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Panic evacuation of single pedestrians and couples

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Understanding the timing requirements for evacuation of people has focused primarily on independent pedestrians rather than pedestrians emotionally connected. However, the main statistical effects observed in crowds, the so-called "faster is slower", "clever is not always better" and the "low visibility enhancement", cannot explain the overall behavior of a crowd during an evacuation process when correlated pedestrians due to, for example feelings, are present. Our research addresses this issue and examines the statistical behavior of a mixture of individuals and couples during a (panic) escaping process. We found that the attractive feeling among couples plays an important role in the time delays during the evacuation of a single exit room.

Keywords: Evacuation; panic; couples; time delays.

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1. Introduction

The basic social force model (SFM) introduced by Helbing *et al.* handles the way how people move upon others.[1] The model is suitable for drawing conclusions about the effects of panic escape for increasing levels of impatience.[1]

The *private sphere* or *territorial effect* is the major behavioral pattern in the basic SFM model due to the interaction with other pedestrians, although other *attractive*

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effects were mentioned from the beginning.[1] It was suggested that the attractive effects could be simply modeled as monotonic increasing potentials.

Braun *et al.*[2] realized that for a better description of a *group structure*, it is necessary to include the properties of altruism and dependency in each pedestrian. These individual characteristics are responsible for some specific changes in the behavioral pattern of pedestrians inside groups. Thus, Braun and co-workers proposed that an attractive force should be added between pedestrians of the same group, while any individual characteristic will regulate its strength.[2]

Although the "family force" (that is, the attractive force between members of a group) seems to be good enough for modeling grouping patterns, it does not fulfill the expected behavior for very asymmetric individual characteristics.[3] The desired velocity of very dependent pedestrians (such as people with disabilities or any individual in need of help) vanishes, and therefore, the whole group may slow down. The SFM needs some kind of tuning for these situations.[3]

Researchers have hypothesized about the proper mathematical definition of the "family force". Braun's definition takes into account the distance between group members and the distance to the target, among other parameters.[2] But Lanman[4] realized that the attraction between members of the same group should hold until a certain cutoff distance. This cutoff is associated with the possibility of the pedestrian to note the other member in a crowded environment.[4]

Santos and Aguirre[5] called the attention on the fact that "social cohesion" is an important characteristic of any evacuating group. People can establish different degrees of social relationships before the panic situation. But other feelings, such as altruism or solidarity during the evacuation, may change the way they get involved. Thus, group size and cohesion are somehow related characteristics.

Social cohesion may cause delays in the evacuation because concern for other people implies interest in their opinions, and thus, more time to arrive to a collective decision.[5] Consensus is expected to be more time consuming in larger groups and in smaller ones.[5] In order to surpass this phenomenon, we will study only two member groups (couples).

In recent years, the social cohesion investigation has been assisted by image detection algorithms.[6] Video analysis has shown that large groups have a tendency to move in spacial patterns. These patterns are supposed to make easier the communication between group members while they keep walking together. However, an appropriate mathematical description seems to need at least three different forces (included the "family force") to reproduce the right pattern.[7] We will not examine the pattern formation, since we want to focus on the cohesion force only. This is the second reason for limiting the scope of our investigation to couples.

In Sec. 2, we will present the highlights of the SFM. In Sec. 2.2, we will define an attractive force that takes into account the requirements mentioned by Braun and Lanman.[2,4] In Sec. 4, we will show the results of our research and the corresponding conclusions can be found in Sec. 5.

2. Background

The basic "SFM" states that human motion depends on the people's own desire to reach a certain destination, as well as other environmental factors.[8,1] The former is modeled by a force called the "desire force", while the others are represented by "social forces" and "granular forces".

Pedestrians are supposed to have the desire to reach a specific target position. But, in order to reach the target at the desired velocity v_d, he (she) needs to accelerate (decelerate) from his (her) current velocity $\mathbf{v}(t)$. This acceleration (or deceleration) represents a "desire force" $\mathbf{f}_d$ because it is motivated by his (her) own willing. Its mathematical expression for pedestrian i is

$$\mathbf{f}_d^{(i)}(t) = m_i \frac{\mathbf{v}_d^{(i)}(t) - \mathbf{v}_i(t)}{\tau}, \tag{1}$$

where τ represents the relaxation time needed to reach his (her) desired velocity. Its value is determined experimentally.[9]

The desired velocity has magnitude v_d and pointing direction $\hat{\mathbf{e}}_d$. While v_d represents his (her) state of anxiety, $\hat{\mathbf{e}}_d$ indicates the target position where the pedestrian is willing to go to. There is no unique behavioral pattern for this magnitude, as pedestrians may handle each situation differently. However, in the context of a panic situation, we can assume that all the pedestrians will point straight forward to the closest exit.

Some environmental agents may produce a reaction on the pedestrians, giving rise to "social forces", and causing the pedestrians to change his (her) current velocity. In the context of an evacuation process, if no acquittance, friendship or family engagements exist, the most common feeling experienced by pedestrians is the tendency to keep some space between each other, or, from the walls.[1] These feelings become stronger as people get closer to each other or to the walls. Thus, the most relevant "social force" in a panic situation is a repulsive monotonic force that depends on the pedestrian–pedestrian (or wall–pedestrian) distance d_{ij}. It is modeled as

$$\mathbf{f}_s^{(ij)} = A_i \, e^{(r_{ij}-d_{ij})/B_i} \mathbf{n}_{ij} \tag{2}$$

for ij representing either pedestrians or walls. $\mathbf{n}_{ij}$ is the unit vector in the $\overrightarrow{ji}$ direction and $r_{ij} = r_i + r_j$ is the sum of pedestrian radius i and j. If j represents a wall, then r_j should be set to zero. The parameters A_i and B_i are estimates given in Ref. 8 and references there in.

The emotional reactions due to friendship or family engagements may also be handled as "social forces".[1] They are responsible for the attractive dynamics between two or more pedestrians. Still, it is not easy to get a mathematical expression for these forces. In Sec. 2.2, we will give a more precise description on this issue.

The sliding friction that appears between contacting people (or between people and walls) is present in the model as a "granular force". It is assumed to be a linear function of the relative (tangential) velocities. Its mathematical expression reads

$$\mathbf{f}_g^{(ij)} = \kappa(r_{ij} - d_{ij})\Theta(r_{ij} - d_{ij})\Delta\mathbf{v}_{ij} \cdot \mathbf{t}_{ij}, \tag{3}$$

where $\Delta\mathbf{v}_{ij}$ is the velocity difference between contacting pedestrians. $\mathbf{t}_{ij}$ is the unit tangential vector, orthogonal to $\mathbf{n}_{ij}$. κ is an experimental parameter. $\Theta(.)$ is the Heaviside cutoff function.

Further details on $\mathbf{f}_s(t)$ and $\mathbf{f}_g(t)$ can be found throughout the literature.[1,8–11] All experimental parameters appearing in Eqs. (1)–(3) are the same as in Ref. 9.

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.

2.1. *Human clusters*

Human clustering arises when pedestrians get in contact between each other. These morphological structures are responsible for the time delays during the evacuation process.[11,10] Thus, for future analysis a precise definition of this kind of structures is needed.

Our definition of 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

$$d_{ij} < r_i + r_j. \tag{5}$$

In Sec. 2, we have already defined the meaning of these magnitudes.

From all granular clusters, the *blocking clusters* are those that are in contact with the walls on both sides of the exit. The *minimum blocking structure* is a term that we will use to address the minimum set of contacting pedestrians (belonging to a *blocking cluster*) that connects the walls on both sides of the exit. Roughly speaking, it refers to the shortest chain of contacting pedestrians that links both sides of the exit door (see Fig. 1).

2.2. *Attraction between individuals (couples)*

It has been proposed that attractive effects should enter the SFM in the same way as the repulsive forces.[1] But, unlike the repulsive potential, attraction makes people to feel comfortable by sharing some space in common. If one of the partners is pushed aside, he (she) will try to move back to the space that he (she) was sharing. Thus, the attractive force holds until the space in common gets restored. At this point, the attractive feelings are supposed to balance the *private sphere* feelings.

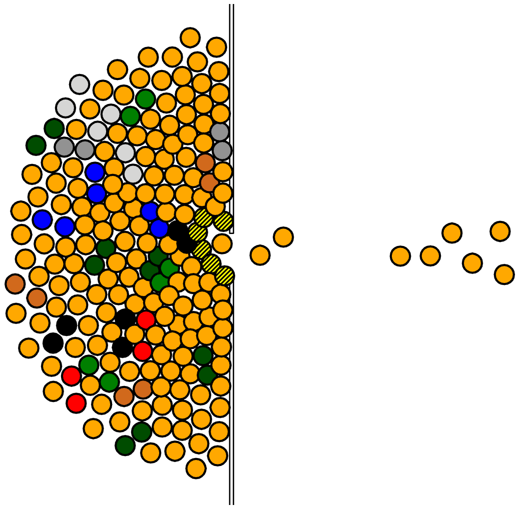

Fig. 1. (Color online) Snapshot of an evacuation process through a single door. Engaged individuals (i.e. couples) are shown in the same color, except for the orange that corresponds to independent individuals (online version only). The *minimum blocking structure* is the set of those individuals represented by a line pattern inside the circles.

Any choice for the attractive potential should meet the above behavior. Actually, a potential well qualifies as a short range function resembling a space in common. A simple potential well is the Fermi-like function. Other functions are also possible, but this one is a good starting point for its simplicity. The Fermi-like potential reads as follows:

$$U^{(ij)}(d_{ij}) = -\epsilon[1 + e^{(d_{ij}-C_i)/D_i}]^{-1} \tag{6}$$

for ϵ representing the intensity of the attraction. C_i and D_i are fixed values. The force associated with this potential can be expressed as

$$\mathbf{f}_a^{(ij)} = -\frac{\epsilon}{4D_i}\cosh^{-2}\left(\frac{C_i - d_{ij}}{2D_i}\right)\mathbf{n}_{ij}. \tag{7}$$

The inspection of Eqs. (6) and (7) shows two main properties. First, the attractive feelings hold for a short range, where the pedestrians are still aware of sharing a place in common. This is in agreement with the cutoff distance introduced by Lanman[4] (see Sec. 1). Secondly, if any partner comes too close to another, the attractive feelings vanish, as expected. Recall that the repulsive feelings should prevail inside the private sphere.

In order to settle the values of C_i and D_i, we may realize that Eqs. (2) and (7) depend on similar arguments. The magnitude B_i in Eq. (2) controls the typical length of the social interactions. The same role plays $2D_i$ in Eq. (7). Therefore, as a first approximation, we can fix $D_i = 0.5B_i$, under the likely hypothesis that pedestrian feelings share similar characteristic lengths.

When $d_{ij} = C_i$, the attractive force $\mathbf{f}_a^{(ij)}$ comes to a maximum (modulus), while the Fermi potential goes down to $\epsilon/2$ (modulus). However, we would not expect the attractive effect to trespass the private sphere of the pedestrians. Recalling Eq. (2), we can see that this occurs for $d_{ij} = 2r_{ij}$, roughly the width of one person. Thus, we fixed $C_i = r_{ij} + 7B_i$, which is close to $2r_{ij}$.

Regardless of the intensity of the attraction, $\mathbf{f}_a^{(ij)}$ should vanish smoothly at $d_{ij} = r_{ij}$. This is a drawback of the Fermi-like function. We explain how to overcome this issue in Sec. 3.

It is worthy of remark that all the attractions between pedestrians $\mathbf{f}_a^{(ij)}$ sum in the same way as $\mathbf{f}_s^{(ij)}$ in Eq. (4).

3. Numerical Simulations

3.1. *Geometry and process simulation*

We simulated the evacuation of a 20×20 m room with a single exit as described in Refs. 9 and 12. This was done for a better comparison of the current situation with those in which pedestrians are not really involved between each other. Any detailed information on the geometry of the room, the initial conditions, or the occupation density can be found there.

We time-integrated Eq. (4) through a velocity Verlet scheme with a time-step of 10^{-4} s. Neither obstacles, nor visibility constrains were included (see for example, Refs. 9 and 12). We ran 30 processes for each situation, in order to get enough data for mean values computation.

All the individuals had the willing to go to the exit door. That is, the desired direction $\hat{\mathbf{e}}_d$ pointed straight to the exit at each time-step. In terms of Refs. 9 and 12, no *herding-like* behaviors were considered. Interaction with the walls was implemented exclusively through the forces shown in Eqs. (2) and (3).

There were two kinds of individuals in each evacuation process: single ones or couples. Single individuals are those who interact upon others through social $\mathbf{f}_s^{(ij)}$ and granular $\mathbf{f}_g^{(ij)}$ forces only. Couples are pairs of individuals that interact with other individuals in the same way as singles, but are also mutually attracted through the force defined by Eq. (7). Note that the $\mathbf{f}_s^{(ij)}$ and the $\mathbf{f}_g^{(ij)}$ forces within the couple do not differ from the ones due to others.

At the beginning of the evacuation process, partners i and j (mutually attracted) had the same velocity (modulus and direction). Their desired velocity $\mathbf{v}_d$ was also set to the same value, since the couple was assumed to share the same willings to escape from the room. The distance between partners was $r_{ij} = r_i + r_j$ (contact distance) in order to vanish the attractive force at the very beginning. The purpose of vanishing the attractive force at time $t = 0$ was to make fair comparisons between situations with very different values of ϵ (see Eq. (7)). Nevertheless, the couples center of mass and the singles position followed the same initial pattern as in Refs. 9 and 12.

3.2. *Attraction implementation*

In order to achieve a smooth vanishing of the Fermi-like function (see Sec. 2.2) at the contact distance, we did a quadratic Bézier interpolation between $r_0 = r_{ij}$ and $r_2 = r_{ij} + 0.1\,\mathrm{m}$. The attractive force values at these positions were $f_0 = 0$ and $f_2 = f_a(r_2)$ (modulus), respectively. The corresponding derivatives were f'_0 and f'_2. The Bézier interpolation was

$$\mathbf{p}(t) = (1-t)^2\mathbf{p}_0 + 2t(1-t)\mathbf{p}_1 + t^2\mathbf{p}_2, \tag{8}$$

where t represents a varying parameter from 0 to 1. $\mathbf{p}_0$, $\mathbf{p}_1$ and $\mathbf{p}_2$ are the three points needed to meet the continuity conditions for a smooth matching at r_0 and r_2. Their values are $\mathbf{p}_0 = (r_0, 0)$, $\mathbf{p}_1 = (r_2 - f_2/f'_2, 0)$ and $\mathbf{p}_2 = (r_2, f_2)$. Figure 2 shows the Fermi-like function and the corresponding Bézier interpolation.

3.3. *Measurements conditions*

Data was recorded at time intervals of 0.05τ. Each process started with all the individuals (singles or couples) inside the room, in the same way as in Refs. 9 and 12. The pedestrians were able to leave the room through a single exit, while no re-entering mechanism was allowed. The measurement period lasted until 90% of the occupants left the room (approximately 180 individuals). If this condition could not be fulfilled within the first 1000 s, the process was stopped.

We focused on two specific cases: (a) 25% of the pedestrians were couples (roughly, 25 couples) and (b) 100% of the pedestrians were couples (approximately 100 couples). The (b) case is an extreme situation, but ensures that our results are valid for very different couples-to-singles ratios.

As mentioned in Sec. 1, we did not include groups of more than two members in order to avoid spurious effects due to the decision making processes (inside the group) or the group walking patterns.

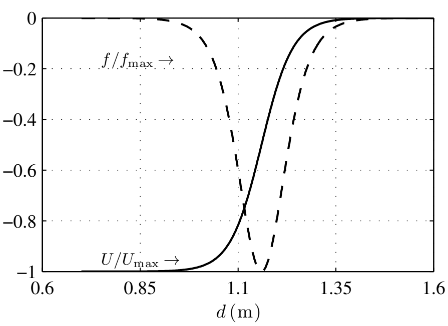

Fig. 2. Attractive potential (continuous line) and force (dashed line). The corresponding parameters, as defined in Eqs. (6) and (7), are $C = 1.16\,\mathrm{m}$, $D = 0.04\,\mathrm{m}$ and $\epsilon = 1000\,\mathrm{joules}$. The Bézier curve interval is 0.6 m–0.7 m. The maximum attraction (dashed line at its minimum) occurs at $d_{\max} = 1.16\,\mathrm{m}$.

4. Results

In the following sections, we present results for an anxiety level of $v_d = 4\,\mathrm{m/s}$. This level is representative of panicking situations[1,9,12] achievable by pedestrians of different ages.

4.1. *The feeling degrees*

At first, we checked off that the presence of couples (i.e. attractive pairs of individuals) among the pedestrians causes a delay in the escaping process from a single exit room. Figure 3 shows the mean evacuation time $\langle t \rangle$ for a crowd in panic when 25% or 100% of the pedestrians are grouped in couples. For extremely weak feelings ($\epsilon \simeq 1\,\mathrm{N\cdot m}$), the mean time is similar to the case of no couples at all (see for example, Refs. 9 and 12). But, a sharp increase in $\langle t \rangle$ for strength feelings can be seen between $10^2\,\mathrm{N\cdot m} \leq \epsilon \leq 10^3\,\mathrm{N\cdot m}$. The worst evacuation performance occurs close to the transition ($\epsilon \sim 10^4\,\mathrm{N\cdot m}$).

As ϵ increases from $10^4\,\mathrm{N\cdot m}$ to $10^{10}\,\mathrm{N\cdot m}$, we observe that the slope of the response curves in Fig. 3 change sign again. This happens on both curves, but it becomes fairly notable when 100% of the pedestrians belong to a couple. Due to this change, a small improvement in the evacuation time occurs for $\epsilon \gg 10^4\,\mathrm{N\cdot m}$. However, the evacuation time is still worse than its level at $\epsilon \leq 10^2\,\mathrm{N\cdot m}$. We will analyze the most intense attractive region in a latter section.

The sharp transition in Fig. 3 was not expected. Consequently, we focused our attention on the underlaying changes in the behavioral pattern of the couples. We measured the distance between partners in each couple. Indeed, we were only interested on the maximum separation distance at each time-step, in order to get a first insight of the behavioral pattern. Figure 4 shows the maximum distance for different processes (see the caption for details).

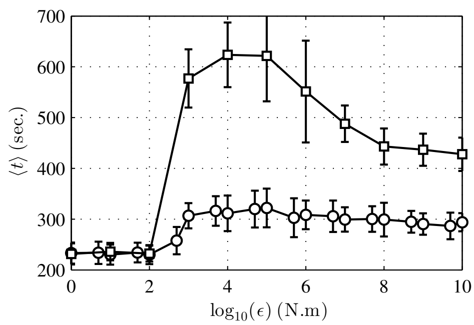

Fig. 3. Mean evacuation time for 160 individuals (singles and couples) as a function of the attractive feeling intensity $\log_{10}(\epsilon)$. The desired velosity is $v_d = 4\,\mathrm{m/s}$. (a) Circles show the evacuation time when 25% of the pedestrians are grouped in couples. (b) Squares correspond to 100% of the pedestrians grouped as couples. The error bars represent the standard deviation interval.

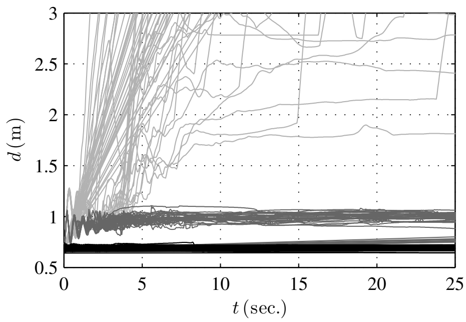

Fig. 4. (Color online) Maximum distance between partners d versus time (t). The maximum distance corresponds to the maximum value taken from the set of all the distances between partners, at each time step. The evacuation processes had 25% of the pedestrians were grouped in couples. The desired velocity was $v_d = 4\,\mathrm{m/s}$. The attractive feelings are: (a) $\epsilon = 10^2\,\mathrm{N}\cdot\mathrm{m}$ in light gray, (b) $\epsilon = 10^4\,\mathrm{N}\cdot\mathrm{m}$ in medium gray, and (c) $\epsilon = 10^8\,\mathrm{N}\cdot\mathrm{m}$ in black.

From a first examination of Fig. 4, we can distinguish three qualitative behavioral patterns. The first pattern corresponds to the evacuation processes where the attractive feelings are weak ($\epsilon = 10^2\,\mathrm{N}\cdot\mathrm{m}$). The partner separations increase most of the time, or keeps far way from the distance where $\mathbf{f}_a^{(ij)}$ comes to a maximum (compare Figs. 2 and 4). In other words, as a consequence of the interactions, couples grow apart. On the contrary, a second behavioral pattern can be seen close to $d = 1\,\mathrm{m}$. This pattern represents more intense attractive feelings since $\epsilon = 10^4\,\mathrm{N}\cdot\mathrm{m}$. Within this behavior, coupled pedestrians never leave the space in common. Some of them may even be in contact for several seconds. Moreover, if the feelings become as intense as $\epsilon = 10^8\,\mathrm{N}\cdot\mathrm{m}$, the couple members remain in contact all the time (see the black lines in Fig. 4).

The different behavioral patterns become distinguishable after a time period of approximately 5 s. This is the time needed for the pedestrians to rush to the exit. Note that in Fig. $4v_d \times 5\,\mathrm{s} = 20\,\mathrm{m}$ gives the width of the room. Thus, weakly attracted partners can still lose the space in common during the clogging period ($t > 5\,\mathrm{s}$).

Figure 5 shows the distribution of the distances exhibited in Fig. 4 for $t > 5\,\mathrm{s}$. The arrow in Fig. 5 points to the threshold $d = 1.3\,\mathrm{m}$ as a limiting value between the weak feelings pattern and the intense one. Couples having weak attractive feelings ($\epsilon \leq 10^2\,\mathrm{N}\cdot\mathrm{m}$) get so separated that no real attraction exists after some time (see Fig. 5(a)). That is, they try to escape no matter what happens to the other one. This behavior is not what we expect between family members, so we envisaged this pattern as just “friendship”.

Figures 5(b) and 5(c) correspond to couples that remain gathered along the escaping process, although there are seldom occasions that force them to separate. Nevertheless, the distance between both of them are bounded by 1.3 m, that is, the limit where the attraction becomes negligible. Feelings in Fig. 5(b) may belong to

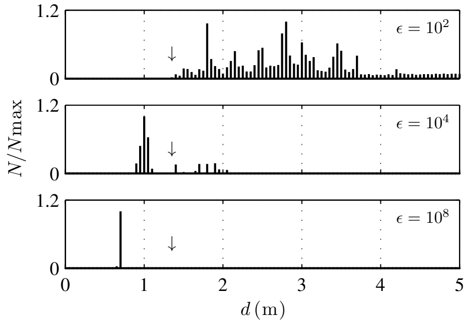

Fig. 5. Histogram of the number of couples versus partners separation d. Data was taken from Fig. 4 excluding the time interval $0 < t < 5\,\mathrm{s}$. The desired velocity was $v_d = 4\,\mathrm{m/s}$. The histogram is normalized to the have its maximum at unity. Each bin has $0.02\,\mathrm{m}$ width. Three attractive levels are shown: (a) $\epsilon = 10^2\,\mathrm{N \cdot m}$, (b) $\epsilon = 10^4\,\mathrm{N \cdot m}$ and (c) $\epsilon = 10^8\,\mathrm{N \cdot m}$. The arrow indicates the $1.3\,\mathrm{m}$ separation. At this place the attractive force decay roughly to 10% of its maximum value.

family members because they try to preserve the space in common. Couples in Fig. 5 (c) are always in contact, so they can be visualized as hugged couples.

So far, we can resume all these observations as follows. The attractive feelings split into three qualitative categories: friendship, family membership and tightly close people (personally close). The presence of family members or personally close pedestrians worsens the evacuation performance, and this worsening is associated to the preservation of the space in common. However, tightly close people (i.e. inside the private sphere) perform pretty better than family members.

4.2. *The broken links*

We realized from the distance distributions in Fig. 5 that there is a critical threshold (say, $d = 1.3\,\mathrm{m}$) that differentiates those couples that are able to preserve the space in common from those who cannot. Recalling from Sec. 2.2, this is approximately the distance bounding the potential well of the attractive feelings. Moving apart from the $1.3\,\mathrm{m}$ threshold makes the attractive feelings negligible with respect to the social or granular forces motivated from other single pedestrians. Thus, many former partners are no longer expected to move together after surmounting this threshold, but to now become single pedestrians.

In order to understand the relationship between the preservation of the "space in common" and the three feeling categories defined in Sec. 4.1, we now classify the couples into to groups: *surviving couples* and *broken couples*. The former are those whose members do not exceed the $1.3\,\mathrm{m}$ threshold. The latter are those that exceeded this threshold. Couples can belong to either group at any time.

At the beginning of the evacuation process, all the couples belong to the surviving group since partners are separated a distance $r_{ij} = r_i + r_j$ (see Sec. 3.1). This does not depend on whether the couples are friends, family members or tightly close people. However, if the feeling degrees have some control on the "space in common",

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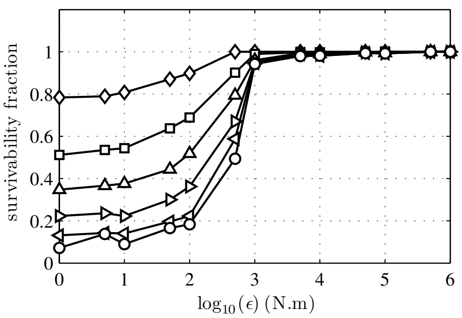

Fig. 6. Fraction of surviving couples versus attractive feelings (ϵ). The survivability was taken at increasing time intervals, represented by each curve. The time intervals are: $\diamond = 5\,\mathrm{s}$, $\square = 50\,\mathrm{s}$, $\triangle = 100\,\mathrm{s}$, $\triangleright = 150\,\mathrm{s}$, $\triangleleft = 200\,\mathrm{s}$ and $\circ = 250\,\mathrm{s}$. All periods began at $t = 0$. The desired velocity was $v_d = 4\,\mathrm{m/s}$. At the beginning of the processes, 25% of the pedestrians were coupled. No distinction was made between couples inside or outside the room (all of them were recorded).

we expect a notable dependency of the surviving couples with respect to ϵ at the end of the evacuation. Figure 6 shows the mean surviving couples as a function of ϵ. Each curve represents the survivability fraction for fixed time intervals (5, 50, 100 s, etc.) and increasing attractive feelings along the horizontal axis (see caption for details).

From the inspection of Fig. 6, we observe that for very weak attractions (say, $\epsilon = 1$) the fraction of surviving couples decreases regularly throughout the evacuation process. This pattern remains the same along the friendship category ($\epsilon \leq 10^2\,\mathrm{N \cdot m}$). But for attractive feelings as intense as those expected for family members, the surviving fraction rises to nearly 1.0. Only a few couples break during the evacuation. Further increase in the attraction levels (personally close partners) allow virtually all the couples to survive, as shown in Fig. 5.

Figure 6 is in perfect agreement with Fig. 3. Both exhibit a corresponding qualitative change between $\epsilon = 10^2\,\mathrm{N \cdot m}$ and $\epsilon = 10^3\,\mathrm{N \cdot m}$. While low evacuation times ($\epsilon \leq 10^2\,\mathrm{N \cdot m}$) are associated with a couple breaking process throughout the evacuation, the worsening in the overall egress times ($\epsilon \geq 10^3\,\mathrm{N \cdot m}$) corresponds to the lack of this breaking.

4.3. *Position of the broken couples*

In Sec. 4.2, we classified the couples into those that were able to preserve the "space in common" and the others whose partners separated from each other. The latter exceeded some threshold distance (say, 1.3 m according to the definition given in Sec. 4.2). We now assume that the pedestrians surrounding the couples should somehow play an important role in the process of couple breaking. So, our next step in the investigation studies the position of the broken pairs inside the *bulk*.

We start with a small amount of coupled pedestrians. Figure 7 shows the pedestrians position for those individuals belonging to any broken pair at different time intervals (see for example, Fig. 6). For weak attractive feelings (meaning

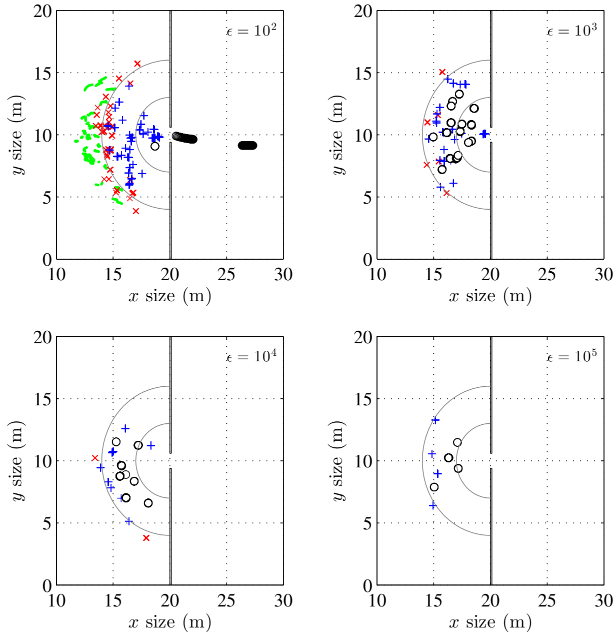

Fig. 7. (Color online) Position of all the partners belonging to *broken* couples for 30 evacuation processes. Each picture corresponds to a fixed attractive intensity (see text at the top-right of the picture). The symbols mean: $t = 5\,\mathrm{s}$ ($\bullet$ in green), $t = 50\,\mathrm{s}$ ($\times$ in red), $t = 150\,\mathrm{s}$ ($+$ in blue) and $t = 250\,\mathrm{s}$ ($\circ$ in black). The desired velocity was $v_d = 4\,\mathrm{m/s}$. At the beginning of the processes, 25% of the pedestrians were coupled. The semi-circles are guides for the view at radii 3 m and 6 m. Colors can only be seen in the online version.

"friendship") we can see many former couples at the surrounding of the *bulk* or clogging area. The maximum number of pedestrians belonging to broken couples appear at the early stage of the process, that is, for $t \leq 50\,\mathrm{s}$ (see Fig. 8, top-left plot). They spread along a circle approaching 6 m radius. For an optimal packing density $\pi/\sqrt{12}$ (corresponding to a hexagonal packing arrangement), this radius encloses nearly 180 pedestrians (see Ref. 12 for details on this computation). Thus, the pedestrians tagged with $\bullet$ (in green) and $\times$ (in red) symbols in Fig. 8 are outbound broken couples.

We can further note a qualitative change in Fig. 8 for attractive strengths $\epsilon \geq 10^3\,\mathrm{N} \cdot \mathrm{m}$. We do not see many broken couples, while the few ones have move closer to the exit. Since they appear at time interval $t \geq 150\,\mathrm{s}$, they still surround the small *bulk* left at that stage of the process. Figure 8 also captures these facts when 100% of the pedestrians have attractive feelings.

4.4. *Separation distance and couple delays*

We examined the location of broken couples in the previous section. We are now going to focus on the surviving couples. Figure 9 shows the separation distance for surviving couples. Four cases are shown, corresponding to four different values of the

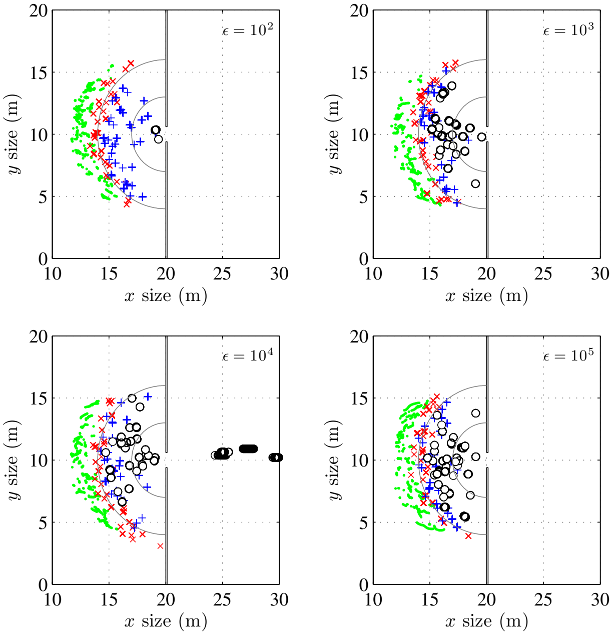

Fig. 8. (Color online) Position of all the partners belonging to *broken* couples for 30 evacuation processes. Each picture corresponds to a fixed attractive intensity (see text at the top-right of the picture). The symbols mean: $t = 5\,$s (• in green), $t = 50\,$s ($\times$ in red), $t = 150\,$s (+ in blue) and $t = 250\,$s (∘in black). The desired velocity was $v_d = 4\,$m/s. At the beginning of the processes, 100% of the pedestrians were coupled. The semi-circles are guides for the view at radii 3 m and 6 m. Colors can only be seen in the online version.

strengths ϵ. The left most distribution and the centered one in Fig. 9 correspond to "family members" (see Sec. 4.1). Further increase in the strength ϵ (not shown) make the partners move tight together or hugged (i.e. "personally close" partners), resembling a single wider pedestrian.

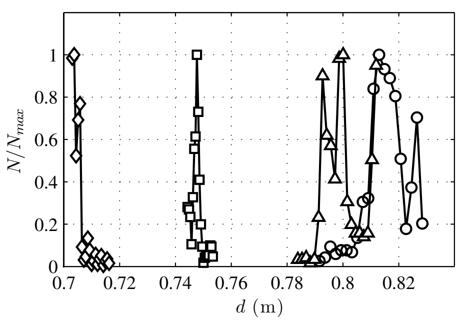

Fig. 9. Normalized distribution of the separation distance between couple partners. No *broken* couples have been included (only surviving ones). Data belong to 30 evacuation processes measured at times $t > 5\,$s. Each line corresponds to a fixed attraction strength (ϵ). The symbols mean: (○) $\epsilon = 10^2\,\mathrm{N}\cdot\mathrm{m}$, (△) $\epsilon = 10^3\,N\cdot\mathrm{m}$, (□) $\epsilon = 10^4\,\mathrm{N}\cdot\mathrm{m}$ and (◇) $\epsilon = 10^5\,\mathrm{N}\cdot\mathrm{m}$. The desired velocity was $v_d = 4\,$m/s. At the beginning of the processes, 25% of the pedestrians were coupled.

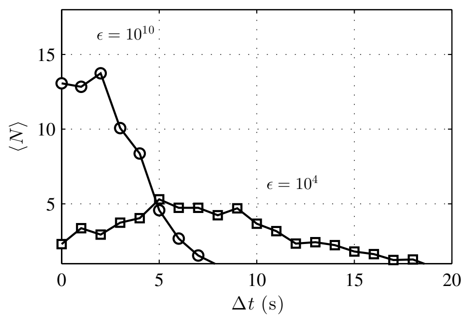

Fig. 10. Distribution of the time interval Δt since one partner leaves the room, until the other partner (belonging to the same couple) also gets out. The vertical axis represents the number of occurrences averaged over 30 evacuation processes. The symbols mean: (○) $\epsilon = 10^{10}\,\mathrm{N \cdot m}$ and (□) $\epsilon = 10^4\,\mathrm{N \cdot m}$. The desired velocity was $v_d = 4\,\mathrm{m/s}$. At the beginning of the processes, 100% of the pedestrians were coupled.

We hypothesize that the tight movement of personally close pedestrians is somehow related to the less worsening of the mean evacuation time for very intense attractive feelings (see Fig. 3). Figure 10 shows the distribution of the elapsed time average Δt since one of the partners leaves the room until the other one (belonging to the same couple) does. We can see that the Δt distribution narrows down to barely few seconds for highly attracted couples. For the "family members" category ($\epsilon \sim 10^4\,\mathrm{N \cdot m}$) the distribution widens. Thus, it appears to be a time saving effect when couples move tight together.

It is worth noting that Fig. 10 correspond to evacuation processes where 100% of the pedestrians are coupled from the beginning. This means that Δt applies to all the pedestrians in the room. The distributions in Fig. 10 correspond to two qualitatively different behaviors. The flat distribution representing the Δt's for the "family members" category ($\epsilon = 10^4\,\mathrm{N \cdot m}$) exhibits long lasting delays during the escaping process. On the contrary, the concentrated distribution for the "personally close" category means that the (contacting) partners escape in a short period of time, while it is very unlikely to find them clogged for a long time interval. This behavior is in agreement with the slight improvement in the evacuation time $\langle t \rangle$ for very high levels of ϵ (that is, "personally close" category) with respect to the "family members" category. Since "personally close" couples resemble a single wider pedestrian, we may conclude that this tight-together movement is responsible for facilitating the evacuation.

5. Conclusions

We examined in detail the evacuation of pedestrians with attractive feelings between each other. We only considered a mix of single pedestrians (no attractive feelings at all) and pedestrians grouped in pairs (couples mutually attracted). Throughout Sec. 4, we presented results on the evacuation performance under a panic situation. The panic level was set to $v_d = 4\,\mathrm{m/s}$ (where the "faster is slower" effect is present).

An unexpected effect appeared for the mean evacuation time $\langle t \rangle$ as the couple's attractive feelings increased. We found a sharp change in $\langle t \rangle$ for moderate attractive feelings. Thus, we were able to envisage three different escaping scenarios, one for low attractive feelings and the other two for intense ones. The feeling threshold remained the same whether 25% or 100% of the pedestrians were grouped in couples, although the latter worsened the evacuation performance.

Another surprising result occurred in the very intense attractive feelings range ($\epsilon \sim 10^6\,\mathrm{N \cdot m}$). Less worsening of the evacuation time $\langle t \rangle$ was observed in comparison to the after-threshold feelings range. Thus, the complete picture showed three different feeling categories: friends, family members or personally close people. Friendship has actually no relevant effects on $\langle t \rangle$, while more intense feelings (family members or personally close people) are responsible for worsening the evacuation performance. The sharp jump in $\langle t \rangle$ occurs between the friendship feelings and the family member feelings. Personally close feelings make a better performance than family member feelings.

We were able to set a bounding distance for the couples attractive feelings. In our model, partners separated beyond $d \simeq 1.3\,\mathrm{m}$ rarely restore their common space again. Thus, after d is exceeded, they behave as single pedestrians. These former couples are now classified as *broken* couples.

An inspection of the dynamics of broken couples showed that friends (i.e. weakly attracted pedestrians) separate from each other at the beginning of the evacuation process ($t \leq 100\,\mathrm{s}$). Surprisingly, friends surrounding the clogging area are more likely to separate than those near the exit.

Nearly all the family members or personally close people preserve their space in common ($d < 1.3\,\mathrm{m}$) along the entire evacuation process. However, we observed a reduction of the worsening in $\langle t \rangle$ for personally close people with respect to family members. Both categories have a survivability ratio close to one, but personally close partners move tight together (in contact) while family members share a wider space (see Fig. 9). Consequently, personally close partners resemble better a single big pedestrian than family members do. This reduces the transit time through the exit, making less severe the worsening in $\langle t \rangle$ with respect to the "family member" category.

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References

1. D. Helbing and P. Molnár, *Phys. Rev. E* **51**, 4282 (1995).
2. A. Braun, S. Musse, L. de Oliveira and B. Bodmann, Modeling individual behaviors in crowd simulation *Proc. of the 16th Int. Conf. on Computer Animation and Social Agents (CASA03)*, (IEEE, New Jersey, 2003), p. 143.

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3. M. Israelsson, *Proc. of the 16th Int. Conf. on Computer Animation and Social Agents (CASA03)*, Department of Science and Technology, Linköpings Universitet, **LITH-ITN-MT-EX–05/061–SE** (2005).
4. A. Lanman, Modeling in Social Dynamics: A Differential Approach (NSF grant BCS-0527545) University of Central Florida (2007).
5. G. Santos and B. E. Aguirre, A critical review of emergency evacuation simulation models in *Proc. of Conf. Building Occupant Movement During Fire Emergencies.* Gaithersburg, Maryland, 10–11 June 2004, Vol. 339 of DRC preliminary paper (Disaster Research Center, University of Delaware, 2004).
6. M. Moussaïd, N. Perozo, S. Garnier, D. Helbing and G. Theraulaz, *PLoS ONE* **5**, 1 (2010).
7. L. Cheng, R. Yarlagadda, C. Fookes and P. K. Yarlagadda, *World J. Mech. Eng.* **1**, 1 (2014).
8. D. Helbing, I. Farkas, and T. Vicsek, *Nature* **407**, 487 (2000).
9. G. Frank and C. Dorso, *Physica A* **390**, 2135 (2011).
10. D. Parisi and C. Dorso, *Physica A* **385**, 343 (2007).
11. D. Parisi and C. Dorso, *Physica A* **354**, 606 (2005).
12. G. Frank and C. Dorso, *Int. J. Mod. Phys. C* **26**, 1 (2015).