,  
314 it can be seen in Fig. 5c that the stream lines gather along the middle of  
315 the clogging area, where “cold” pressure colors can be found in Fig. 4c. The  
316 “warm” pressure colors are placed on the sides of this region.

317



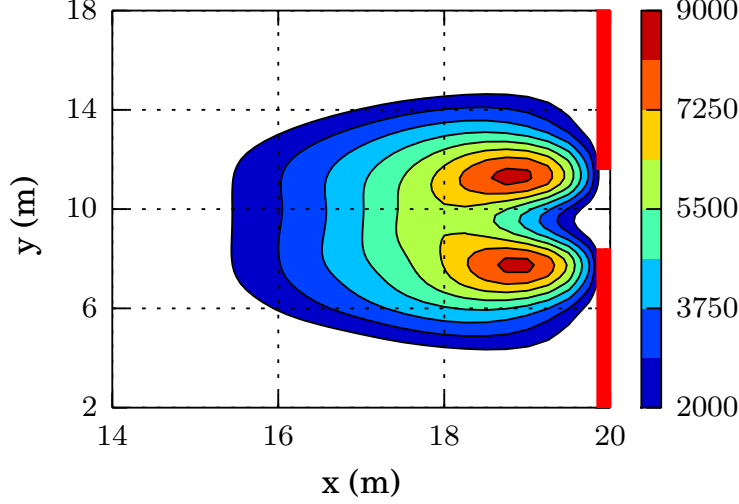
318

(a) Opening of  $d_w = 1.2$  m width.



319

(b) Opening of  $2d_w = 2.4$  m width.



(c) Opening of  $3d_w = 3.6$  m width.

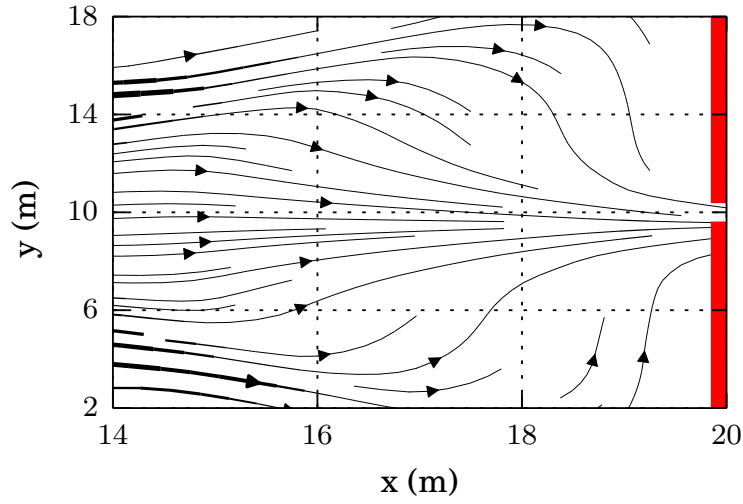
Figure 4: Mean pressure contour lines computed from 30 evacuation processes until 100 pedestrians left the room ( $20\text{ m} \times 20\text{ m}$  size). The scale bar on the right is expressed in  $\text{N.m}^{-1}$  units (see text for details). The red lines at  $x = 20\text{ m}$  represent the walls on the right of the room. The pedestrian's desired velocity was  $v_d = 4\text{ m/s}$ . The contour lines were computed on a square grid of  $1\text{ m} \times 1\text{ m}$  and then splined to get smooth curves. Level colors can be seen in the on-line version only.

We checked over the trajectory of the single pedestrian represented in Fig. 3b and we observed that he (she) managed to get out of the room through the path where the stream lines get denser. Thus, Fig. 3b resembles the stop-and-go process for the pedestrians passing through the middle of the clogging area, that is, along the low pressure (middle) region. The pedestrians on the sides of this region (high pressure region) are expected to slow down since Fig. 5c shows no stream lines to the exit.

Recalling the results in Fig. 3a for the same single individual as in Fig. 3b, we realize that the single door scene is likely to differ from the  $d_g = 0$  situation since both patterns (for the same individual) do. Thus, we examined the pressure contour map for the single door and for an opening of twice the single door width. The results are shown in Fig. 4. Fig. 4b exhibits a similar pressure map pattern as Fig. 4c, but the single door pressure map in Fig. 4a does not. For the single door situation, we do not observe the lower

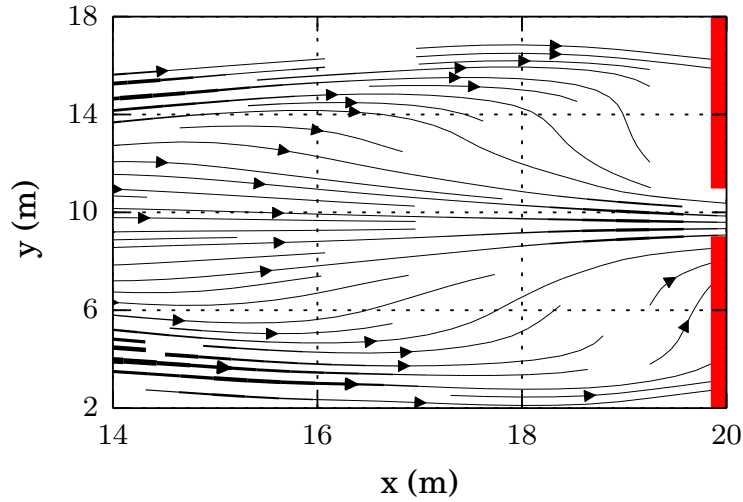
337 pressure pathway in the middle of the clogging area. Instead, high pressure  
 338 is acting on the pedestrians, as shown in the (normalized) pressure evolution  
 339 in Fig. 3a. The corresponding velocity evolution (Fig. 3a) informs that the  
 340 pedestrians in this region experience a slow down.

341



342

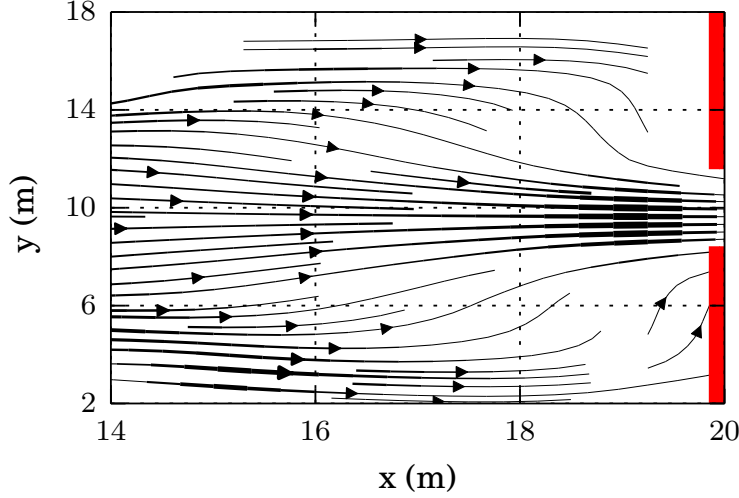
(a) Opening of  $d_w = 1.2$  m width.



343

(b) Opening of  $2d_w = 2.4$  m width.





(c) Opening of  $3d_w = 3.6$  m width.

Figure 5: Mean stream lines computed from 30 evacuation processes until 100 pedestrians left the room ( $20\text{ m} \times 20\text{ m}$  size). The lines connect the normalized velocity field ( $v/v_{\max}$ ). The arrows indicate the stream direction. Data was recorded on a square grid of  $1\text{ m} \times 1\text{ m}$  and then splined to get smooth curves. The red lines at  $x = 20\text{ m}$  represent the walls on the right of the room. The pedestrian's desired velocity was  $v_d = 4\text{ m/s}$  for all the cases.

Notice, once again, that the results shown in Figs. 3 only resembles the situation in the middle of the room. Fig. 5c and Fig. 4c exhibit the situation for the whole crowd. However, the mid-path in “cold” colors in Fig. 4c is the most meaningful region to our research, since it completes the picture for the stop-and-go process, firstly evidenced in Fig. 3b.

At this stage of the investigation we are able to point out a few conclusions. The widening of the single door increases the pedestrian's flux, as asserted in Ref. [7]. In the narrow situation (see Fig. 3a), the pedestrians experience a slow down. The corresponding time delays have been associated to blocking structures (see Refs. [9, 11]) and causes the pressure acting on the nearby individuals to raise. Fig. 4a resembles this situation. However, as the opening widens (*i.e.* the null separation situation), the pressure pattern changes qualitatively (see Fig. 4b and Fig. 4c), allowing the pedestrians in the middle of the clogging area to make a pathway to the exit. This pathway corresponds to the breaking of the blocking structures.

### 363 4.3. Separated doors

364 We will now analyze the case in which the evacuation process is through  
 365 two doors, symmetrically placed on the same side of the room. We will ex-  
 366 plore the dependence of such a process on the doors separations. We will  
 367 assume that each door width is  $d_w = 1.2$  m.

368

369 It has been shown in Fig. 2 that separating the doors a distance  $d_g = 1$  m  
 370 worsens the evacuation performance with respect to the null separation. We  
 371 further explored this worsening by increasing  $d_g$  at steps of 0.5 m, starting  
 372 from the null separation distance. Fig. 6 shows the mean evacuation time  
 373 and the corresponding error bars (indicating the  $\pm\sigma$  limits). The desired  
 374 velocity was set to  $v_d = 4$  m/s, where the “faster is slower” effect takes place.

375

376 The evacuation time as a function of  $d_g$  shown in Fig. 6 is one of our main  
 377 results. The worsening in the evacuation performance raises to a maximum  
 378 value at 1 m while its slope changes sign for  $d_g > 1$  m. Thus,  $d_g = 1$  m ap-  
 379 pears to be the worse evacuation scenario for the  $20\text{ m} \times 20\text{ m}$  room with 225  
 380 individuals and two doors of  $d_w = 1.2$  m each (see Fig. 6).

381

382 We further computed the mean evacuation time for an increasing number  
 383 of pedestrians (and room sizes). We kept the pedestrian density unchanged  
 384 (at  $t = 0$ ) for all the simulation processes. Fig. 7 exhibits the mean evacua-  
 385 tion time per pedestrian as a function of the separation distance (*i.e.* gap).  
 386 We divided the evacuation time by the total number of pedestrians for visu-  
 387 alization reasons.

388

389 The results shown in Fig. 7 were not expected. The evacuation time set-  
 390 tles to an asymptotic value for separation distances  $d_g > 5$  m. The mean  
 391 evacuation time becomes almost independent of the separation distances  $d_g$   
 392 despite that the clogging areas around the doors might still overlap.

393

394 Fig. 7 includes (half) the evacuation time for the  $20 \times 20$  room with a  
 395 single exit (see caption for details). Notice that the asymptotic limit for the  
 396 evacuation time (when two doors are separated 6 m) does not match exactly  
 397 the single exit situation. This fact corresponds to the difference in the bulk

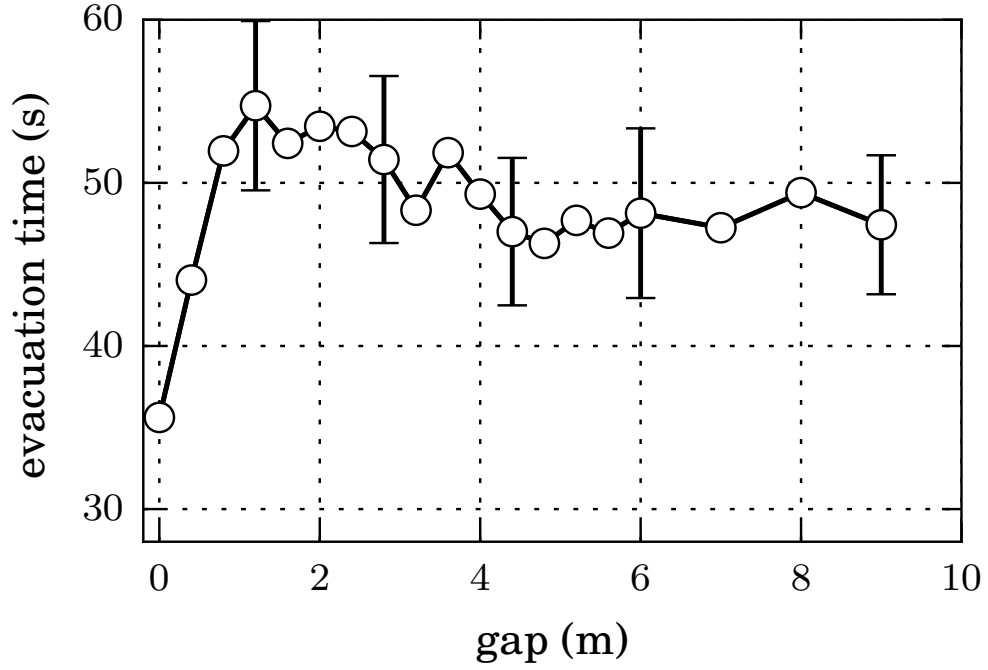


Figure 6: Mean evacuation time for 225 pedestrians (room of  $20 \times 20$  m size) as a function of the doors separation distance. Mean values were computed from 30 evacuation processes until 160 pedestrians left the room. Each door was  $d_w = 1.2$  m width for non-vanishing gaps. The null gap means a single door of  $2d_w$  width. The desired velocity was  $v_d = 4$  m/s.

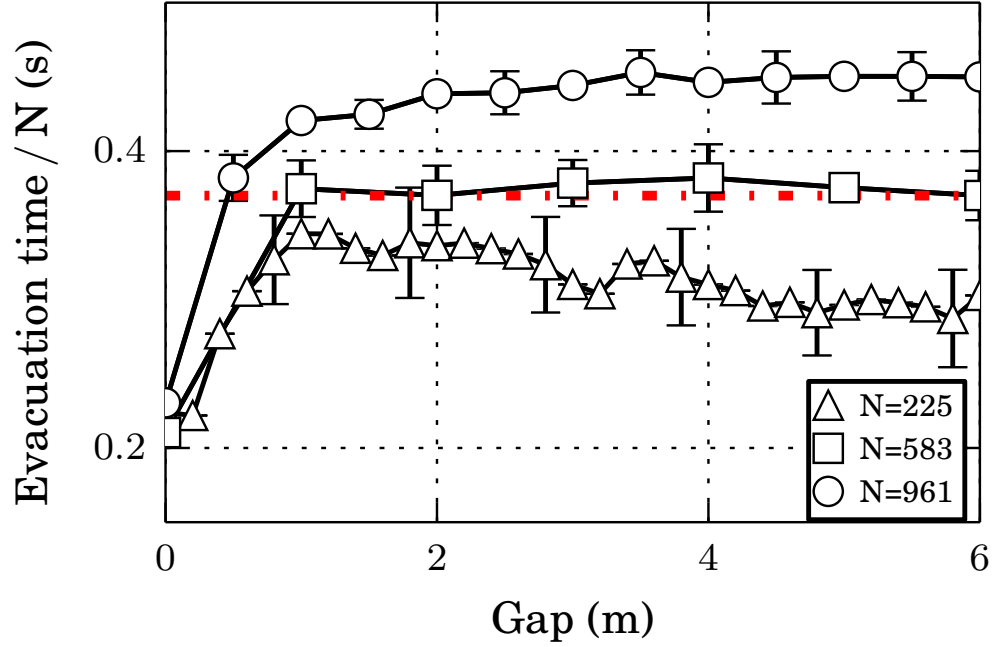


Figure 7: Mean evacuation time per total number of pedestrians that left the room ( $N$ ), as a function of the doors separation distance. Mean values were computed from 30 evacuation processes. Each door was  $d_w = 1.2$  m width for non-vanishing gaps. The null gap means a single door of  $2d_w$  width. Three situations are shown:  $\triangle$  corresponds to the  $20 \times 20$  m room when 160 pedestrians left the room,  $\square$  corresponds to  $30 \times 30$  m room when 530 pedestrians left the room, and  $\circ$  corresponds to  $40 \times 40$  m room when 865 pedestrians left the room. The red (online version only) dashed line represents half the evacuation time for 225 individuals in a room with a single door of  $d_w = 1.2$  m. The desired velocity was  $v_d = 4$  m/s. for all cases.

398 pressures on each case. That is, the bulk pressure for the single door situa-  
 399 tion is expected to be higher than the one for the two doors situation (and  
 400 a 6 m gap) because of the difference in the number of individuals pushing  
 401 towards each door. Thus, the evacuation time worsens for the single door  
 402 situation.

403

404 Fig. 7 also shows that the slope not always changes sign at  $d_g \simeq 1$  m.  
 405 Furthermore, as the number of pedestrians is increased for  $d_g > 1$  m, the  
 406 evacuation time slope raises to positive values. The greater the number of  
 407 pedestrians, the worst the evacuation time (per individual). This appears  
 408 to occur for  $d_g > 1$  m, regardless of the crowd size. That is, according to  
 409 Fig. 7, there exists a separation distance value  $d_g \simeq 1$  m where the evacua-  
 410 tion slope changes sharply to negative or positive values (for  $d_g > 1$  m). This  
 411 phenomenon has not been studied in the literature, to our knowledge.

412

413 We can resume the results in Fig. 7 in the following way: the evacuation  
 414 time raises when the doors separation increases from a wide opening (null  
 415 separation distance) to the distance  $d_g \simeq 1$  m. At this gap, the evacuation  
 416 time slope changes notably, entering a much slowly varying regime towards  
 417 an asymptotic value (for  $d_g \gg 1$  m). The former can be identified as a regime  
 418 for small values of  $d_g$ , while the latter is valid for moderate to large values  
 419 of  $d_g$ . The fact that a sharp change occurs at  $d_g \simeq 1$  m, no matter the crowd  
 420 size, suggests that both regimes are somehow different in nature. This moved  
 421 us to explore the two regimes separately.

422

#### 423 4.3.1. *The regime for $d_g < 1$ m*

424 Our starting point is the pressure contour map, since we can easily com-  
 425 pare the current patterns with those presented in Section 4.2.2. Fig. 8a shows  
 426 the mean pressure pattern for the separation distance  $d_g = 1.5$  m, that is,  
 427 close to the gap value where the sharp change in the slope occurs. The dif-  
 428 ferences between Fig. 8a and Figs. 4 are noticeable. We can now see a wide  
 429 region in the center of the clogging area representing the high pressure ( $P_i$ )  
 430 acting on each pedestrian (warm colors in Fig. 8a). The regularity in the col-  
 431 ors of this region is meaningful: the high pressure acting on the pedestrians  
 432 does not allow a regular stream (pathway) to the exit. This is in agreement  
 433 with the evacuation time worsening shown in Fig. 6. Furthermore, in all  
 434 cases the pressure maps show a resemblance with those reported in Ref. [18].

435

436 Fig. 8a suggests that blocking structures might be present for long time  
 437 periods, since the pedestrians cannot manage to get out easily. The relevance  
 438 of this blocking structures has also been achieved for other kind of systems  
 439 (see Ref. [19]). We examined this possibility through the *blocking probability*.  
 440 In this context, the blocking probability is associated to the ratio between  
 441 the time that each door remains blocked with respect to the total evacuation  
 442 time (cf. Section 2.2). Fig. 9 presents two kinds of blockings: the simultane-  
 443 ous blocking of both doors, and the blocking of a single door (say, the one on  
 444 the left). The former connects the left most wall with the right most wall, but  
 445 does not contact the separation wall in the middle of the walls. The latter  
 446 connects the walls on both sides of the selected door (say, the one on the left).

447

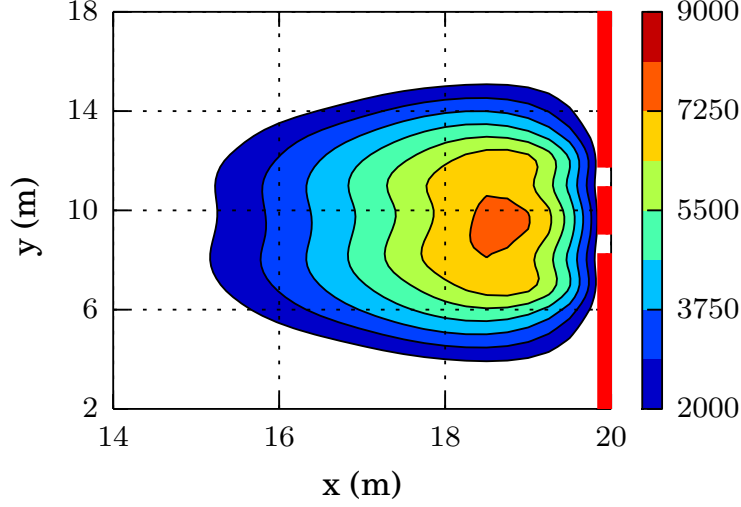
448 According to Fig. 9, the single door blockings are not relevant until  
 449  $d_g \simeq 1$  m, while the simultaneous blockings weaken as the gap (separation  
 450 distance  $d_g$ ) increases. The single door blockings resemble the response in  
 451 Fig. 6, and thus, we conclude that this kind of blockings should play an im-  
 452 portant role in the increase of the evacuation time for small gaps  $d_g$ . Notice  
 453 that the single door blocking probability explains the 75% of the evacuation  
 454 time, as can be seen in Fig. 9.

455

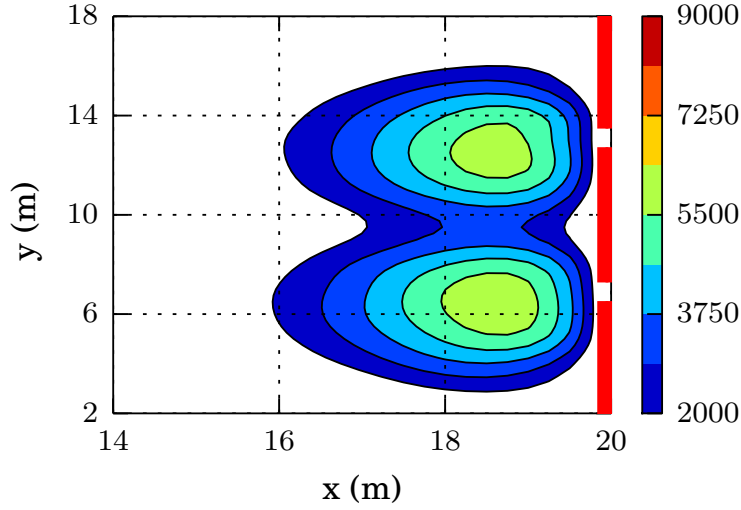
456 The results so far moved us to focus closer on the dynamics around each  
 457 door. We watched many animations of the evacuation process for gap dis-  
 458 tances between the null separation to  $d_g = 1.5$  m (not shown). We realized  
 459 that single door blockings hold if the gap is large enough to accommodate at  
 460 least two pedestrians. That is, any blocking structure enclosing a single door  
 461 can hold for some time if the pedestrians at the end of the structure (and in  
 462 contact with the walls) do hardly leave the structure. Two pedestrians are  
 463 needed at the gap wall to ensure that both doors remain blocked.

464

465 We want to call the attention on the fact that when  $d_g$  passes through the  
 466 1 m situation, the kind of simultaneous blocking without contacting the gap  
 467 wall, is replaced by the kind of single door blockings acting (usually) simul-  
 468 taneously. This achieves a qualitative different pressure and stream pattern.  
 469 As shown in Fig. 4b, the widening of the exit allows a pathway through the  
 470 middle of the clogging area. This is likely to occur even for very small gaps  
 471 (see Fig. 9). However, the single door blockings follow a pressure pattern  
 472 similar to Fig. 4a on each door. What we see in Fig. 8a is the combined



(a) Separation distance of  $d_g = 1.5$  m.



(b) Separation distance of  $d_g = 5$  m.

Figure 8: Mean pressure contour lines computed from 30 evacuation processes until 100 pedestrians left the room ( $20\text{ m} \times 20\text{ m}$  size). The scale bar on the right is expressed in  $\text{N.m}^{-1}$  units (see text for details). The red lines at  $x = 20\text{ m}$  represent the walls on the right of the room. The pedestrian's desired velocity was  $v_d = 4\text{ m/s}$ . The contour lines were computed on a square grid of  $1\text{ m} \times 1\text{ m}$  and then splined to get smooth curves. Level colors can be seen in the on-line version only.

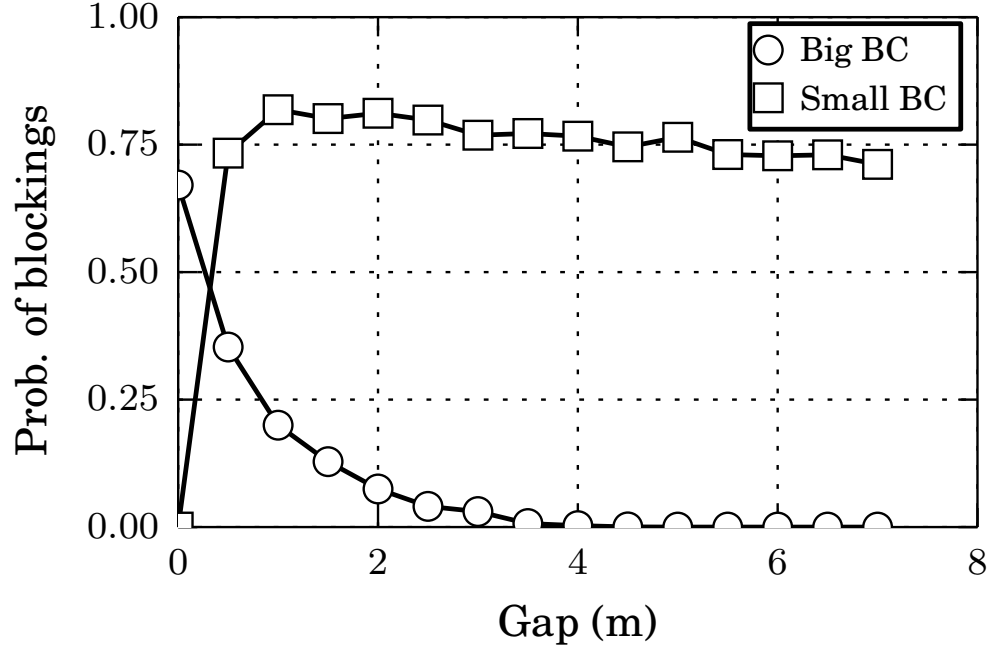


Figure 9: Ratio between time steps including blocking structures and the total number of time steps for 30 evacuation processes, as a function of the doors separation distance. The room size was  $20 \times 20$  m with 225 occupants. Each door was  $d_w = 1.2$  m width for non-vanishing gaps. The null gap means a single door of  $2d_w$  width. The desired velocity was  $v_d = 4$  m/s.  $\circ$  corresponds blocking structures connecting both the left side wall of the left door with the right side wall of the right door (see text for details).  $\square$  corresponds to blocking structures connecting both sides of a single door (see text for details).



473 pattern built from two single door patterns as in Fig. 4a.

474

475 We conclude from the analysis of small gaps ( $d_g < 1$  m) that a door  
476 separation distance roughly equal to two pedestrian widths is critical. This  
477 distance allows persistent single door blockings. Small distances (close to the  
478 null separation) do not actually allow single door blockings to hold for long  
479 time. Thus, the role of  $d_g = 2r_{ij}$  (two pedestrian's width) is decisive to move  
480 the evacuation process from one regime to another.

481

#### 482 4.3.2. *The regime for $d_g > 1$ m*

483 Fig. 9 shows that the single door blockings (see Section 4.3.1) remains  
484 around 75% of the total evacuation time for  $d_g > 1$  m (225 individuals in  
485 the room). We also computed this magnitude for situations with increasing  
486 number of individuals (see Fig. 10). The probability of single door block-  
487 ings approaches unity as the crowd size increases. This means, according to  
488 our definition of blocking probability, that the blocking time raises as the  
489 number of individuals increases. The gap distance, however, does not play a  
490 significant role for  $d_g > 1$  m.

491

492 There is a noticeable difference between the evacuation time shown in  
493 Fig. 7 and the blocking probability exhibited in Fig. 10. Fig. 7 presents  
494 the evacuation time for three different room sizes and increasing number of  
495 pedestrians. The slope of the evacuation curve is negative for the  $20 \times 20$  m  
496 room, it vanishes for the  $30 \times 30$  m situation and it becomes slightly positive  
497 for the  $40 \times 40$  m room (for  $d_g > 1$  m). Thus, as the number of pedestrians  
498 increases, the slope of the evacuation time changes sign. However, this does  
499 not occur for the blocking probability (see Fig. 10). The slope of the blocking  
500 probability remains always negative for an increasing number of pedestrians  
501 (and desired velocities). Therefore, the changes in the slope observed in  
502 Fig. 7 cannot be explained by changes in the blocking time (*i.e* blocking  
503 probability).

504

505 We checked the pressure patterns for  $d_g > 4d_w$  (see Fig. 8b as an exam-  
506 ple). We came to the conclusion that since the evacuation slope in Fig. 7  
507 changes with an increasing number of individuals, the whole bulk should be  
508 involved in this phenomenon. Therefore, we focused our investigation on the  
509 pressure contribution of the whole bulk.

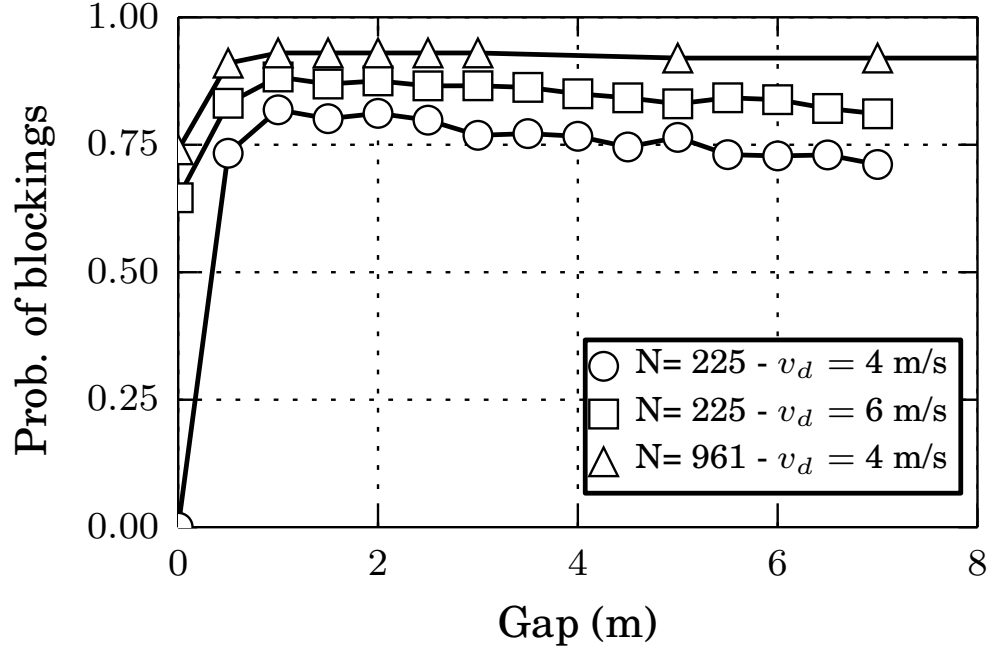


Figure 10: Ratio between time steps including blocking structures and the total number of time steps for 30 evacuation processes, as a function of the doors separation distance. The only blocking structures considered were those connecting both sides of one single door (see text for details). Each door was  $d_w = 1.2$  m width for non-vanishing gaps. The null gap means a single door of  $2d_w$  width. Three scenarios are shown:  $\circ$  corresponds to the room of size  $20 \times 20$  m with 225 occupants and a desired velocity of  $v_d = 4$  m/s.  $\square$  corresponds to the room of size  $20 \times 20$  m with 225 occupants and a desired velocity of  $v_d = 6$  m/s.  $\triangle$  corresponds to the room of size  $40 \times 40$  m with 961 occupants and a desired velocity of  $v_d = 4$  m/s.

510

511 As shown in Eq. (A.3) of Appendix A , we can realize that the pressure of  
 512 the whole bulk (left-hand side) is related to the total desire force contribution  
 513 (right-hand side). Thus, the pressure of the bulk can vary in two possible  
 514 ways: if the desire force of the individuals (*i.e.* anxiety levels) changes, or,  
 515 if the crowd size changes. An increase on either the number of evacuating  
 516 pedestrians ( $N$ ) or their corresponding anxiety level ( $v_d$ ), will increase the  
 517 pressure of the whole bulk. This result is in agreement with the experiments  
 518 performed in Ref. [15]. We also present a simple example in the Appendix B.

519

520 Fig. 7 exhibits the evacuation time for an increasing number of pedestri-  
 521 ans. But, an increase in the pedestrians anxiety level should resemble similar  
 522 results, if the above reasonings are true. Fig. 11 shows the evacuation time  
 523 as a function of the separation distance for two different desired velocities.  
 524 As expected, the sharp change in the slope occurs around  $d_g = 2r_{ij}$ . Also  
 525 the slope changes as the desired velocity ( $v_d$ ) is increased (*i.e.* higher anx-  
 526 iety level). This confirms that the social pressure is responsible the slope  
 527 behaviour shown in Fig. 7.

528

529 Notice that Fig. 11 exhibits a crossover for a gap of 0.5 m. This crossover  
 530 is related to the slightly negative slope shown in Fig. 2. We want to stress  
 531 the fact that this crossover appears for desired velocities between 6 m/s and  
 532 8 m/s (see Fig. 2), but not for increasing number of pedestrians at lower  
 533 desired velocities (see Fig. 10). Despite the fact that we are able to see a  
 534 crossover in the range of 6 m/s to 8 m/s, we prevent the reader that not no-  
 535 ticeable consequences were found that could affect further conclusions, since  
 536 the “faster is slower” effect remains valid within the studied range.

537

538 We conclude from the analysis of large gaps ( $d_g > 1$  m) that the evacu-  
 539 ation time is controlled by the social pressure in the bulk. The crowd size  
 540 and the desired velocity  $v_d$  affects the pressure acting on the pedestrians.  
 541 For  $d_g > 5$  m in our simulations, the evacuation time is very close to the cor-  
 542 responding asymptotic value, although the bulks around each door are not  
 543 completely independent. This means that the mixing of both crowds (that is,  
 544 the fact that the bulks are in contact) do not affect strongly the evacuation  
 545 performance.

546

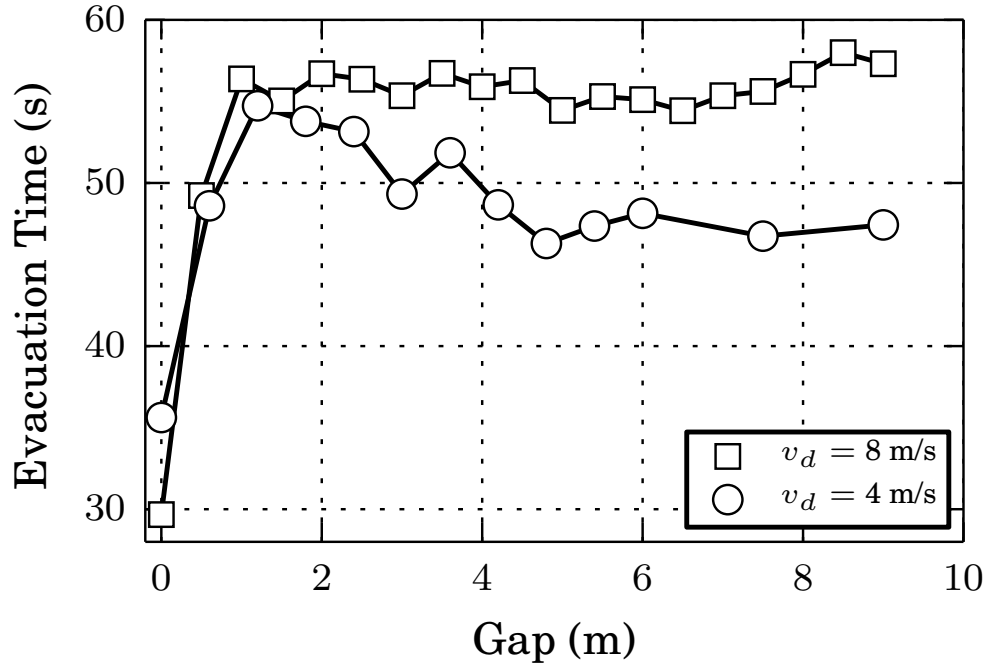


Figure 11: Mean evacuation time for 225 pedestrians (room of  $20 \times 20$  m size) as a function of the doors separation distance. Mean values were computed from 30 evacuation processes until 160 pedestrians left the room. Each door was  $d_w = 1.2$  m width for non-vanishing gaps. The null gap means a single door of  $2d_w$  width.  $\circ$  corresponds to pedestrians with desired velocity of  $v_d = 4$  m/s.  $\square$  corresponds to pedestrians with desired velocity of  $v_d = 8$  m/s.

## 5. Conclusions

We examined in detail the evacuation of pedestrians for the situation where two contiguous doors are available for leaving the room. Throughout Section 4 we presented results on the evacuation performance under high anxiety levels and increasing number of pedestrians. Both conditions exhibit the novel result that a worsening in the evacuation time exists as the door separation distance  $d_g$  increases from the null value to roughly the width of two pedestrians. Special situations may enhance the evacuation performance for larger values of  $d_g$ .

The range from  $d_g = 0$  to  $d_g \gg d_w$  was inspected. In the interval  $0 \leq d_g \leq 2r_{ij}$  (two pedestrian's width), the evacuation performance worsened for all the explored situations, as the separation distance between doors  $d_g$  increased. But, from  $d_g > 2r_{ij}$  the evacuation time enhanced for relatively small crowds and moderate anxiety levels. We realized that the sharp change in the evacuation behaviour at  $d_g = 2r_{ij}$  corresponded to qualitative differences in the pedestrian dynamics close to the exits.

After a detailed comparison of the dynamics for the single door situation and for two doors very close to each other (that is,  $d_g < 2r_{ij}$ ), we concluded that the blocking structures (*i.e.* blocking arcs) around the openings were released intermittently, allowing the pedestrians to leave the room in a stop-and-go process. As the separation distance approached  $2r_{ij}$ , the blocking arcs around each door, resembled the blocking situation of two single doors. This changes only affected the local dynamics (close to the doors), while the crowd remained gathered into a single clogging area.

For  $d_g > 2r_{ij}$  the single door blocking structures become relevant even for large values of  $d_g$  (see Fig. 9). No further qualitative changes were observed locally around each door. However, increasing the crowd size ( $N$ ) or the pedestrian's anxiety level ( $v_d$ ) slowed down the evacuation. Both magnitudes are linked to the pressure acting on the pedestrians, and therefore, enhanced the "faster is slower" effects.

For a better understanding of the relationship between  $N$ ,  $v_d$  and the pressure in the bulk, a simple lane example complemented our analysis. It was shown that the classical virial expression is still suitable for the investi-

584 gation of social systems.

585

## 586 6. Acknowledgments

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 590 of the CONICET, Argentina. I.M. Sticco and S. Cerrotta have degree in  
 591 Physics.

## 592 Appendix A. Alternative definition for the social pressure

593 Recall that the social force model (SFM) deals with the pedestrians de-  
 594 sire and their private space preservation. Although the desire force  $\mathbf{f}_d$  is a  
 595 “unilateral” force, the Newton equations of motion remain valid. Therefore,  
 596 it can be derived from the virial relation that [20]

$$\left\langle \sum_{i=1}^N \frac{p_i^2}{m_i} + \sum_{i=1}^N \mathbf{r}_i \cdot \mathbf{f}_i \right\rangle = -2\mathcal{P}\mathcal{A} \quad (\text{A.1})$$

597 for the set of  $N$  pedestrians inside an area  $\mathcal{A}$ .  $p_i$  and  $\mathbf{f}_i$  are the momentum  
 598 and total force acting on the individual  $i$  (excluding the interaction with the  
 599 walls).  $\langle \cdot \rangle$  corresponds to the mean value along time. The right hand side  
 600  $-2\mathcal{P}\mathcal{A}$  defines the global pressure on the curve enclosing the surface  $\mathcal{A}$ .

601

602 Following Ref. [20] we can define the “social pressure function”  $P_i$  as

603

$$2P_i\mathcal{A}_i = \frac{p_i^2}{m_i} + \frac{1}{2} \sum_{j=1}^{N-1} \mathbf{r}_{ij} \cdot \mathbf{f}_s^{(ij)} \quad (\text{A.2})$$

604 where  $\mathcal{A}_i$  is the area enclosing the pedestrian  $i$  and  $\mathbf{r}_{ij} = \mathbf{r}_i - \mathbf{r}_j$ . Notice that  
 605 the inner product  $\mathbf{r}_{ij} \cdot \mathbf{f}_s^{(ij)}$  is always positive for repulsive feelings.

606

607 The “social pressure function”  $P_i$  is roughly similar to the literature defini-  
 608 tion [10], as expressed in Eq. (4), for neglectable momentum  $p_i$ . Furthermore,  
 609 Eqs. (4) and (A.2) become equal if the area  $\mathcal{A}_i$  and  $r_{ij}$  are replaced by  $\pi r_i^2$

610 and the contacting distance  $2r_i$ , respectively.

611

612 We can further compute the pressure on all the pedestrians according  
 613 to Eq. (A.1). Notice that the force sum can be split into the summation  
 614 of three contributions: the desire forces, the social forces and the granular  
 615 forces. Actually, the granular force does not play a role because of orthog-  
 616 onality ( $\mathbf{r}_{ij} \cdot \mathbf{f}_g^{(ij)} = 0$ ). Consequently, replacing Eq. (A.2) into the virial  
 617 relation (A.1) gives

618

$$\sum_{i=1}^N \langle 2P_i \mathcal{A}_i \rangle = -2\mathcal{P}\mathcal{A} - \sum_{i=1}^N \langle \mathbf{r}_i \cdot \mathbf{f}_d^{(i)} \rangle \quad (\text{A.3})$$

619 We should remark that Eq. (A.3) holds either if the pedestrians are in  
 620 contact or not. The “social pressure function”  $P_i$  makes possible for the in-  
 621 dividuals to change their behavioural pattern when they come too close to  
 622 each other.

623

## 624 Appendix B. The lane example

625 We decided to open this supplementary section in order to make clear the  
 626 meaning of the “social pressure” acting on an individual and the collective  
 627 pressure (that is, the *bulk* pressure) on a set of individuals. We will follow a  
 628 simple example as a guide for more general situations.

629

### 630 Appendix B.1. The social pressure

631 Fig. B.12 represents a lane of individuals pushing to the right. The ending  
 632 wall prevents the individuals from moving. All the pedestrians in the lane  
 633 are at their equilibrium positions  $x_1, x_2, \dots, x_i, \dots, x_N$ , while the wall is placed  
 634 at the position  $x_0 = 0$  (see Fig. B.12).

635

636 The pedestrians push to the right acknowledging a desired force  $f_d^{(i)} =$   
 637  $mv_d/\tau$ , according to Eq. (2). The social repulsion feelings balance this desire  
 638 force, but only the contacting neighbors are relevant to these feelings. Thus,  
 639 the balance equation for any pedestrian in the lane reads

640

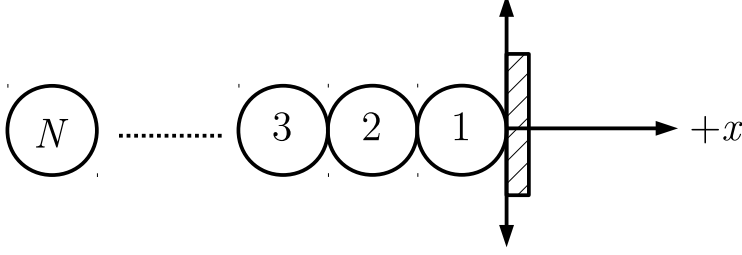


Figure B.12: Lane of individuals pushing to the right. The horizontal axis indicates the positive direction.

$$f_s^{(i,i+1)} - f_s^{(i,i-1)} + \frac{mv_d}{\tau} = 0 \quad (\text{B.1})$$

for  $f_s^{(i,j)}$  meaning the repulsive feelings of pedestrian  $i$  due to the presence of pedestrian  $j$ . Notice that the boundary condition at the wall-end is  $x_0 = 0$  (Dirichlet condition), while the condition at the free end is  $f_s^{(N,N+1)} = 0$  (Neumann condition). The forces on the pedestrians can be obtained recursively from Eq. B.1, starting at the free ended individual ( $i = N$ ). The resulting expression is

$$f_s^{(i,i-1)} = (N - i + 1) \frac{mv_d}{\tau}, \quad i = 1, \dots, N \quad (\text{B.2})$$

while the corresponding positions  $x_1, x_2, \dots, x_i, \dots, x_N$  are obtained by a backward substitution of the social forces expressed in Eq. (2), starting at the wall-end

$$x_i = x_{i-1} - (r_i + r_{i-1}) + B \ln \left[ (N - i + 1) \frac{mv_d}{A\tau} \right] \quad (\text{B.3})$$

The pressure on a single pedestrian  $P_i$  corresponds to the forces acting on him (her) (per unit length) due to the neighboring pedestrians. According to Eqs. (4), the pressure for any individual  $i$  in the lane is

$$P_i = \frac{1}{2\pi r_i} \left[ f_s^{(i,i+1)} + f_s^{(i,i-1)} \right] \quad (\text{B.4})$$

We can also arrive to this expression through the “social pressure function” definition (A.2)

$$P_i = \frac{1}{2} \left[ \frac{x_i - x_{i+1}}{2\mathcal{A}_i} f_s^{(i,i+1)} + \frac{x_{i-1} - x_i}{2\mathcal{A}_i} f_s^{(i,i-1)} \right] \quad (\text{B.5})$$



655 where the magnitude  $x_{ij}/2\mathcal{A}_i$  corresponds to the (inverse) effective length of  
 656 the pedestrian. For individuals modeled as circles, the inter-pedestrian dis-  
 657 tance is roughly  $x_{ij} = 2r_i$  and the area is  $\mathcal{A}_i = \pi r_i^2$ . Thus, both definitions  
 658 agree. However, the last one is preferred since it does not assume that the  
 659 forces actuate exactly at the distance  $r_i$ , as already mentioned in Section 2.3.  
 660

### 661 *Appendix B.2. The bulk pressure*

662 We can now illustrate on how to compute the virial relation (A.3). We  
 663 can add the social pressures expressed in (B.5) for the  $N$  pedestrians in the  
 664 lane.

$$\left\{ \begin{array}{lcl} 2P_1\mathcal{A}_1 & = & \frac{x_1}{2}f_s^{(1,2)} - \frac{x_2}{2}f_s^{(1,2)} \\ 2P_2\mathcal{A}_2 & = & \frac{x_2}{2}[f_s^{(2,3)} - f_s^{(2,1)}] - \frac{x_3}{2}f_s^{(2,3)} + \frac{x_1}{2}f_s^{(2,1)} \\ 2P_3\mathcal{A}_3 & = & \frac{x_3}{2}[f_s^{(3,4)} - f_s^{(3,2)}] - \frac{x_4}{2}f_s^{(3,4)} + \frac{x_2}{2}f_s^{(3,2)} \\ \dots & & \\ 2P_N\mathcal{A}_N & = & -\frac{x_N}{2}f_s^{(N,N-1)} + \frac{x_{N-1}}{2}f_s^{(N,N-1)} \end{array} \right. \quad (\text{B.6})$$

665 These are the local pressures on each pedestrian due to the contacting  
 666 neighbors (and excluding the wall). Adding the terms results in the virial  
 667 relation, as expressed in (A.3)

$$\begin{aligned} \sum_{i=1}^N 2P_i\mathcal{A}_i &= (x_1 - x_2)f_s^{(1,2)} + (x_2 - x_3)f_s^{(2,3)} + \dots \\ &+ (x_{N-1} - x_N)f_s^{(N,N-1)} \end{aligned} \quad (\text{B.7})$$

$$= x_1 \frac{N m v_d}{\tau} - \sum_{i=1}^N x_i \frac{m v_d}{\tau}$$

668 where the first term on the right corresponds to the global pressure  $-2\mathcal{P}\mathcal{A}$ .  
 669 Notice that  $x_1$  is negative, and thus,  $2\mathcal{P}\mathcal{A}$  is defined as a positive magnitude.  
 670 The last term is also positive, adding pressure to the bulk due to the desire

671 forces.

672

673 The virial relation (A.3) allows to compute the *bulk* pressure on a group  
 674 of pedestrians. For example, the pressure on the  $M$  pedestrians closest to the  
 675 wall corresponds to the force acting on this group due to the other  $N - M$   
 676 pedestrians. According to Eq. (A.3), the pressure on the  $M$  individuals is

$$\sum_{i=1}^M 2P_i \mathcal{A}_i = -2\mathcal{P}\mathcal{A} - \sum_{i=M+1}^N 2P_i \mathcal{A}_i - \sum_{i=1}^N x_i \frac{mv_d}{\tau} \quad (\text{B.8})$$

677 The *bulk* pressure on the first  $M$  individuals increases as more individuals  
 678 are included in the crowd. This can be verified by evaluating Eq. (B.7) and  
 679 Eq. (B.8) for increasing values of  $N$ .

680

681 The Eqs. (B.2) and (B.3) allow to compute the pedestrian pressure profile  
 682 as a function of the distance to the wall. The profile is qualitatively similar  
 683 to the one measured during an evacuation process. Fig. B.13 represents the  
 684 histogram for the pressure on each pedestrian, computed as in Eq. 4 and  
 685 Eq. A.2 (see caption for details).

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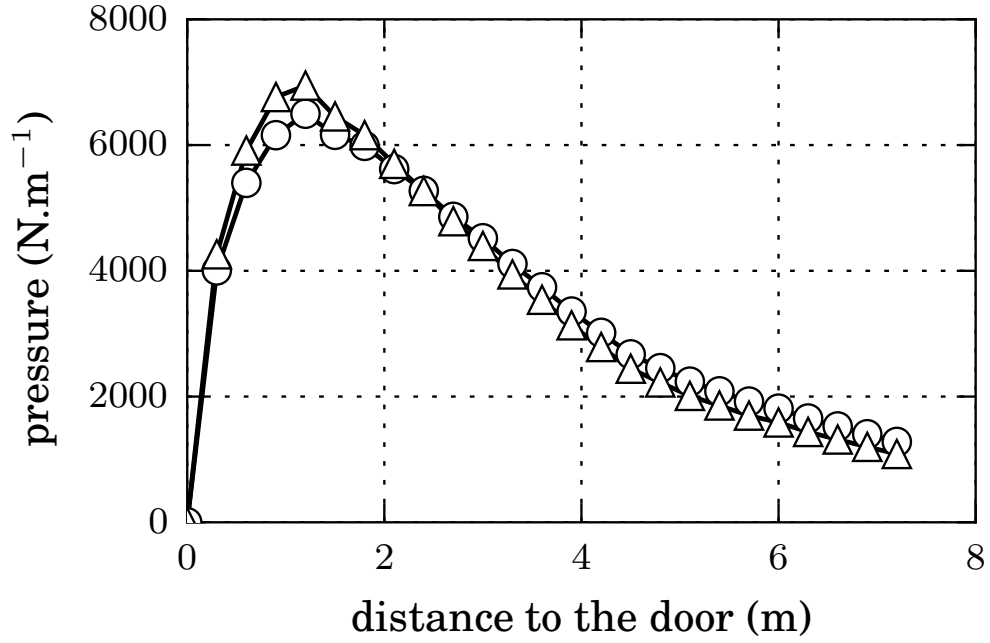


Figure B.13: Mean pressure as a function of the distance to the exit. The room was  $20\text{ m} \times 20\text{ m}$  size and included one door of  $d_w = 1.2\text{ m}$  width. Mean values were computed from 30 evacuation processes, until 100 pedestrians left the room. The desired velocity was  $v_d = 4\text{ m/s}$ . The distance to the door was binned into equal intervals of  $0.3\text{ m}$ . The  $\circ$  symbols correspond to the mean pressure computed as in A.2 for neglectable momentum ( $p_i = 0$ ) and  $\mathcal{A}_i = \pi r_i^2$ . The symbols  $\triangle$  correspond to the mean pressure computed as in 4 (see text for details).

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