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How to push one's way through a dense crowd

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Abstract – Moving through a dense crowd to help someone can be a tough task for emergency services as well as for security agents willing to ease a star to cross a crowd of fans. High densities reduce the mobility of an individual who wants to move and cross a crowd by pushing their way through. In this work, we study two situations. The first considers a person who moves through a static crowd while the second reports on a moving person (*e.g.*, a star) who crosses a crowd of fans. Despite the simplicity of the mechanical model we use to describe a moving person who pushes apart the people of the crowd or tries to avoid them, we obtain some non-trivial results. Depending on the rigidity of a static crowd or on the aggressiveness of fans we extract quantities like the average velocity of a person moving across a crowd or the critical number of fans above which any motion of a star is impossible.

Introduction. – The study of pedestrian dynamics has become a very important issue [1] during the last two decades. A key challenge facing civil security [2] over the next years will be how to keep security expectations at a high level while confronted to the increasing number of mass events, where several thousands of people gather in confined areas. Depending on the event and the social context, situations can markedly vary. For example, crowd stampede induced by panic or jamming during escape panic [3] or motion of people during rock concerts [4] are collective phenomena currently observed in specific social settings which can emerge from simple rules at the scale of each individual [5]. Numerical simulations are generally inspired from social force models [3,6–10], cellular automata [11–14], and artificial intelligence-based models [15,16]. These models start from inter-individual "social" forces and describe quite well the currently observed collective effects at the scale of the crowd.

Beside the collective behaviours, we consider here the motion of a person who needs or wants to move through a static crowd of standing people or through a crowd of converging fans. Surprisingly, this knowledge has been largely neglected but can be essential to know how to provide assistance to someone in a middle of a crowd for example or to evaluate the time necessary for someone to escape from a crowd. People in the crowd can be more or less reluctant to let someone pass. For example, during a rock concert, moving toward the stage can be very difficult while moving back from the stage by leaving your place, will encourage people to let you pass.

In this work, a simple model is used to extract general tendencies and strong effects. We believe that this could pave the way to more elaborated models in order to describe quantitatively specific real situations. We develop a simple mechanical force model, from which emerges a non-trivial dynamics for the moving person (MP). In particular, we examine two strategies that can be used to move through a crowd. In the first one, the MP can push people without trying to avoid them when moving in a given direction. In the second one, the MP tries to avoid people in front of him/her and pushes them if necessary. Note that we will use the term "push" when we consider a mechanical contact between the moving person and an individual of the crowd. This contact can simply be a visual contact or a real mechanical contact depending on the situation. However, we always use the term "push" for simplicity and we model it as a mechanical force. We define a dimensionless parameter that allows to quantify this social rigidity (see below). For a very soft crowd, we observe that a person can move with a maximum attainable velocity which depends on the crowd density with a simple polynomial law.

Then, we examine the case of a star moving through a crowd of fans. The fans converge toward the star at

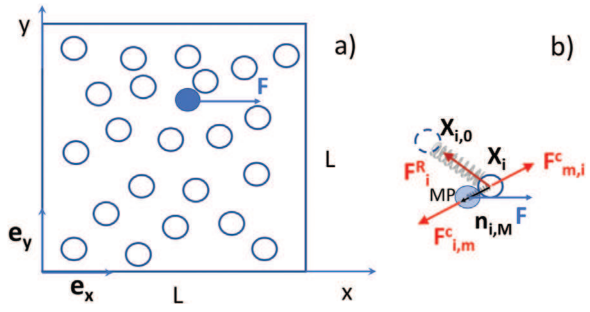

Fig. 1: (Colour online) (a) Schematic representation of the system: MP (closed symbol) and individuals (open symbols). (b) Exerted mechanical forces exerted when the MP is in contact with the i-th individual of the crowd ($\epsilon_{iM} = 1$).

a given desired velocity. We define a dimensionless parameter which measures the ratio between a fan's and the star's desired velocities. Then, we study the critical number of fans above which the motion of the star becomes impossible as a function of this dimensionless parameter. It appears that the motion of the star can be stopped for a very small initial density of fans ($14\% \approx 1.1$ discoidal person $/\mathrm{m}^2$), much below the values usually known as critical for evacuation processes [17].

A moving person through a static crowd. – We use a simple mechanical model based on forces exerted between individuals. The model is similar to a social force model [3,8,18] for crowds. In force models, the main ingredients are a driving force which makes an individual move, a repulsion force between people to model contacts and a possible attraction force which represent some affinity of people (friends, street artist, favourite position, ...).

Usually, the social force is such that $\mathbf{F} \propto -(\mathbf{v} - \mathbf{v}_0)/\tau_r$ [8] for an individual who has an actual velocity $\mathbf{v}$ and a desired velocity $\mathbf{v}_0$. This force tends to restore the desired velocity with an inertial (or reaction) time τ_r. Injecting this force into Newton's second law gives $\dot{\mathbf{v}} = -\mathbf{v}/\tau_r + \mathbf{v}_0/\tau_r + \mathbf{F}'$ (the mass is usually set to 1, $\mathbf{F}'$ represents other forces in the system). The first term of the right-hand side is a dissipation and the second term is a driving force. In our study, we use an overdamped dynamics approach, *i.e.* without inertia: we assume that τ_r is very small so that once released from contacts (*i.e.* $\mathbf{F}' = 0$), the individuals can instantaneously reach their desired limit velocity $\mathbf{v}_0$. Estimation of the reaction time is about $\tau_r \approx 0.5\,\mathrm{s}$ [19]. The overdamped dynamics approach also prevents the appearance of unrealistic effects due to Newton's equation of motion describing particles with inertia [20] such as overlapping and oscillations of the modelled pedestrians [21]. In our case, the absence of inertia also allows to avoid unrealistic oscillations when an individual moves back to its favourite position.

We consider a moving person (MP) at some position $\mathbf{x}_M = x_M\mathbf{e}_x + y_M\mathbf{e}_y$ who wants to go in a given direction ($x > 0$) and must cross a crowd of people on the way (fig. 1). The crowd consists in N individuals (including the MP), initially uniformly distributed at random positions $\mathbf{x}_i = x_{0,i}\mathbf{e}_x + y_{0,i}\mathbf{e}_y$ ($i = 1, \ldots, N$) in a square domain of size $L \times L$. We denote R the "radius" of an individual modelled as a disk, and assume $L \gg R$. In our simulations, we use $1 < N < 410$ and $L/R = 40$. The N individuals are free to move out of the initial $L \times L$ domain (open boundary conditions). The surface fraction of discoidal people is defined as $\phi = N\pi R^2/L^2$. To account for the more realistic human elliptical shape, we average the estimated semi-major and semi-minor axes $a \approx 0.25$ m and $b \approx 0.15\,\mathrm{m}$, and assume that the typical radius is $R \approx 0.2$ m for each "discoidal" individual. This leads to a surface of $\approx 0.13\,\mathrm{m}^2$ per person. Thus, the number of persons per square meters is given by $N/L^2 \approx \phi(\%)/13$ for discoidal people. In order to obtain random configurations with high surface fractions (close to maximum packing), we first distribute the N individuals into a larger square domain ($L' \times L'$) with $L' = 1.2L$ and then apply a convergent force to each individual to make them converge into the $L \times L$ domain. With this method, we can reach densities up to $\phi \approx 80\%$, very close to the maximum random packing value $\phi_{\max} \approx 82\%$ [22]. Note that in this model, R represents the typical scale for local interactions. In case of real mechanical contacts, it represents for instance the average size of a person; but it can also account for individual territories if social interactions are considered.

The individuals of the crowd (except the MP) are static until they are pushed by the MP or their neighbours. They can be more or less reluctant to move from their initial position, as it is usually the case for standing people during a show for example.

The MP has a "free-state" ($\phi \to 0$) desired velocity $\mathbf{v}_M(\phi \to 0) \equiv v_0\mathbf{e}_x$, which in an overdamped approach is equivalent to having a driving force $\mathbf{F}_0 = \eta\,\mathbf{v}_M(\phi \to 0)$, where $\frac{1}{\eta}$ can be regarded as a mobility. Without loss of generality, we can take $\eta = 1$. In the presence of the crowd, $\mathbf{v}_M(\phi)$ depends on the surface fraction ϕ.

We define the MP velocity $\mathbf{v}_M$ as well as the velocity of the i-th individual ($i \neq M$) as follows:

$$\begin{cases} \eta\,\mathbf{v}_M = \mathbf{F}_0 + \mathbf{f} + \displaystyle\sum_{i \neq M}^{N} \epsilon_{i,M}\mathbf{F}^C_{i,M}, \\ \eta\,\mathbf{v}_{i \neq M} = \mathbf{F}^R_i + \displaystyle\sum_{j \neq i}^{N} \epsilon_{i,j}\mathbf{F}^C_{j,i}, \end{cases} \tag{1}$$

where $\mathbf{f}$ is a noise term which takes into account random fluctuations of the MP's behaviour arising from accidental or deliberate deviations from the usual rule of motion (determined by $\mathbf{F}_0$). Interactions between individuals (including the MP) are accounted for through a contact force which prevents inter-penetrations and which depends only on individuals interdistance. The force $\mathbf{F}^C_{i,j}$ is the contact repulsive force acting between the i-th and j-th individuals (fig. 1). Note that this contact force, usually used in crowd models, does not take into account tangential friction between individuals. The parameter $\epsilon_{i,j}$ measures if there is a contact between the i-th and j-th individuals, if $|\mathbf{x}_j - \mathbf{x}_i| > 2R$ then $\epsilon_{i,j} = 0$ and $\epsilon_{i,j} = 1$ otherwise. We use a social elastic force which links an individual to their favourite position: the retraction force is all the greater as the person moves away from his initial (favourite) position, with a linear dependence on the distance to the initial position. The elastic retraction force $\mathbf{F}_i^R$ acts on the i-th ($i \neq M$) individual if $\mathbf{x}_i \neq \mathbf{x}_{0,i}$. The unitary vector $\mathbf{n}_{i,j}$ is oriented from i-th to j-th individual. The retraction and contact forces are, respectively, defined as follows:

$$\begin{cases} \mathbf{F}_{i\neq M}^R = -k_R\left(\mathbf{x}_i - \mathbf{x}_{i,0}\right), \\ \mathbf{F}_{i,j}^C = -k_C\left(|\mathbf{x}_j - \mathbf{x}_i| - 2R\right)\mathbf{n}_{i,j}, \end{cases} \tag{2}$$

where k_R and k_C are spring constants. The contact spring repels two close bodies which are below a diameter apart from each other, while the retraction spring elastically maintains an individual to its initial position except the MP who is not linked to its initial position. Each individual can move pushed by the MP or by another individual through a cascade of contacts. Note that we consider that the non-moving individuals are static when not affected by the MP or their neighbours. Therefore we do not consider any random fluctuation for the individuals around their favourite position.

We use an explicit Euler scheme to discretize the system of dynamic equations $\dot{\mathbf{x}}_i = \mathbf{v}_i$, $\forall i$, *i.e.*, writing $\mathbf{X} = \{\mathbf{x}_i\}$ and $\mathbf{V} = \{\mathbf{v}_i\}$, we have $\mathbf{X}^{n+1} = \mathbf{X}^n + \mathbf{V}^n\Delta t$, with $\mathbf{V}^n$ given by (1), and where Δt is the time step, the superscripts denoting time. We also write the noise term as $\mathbf{f} = \alpha\,\mathrm{d}\mathbf{w}/\mathrm{d}t$, where $\mathbf{w}(t)$ is a Wiener process. Its time discretization then writes $\mathbf{w}^{n+1} = \mathbf{w}^n + \boldsymbol{\xi}^n$, with $\boldsymbol{\xi}^n \sim \mathcal{N}^{2D}(0,1)$ some normally distributed vector in the (x,y)-plane. We assume that a reasonable amplitude for the noise corresponds to $\alpha \approx F_0/10$.

We can define a relaxation time associated to the retraction spring such as $\tau = \eta/k_R$ and a ballistic time associated with the MP motion, $\tau_B = 2R/v_0$. We define the dimensionless relaxation time $T = \tau/\tau_B$. Note that T also represents the ratio between the driving force $F_0 = \eta v_0$ and the typical retraction force $2k_R R$. When $T \ll 1$, the crowd can be considered as rigid: individuals are very reluctant to move. On the contrary, for $T \gg 1$, the crowd is soft and individuals can move away from their initial position, even without any retraction force if $T \to \infty$.

We compute the motion of the MP as a function of time for some given driving force $\mathbf{F}_0$. We consider two cases for the choice of $\mathbf{F}_0$. The first consists in fixing $\mathbf{F}_0 = F_0\mathbf{e}_x$. This is the "mindless" option, where no local strategy is used to help the motion. In the second option, $\mathbf{F}_0$ is chosen depending on the neighbourhood of the MP: we consider 180 possible directions from the actual MP's position from $\theta = -\pi/3$ to $\theta = \pi/3$, where θ is the angle between $\mathbf{F}_0$ and $\mathbf{e}_x$, and calculate the density of people along each direction on a distance equal to two diameters in front of the MP. We then select the direction associated with the smallest density, and the MP moves with the selected driving force during a time $4R/v_0$. After this time, a new direction is selected with the same method. This way of avoiding people in front of the MP is of course not an optimal strategy to find a path through the labyrinthic crowd (for example, MP cannot go backward to find another path). However, it seems to be the kind of strategy used by a person who cannot evaluate all the possibilities to get out from the crowd. Note, that finding an optimal way is not an easy process, since the crowd is not simply labyrinthic but also deformable.

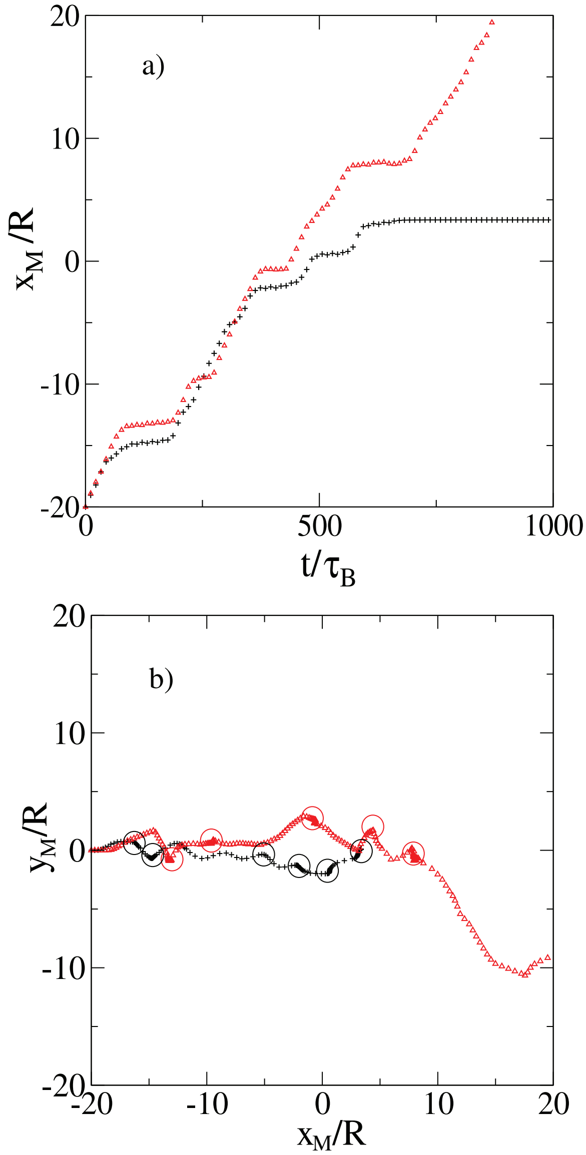

Fig. 2: (Colour online) (a) Dimensionless time-dependent position along x_M/R as a function of t/τ_B. Plus: first option (only pushing); triangles: second option (pushing and avoiding). The first option leads to a trapping while the second allows the MP to move forward ($T = 0.5$ and $\phi = 40\%$). (b) Corresponding trajectories of the MP. The circles indicate when the MP is temporarily trapped. With the first strategy, the MP ends in a trap.

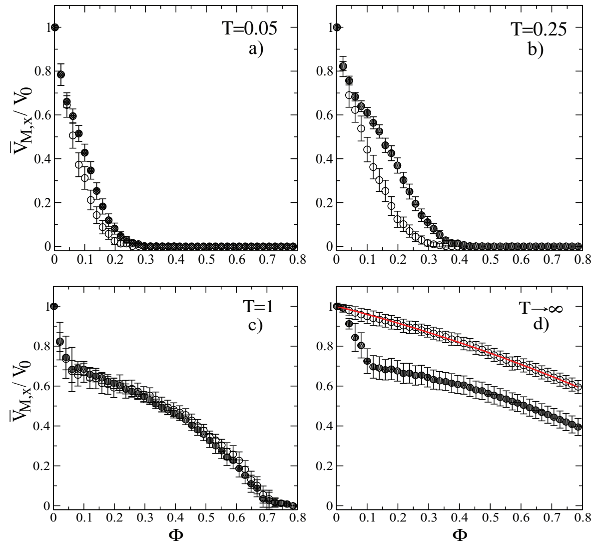

Fig. 3: (Colour online) Dimensionless MP velocity $\bar{v}_{M,x}/v_0$ (averaged on 1000 trials) as a function of ϕ for different T values: (a) $T = 0.05$, (b) $T = 0.25$, (c) $T = 1$ and (d) $T \to \infty$. Open circles: without avoidances; closed circles: with avoidances. (d) The solid curve is a fit (see text).

Results. In fig. 2, we observe that the motion of the MP is characterized by a stick-slip–like motion. The MP can move for a while and can be temporarily stopped or even definitively trapped behind a group of people. If MP uses the second option and tries to avoid the people of the crowd (still pushing people in case of contacts), we clearly see that some stick events can be eliminated. Of course, depending on the crowd configuration —*i.e.*, the initial position of each individual— the MP velocity can vary: sometimes the MP can never escape from a trap and remains at the same position while for some other configurations they find their way easily. Therefore, for each measure of $\mathbf{v}_M$ we make a sampling on 1000 trials on which we calculate the average value $\bar{\mathbf{v}}_M$.

In fig. 3, we plot $\bar{v}_{M,x}/v_0$ as a function of ϕ for different values of the dimensionless parameter T. For a rigid crowd ($T \ll 1$) (fig. 3(a)), we clearly see that the strategy of avoiding people rather than only pushing them is more efficient when the MP crosses the crowd. However, above a given critical density ϕ_c, v_M vanishes for both options, meaning that the MP is trapped in the crowd. This "avoiding" strategy, though obvious (it is easier to avoid fixed and rigid obstacles than trying to push them apart), becomes even more efficient for a less rigid crowd associated with a given value of T such as $0 < T < 1$ (fig. 3(b)). Both options are equivalent when $T \approx 1$ (fig. 3(c)). However, when the crowd is soft enough ($T \gg 1$) (fig. 3(d)), it becomes more efficient to push people, since avoidances lead the MP to spend time on "side paths" which are not parallel to the x-axis and that are thus much less efficient to get out from the crowd.

Note that we can extract the maximum possible velocity of a MP in an infinitely soft crowd ($T \to \infty$) as a function

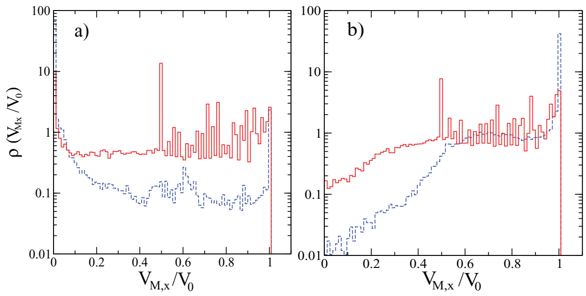

Fig. 4: (Colour online) Probability distribution of MP velocities along x. Dashed curves correspond to motion without strategy and solid curves to motion with avoidance strategy. (a) $\phi = 20\%$ and $T = 0.25$, (b) $\phi = 60\%$ and $T \to \infty$.

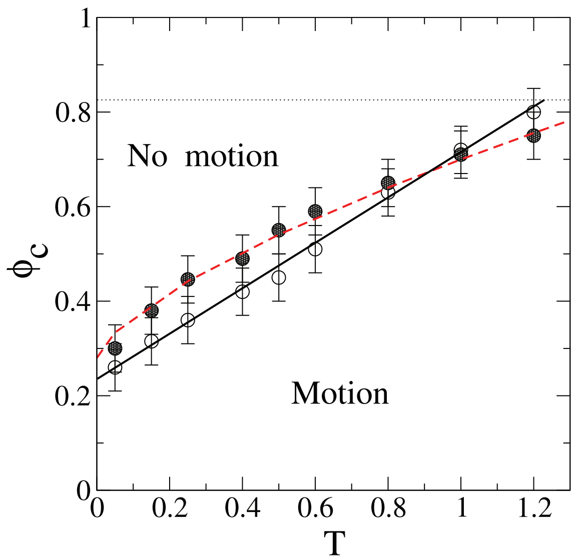

Fig. 5: (Colour online) Critical density ϕ_c above which the MP motion becomes impossible as a function of the crowd rigidity T. Open circles: first option, close symbols: second option. The horizontal dotted line indicates the maximum crowd density attainable with a random packing at 0.82%. Solid and dashed lines are just guides for the eyes.

of ϕ (fig. 3(d)). The MP velocity can be described with a simple polynomial dependence $v_M = v_0(1 - \alpha\phi - \beta\phi^2)$ with $\alpha = 0.39 \pm 0.01$ and $\beta = 0.16 \pm 0.01$. This expression somehow represents the rheological law of a soft crowd as a virial expansion of the velocity. It also gives an upper bound for the velocity of a moving person knowing the density ϕ and can help to evaluate the minimal time needed to provide assistance to a given person in a middle of a static crowd. We can compare our result obtained with open boundary conditions (and for $T \to \infty$) with the same situation with periodic boundary conditions (PBC) [23]. In our case the motion is still possible for an initial high packing density which is not the case with PBC. We also plot the probability distribution ρ of MP velocities (fig. 4). We clearly see that for a rigid crowd ($T = 0.25$), the MP tries to avoid the quasi-static

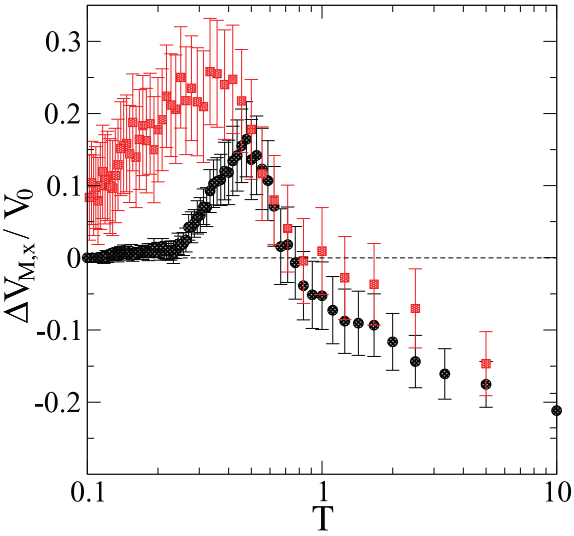

Fig. 6: (Colour online) Difference of MP dimensionless velocities with and without avoidances ($\Delta\bar{v}_{m,x}/v_0$) as a function of T for two different density values. Circles: $\phi = 40\%$ and squares $\phi = 20\%$. The value $\Delta\bar{v}_{m,x}$ is averaged over 1000 trials.

individuals, the peak at $V_{M,x}/V_0 = 0.5$ in fig. 4 corresponds to situations where the MP avoids an individual and deviates form the x-axis by an angle of ± 60 degrees and this strategy of avoidance allows the MP to move faster. On the contrary, for a very soft crowd ($T \to \infty$) the first option is better, the MP moves with higher horizontal velocities (fig. 4(b)).

Figure 5 shows the critical density for the two options as a function of the crowd rigidity T. We clearly observe that the two curves cross each other at $T \approx 1$.

In fig. 6, we plot the difference of MP velocities with and without avoidances [resp. option (2) and (1)]: $\Delta\bar{v}_{M,x} = \left[\bar{v}^{(2)}_{M,x} - \bar{v}^{(1)}_{M,x}\right]/v_0$ as a function of T for two values of the crowd density $\phi = 20\%$ and $\phi = 40\%$. For both densities, an optimal velocity difference is obtained for $0 < T < 1$, but this optimum depends on ϕ. The second option (with avoidances) drives the MP in corridors of low density and in general leads the MP in front of two individuals separated by a distance $d \ll R$ (fig. 7(a)). We have numerically calculated the threshold value T_s above which the MP can open a gap between two individuals (fig. 7(b), (c)). We obtain that $T_s \approx 0.53$–$0.72\, d/R + \mathcal{O}[(d/R)^2]$ (fig. 8). This very simplified approach cannot describe precisely what happens at high density because of the multiple contacts between individuals. However, this qualitative behavior is interesting and shows that when $d/R \ll 1$, an optimal value for $\Delta\bar{v}_{M,x}$ is obtained close to $T_s \approx 0.5$ in surprisingly good agreement with our numerical results. The value of T_s decreases when the crowd density decreases, *i.e.*, when d increases (fig. 6).

A star moving through a group of fans. – Let us now consider that the crowd is a group of fans converging with some desired velocity $\mathbf{v}_f$ towards the moving person

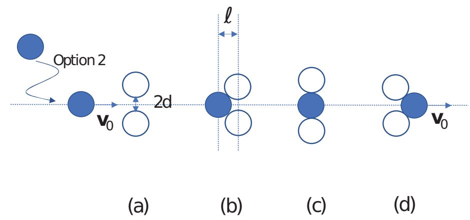

Fig. 7: (Colour online) The MP opens a gap between two individuals at distance $2d$. (a) Due to the second option the MP moves at velocity $\mathbf{v}_0$ and arrives in front of two individuals. (b) MP collides the individuals and can open the gap once MP moves on a distance ℓ and reaches position (c) if $T > T_s$. (d) MP can escape at velocity $\mathbf{v}_0$.

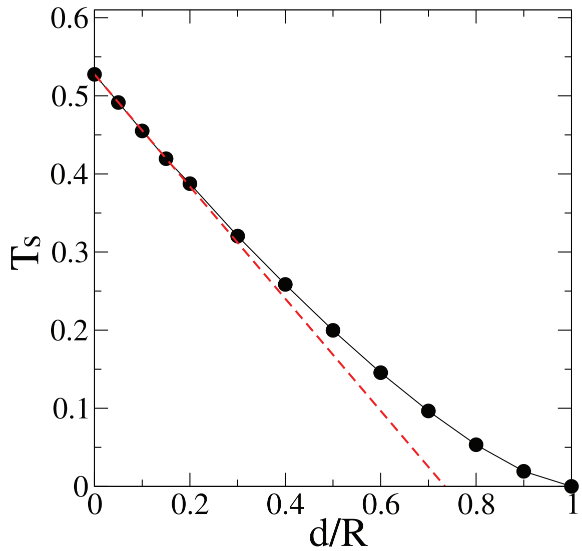

Fig. 8: (Colour online) Threshold value T_s as a function of d/R. The dashed curve corresponds to $d/R \ll 1$: $T_s \approx 0.53$–$0.72d/R$.

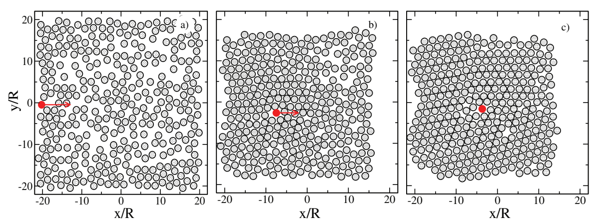

Fig. 9: (Colour online) Snapshot of a star moving through a crowd of fans at $\psi = 0.2$. Gray circles represent the fans, the dark coloured symbol is the star, the arrow symbolises the velocity. (a) Initially the star penetrates in the crowd (initial density $\phi \approx 65\%$); (b) the star's velocity decreases during the convergence of fans; (c) the velocity reaches an asymptotic limit value V_L: at this density $V_L = 0$.

(MP) while the latter (now a star) is still moving with the desired velocity $\mathbf{v}_0$. Each individual is no longer attached to any favourite position ($T \to \infty$) and the star moves in the x-direction as before without trying to avoid people (first option only). We define the dimensionless parameter

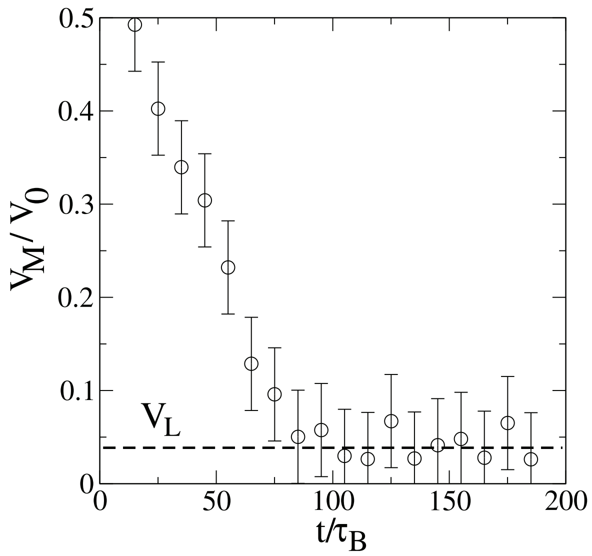

Fig. 10: Star velocity as a function of time ($N = 128$ and $\psi = 0.2$). An asymptotic limit velocity V_L is reached.

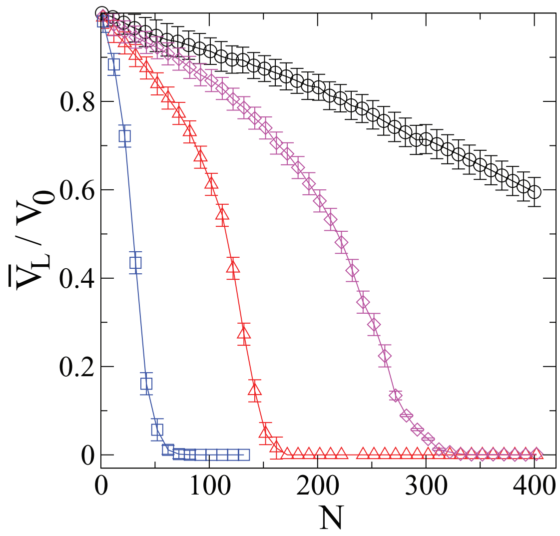

Fig. 11: (Colour online) Star's limit velocity as a function of the number of fans N for different values of parameter ψ. Circles: $\psi = 0$, diamonds: $\psi = 0.1$, triangles: $\psi = 0.2$, squares: $\psi = 0.5$.

$\psi = v_f/v_0 = F^F/F^0$ which measures the degree of attraction of the fans to the star, ranging from indifferent fans ($\psi = 0$) to very motivated fans ($\psi = 1$). We restrict our study to the interval $0 < \psi < 1$ (above this value the star cannot move at all). Expressions for the velocities show similarities with eq. (1) except that retraction force $\mathbf{F}_i^R$ acting on the i-th individual is now replaced by a force $\mathbf{F}_i^F$ which is oriented from its i-th position to the position of the star: $\mathbf{F}_i^F = F^F\,\mathbf{n}_{i,M}$ with $F^F = \eta\, v_f$. This force vanishes for a given i-th fan who is in contact ($\epsilon_{iM} = 1$) and behind ($x_i < x_{MP}$) the star, this makes the fan moving with the star when they are together in contact. However, the force does not vanish if the fan is in contact but in front ($x_i > x_{MP}$) of the star. This fore-and-aft asymmetry creates a congestion in front of the star which stops the motion above some given density. Without this asymmetry the forces applied by fans behind and in front of the star mutually compensate on average and do not really affect the motion of the star. The star's velocity $\mathbf{v}_M$ remains as given in eq. (1) while the velocity of the i-th fan is such as

$$\eta\,\mathbf{v}_{i\neq M} = \mathbf{F}_i + \sum_{j\neq i}^{N} \epsilon_{i,j}\mathbf{F}_{j,i}^C, \tag{3}$$

with the fore-and-aft asymmetry:

$$\mathbf{F}_i = (1 - \epsilon_{i,M})\mathbf{F}_i^F + \epsilon_{i,M}\mathcal{R}\left(\mathbf{e}_x.\mathbf{n}_{M,i}\right)\mathbf{F}_i^F, \tag{4}$$

using the ramp function $\mathcal{R}(x)$ which is such that $\mathcal{R}(x) = x$ if $x > 0$ and $\mathcal{R}(x) = 0$ otherwise.

Results. Figure 9 shows snapshots for $\psi = 0.2$. We start the simulation with a crowd of N fans uniformly distributed in a square $L \times L$ domain, much larger than

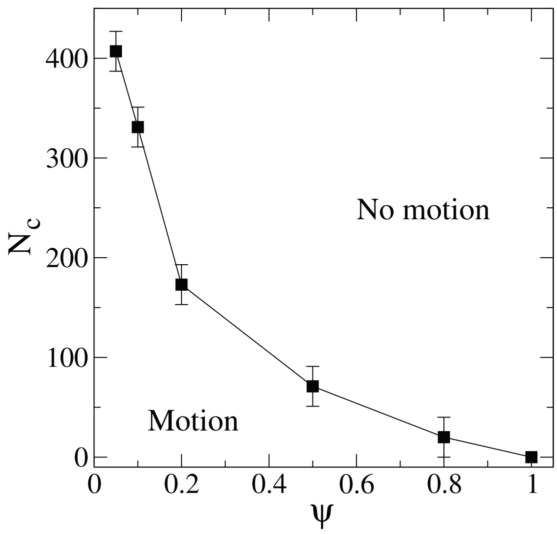

Fig. 12: Critical number of fans above which a star cannot move once surrounded as a function of parameter ψ.

the size of a given individual. As before the individuals are free to move out of the initial domain. Note that the $\psi = 0$ case is similar to the preceding case where individuals have no favourite position and the MP chooses the first option (fig. 3(d)). But when the star starts to cross the crowd with $\psi = 0.2$, fig. 10 shows a transient regime where the MP's velocity progressively decreases while the fans converge toward the star. Then, the N fans form a very dense cluster around the star (fig. 9(c)), who moves at a constant limit velocity with the group. The transient regime depends on the initial density of the fans. But here, we investigate the limit velocity of the star surrounded by

N fans. Figure 11 shows this limit velocity $\bar{v}_L$ (averaged on 1000 trials) as a function of N. Figure 12 shows the rapid decrease of the critical number of fans N_c above which the motion of the star becomes impossible ($\bar{v}_L = 0$) as a function of ψ. Note that even when $\psi = 1$, the star can move through a very small number of fans (*i.e.*, $N < 5$) which simply means that the star has the time to cross the entire domain without encountering a fan. This is of course a finite-size effect, since with a smaller domain and the same number of fans, the star should be "captured" by the fans.

Regarding the limit velocity, we observe that the motion of the star is impossible above a number of fans $N \approx 70$ for $\Psi = 0.5$. Here, it corresponds to a density of 14% in the initial domain. This is equivalent to about 1.1 person per square meter, a density which is usually considered as a safe situation regarding crowd evacuation processes, where a density of six persons (with non-discoidal shape) per meter square starts to be critical in real situations [17].

Conclusion. – Despite the simplicity of our mechanical force model, we hope that our results will help to elaborate strategies to provide assistance to someone in a middle of a static crowd through more specific modelisations. Especially, knowing the MP desired velocity, it helps to evaluate the time necessary to move from one location to another in a static or converging crowd. Let us mention some potential improvements for future investigations. The shape of pedestrians should be more elliptic, as this morphology is an important parameter at high density. The retraction force could also be non-linear to describe cases where an individual is very reluctant to move too far from its favorite position but more flexible for smaller distances. Considering polydisperse sizes of individuals could also be of great interest at high densities in order to avoid local crystal ordering. We also plan to study the motion of a moving person in a gradient of density as it is usually the case when moving toward a stage or in a panic situations, where people are running in several directions.

* * *

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REFERENCES

[1] Low D. J., *Nature*, **407** (2000) 465.
[2] Vermuyten H., Beliën J., de Boeck L., Reniers G. and Wauters T., *Saf. Sci.*, **87** (2016) 167.
[3] Helbing D., Farkas I. and Vicsek T., *Nature*, **407** (2000) 487.
[4] Silverberg J. L., Bierbaum M., Sethna J. P. and Cohen I., *Phys. Rev. Lett.*, **110** (2013) 228701.
[5] Moussaïd M., Helbing D. and Theraulaz G., *Proc. Natl. Acad. Sci. U.S.A.*, **108** (2011) 6884.
[6] Vicsek T., Czirók A., Ben-Jacob E., Cohen I. and Shochet O., *Phys. Rev. Lett.*, **75** (1995) 1226.
[7] Nagy M., Akos Z., Biro D. and Vicsek T., *Nature*, **464** (2010) 890.
[8] Helbing D. and Molnar P., *Phys. Rev. E*, **51** (1995) 4282.
[9] Löhner R., *Appl. Math. Model.*, **34** (2010) 366.
[10] Chraibi M., Seyfried A. and Schadschneider A., *Phys. Rev. E*, **82** (2010) 046111.
[11] Kirchner A. and Schadschneider A., *Physica A: Stat. Mech. Appl.*, **312** (2002) 260.
[12] Fukui M. and Ishibashi Y., *J. Phys. Soc. Jpn.*, **68** (1999) 2861.
[13] Blue V. and Adler J., *Transp. Res. Rec.: J. Transp. Res. Board*, **1644** (1998) 29.
[14] Burstedde C., Klauck K., Schadschneider A. and Zittartz J., *Physica A: Stat. Mech. Appl.*, **295** (2001) 507.
[15] Gopal S. and Smith T., *Environ. Plan. A*, **22** (1990) 169.
[16] Reynolds C. W., *Anim. Animats*, **3** (1994) 402.
[17] Helbing D., Johansson A. and Al-Abideen H. Z., *Phys. Rev. E*, **75** (2007) 046109.
[18] Maury B. and Venel J., *ESAIM: Math. Model. Numer. Anal.*, **45** (2011) 145.
[19] Moussaïd M., Perozo N., Garnier S., Helbing D. and Theraulaz G., *PLoS ONE*, **5** (2010) e10047.
[20] Chraibi M., Schadschneider A. and Seyfried A., *On force-based modeling of pedestrian dynamics*, in *Modeling, Simulation and Visual Analysis of Crowds* (Springer) 2013, pp. 23–41.
[21] Pelechano N., Allbeck J. M. and Badler N. I., *Controlling individual agents in high-density crowd simulation*, in *Proceedings of the 2007 ACM SIGGRAPH/Eurographics Symposium on Computer Animation* (Eurographics Association) 2007, pp. 99–108.
[22] Sutherland D., *J. Colloid Interface Sci.*, **60** (1977) 96.
[23] Reichhardt C. O. and Reichhardt C., *Phys. Rev. E*, **82** (2010) 051306.