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PROJECT REPORT

The role of panic in evacuations

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Abstract

It is shown that for a dual population model, consisting of calm and panicked individuals, total evacuation time increases with increasing number of panicked people. However, panic reduces the severity of dangerous effects and may indeed be advantageous in many cases. In some situations, more panic may even increase the speed of an evacuation.

1 Introduction

Crowd Crush is a term to describe a situation when the density of a crowd reaches a critical point and people begin to suffer from compressive asphyxiation - inability to breathe due to compression of the chest. This typically happens in situations where a lot of people want to move in a certain direction in a panicked or excited state, for example when running from a disaster. In these situations, panic will often arise, which can then further influence the course of events, for example by causing increased crowd pressure as they try to force others away [2]. For understanding the mechanics of collective motion in these extreme situations, knowing the effects of panic is of great interest.

Real life experiments on the subject would be dangerous to set up, so to understand when and how these dangerous situations appear, one can simulate a potentially dangerous scenario using numerical models that describe crowd dynamics and collective motion. One such model is the MASHer model, a particle-force model put forth by Jesse L. Silverberg et al [1], which describes formation of, and collective motion in, mosh pits - a phenomenon occurring in crowds during heavy metal concerts, where a group of people move around in an area contained by passive bystanders.

Using the MASHer model as a foundation, we implement a new model capable of simulating and measuring crowd crush effects during an evacuation scenario. This includes evaluating suitable ways of measuring relevant effects. The development and the testing of the model is done in MATLAB. Once feature complete, the new model is ported to a compiled language (C) for speed and to make further optimization possible (as crowds typically consist of a large number of people, these simulations can become very computationally demanding). We then investigate how evacuation efficiency and crowd crush severity correlates with the amount of panicked people in the room in two different settings.

2 The model

2.1 Developing the model

When working on the model, we have made a vast amount of decisions and modifications - far too many to describe in detail here, so we will limit ourselves to a few key points in the design.

One of the main features distinguishing the MASHer model from other pedestrian models is having two separate populations behaving in different ways. In the original model they were "active" and "passive" MASHers representing, respectively, people that want to stay on the move and flock to other moving people and people that try to stand still. For our model, we changed the external setting from a metal concert to a room with limited vision from which people want to escape. With this in mind, we translated the two populations to "panicked" and "calm", and made a few key assumptions regarding their behaviour. Panicked people are assumed to have no knowledge of the location of the exit and will use the same social flocking behaviour present in the original model to find their way. They will, however, be able to discover the exit by proximity. Calm people, on the other hand, are assumed to have full knowledge of the exit location and will move straight towards it, ignoring where other people are going.

When developing a model describing pedestrian motion, there is a choice between trying to imitate a large range of human behaviour or focusing on a few key aspects and seeing what results and patterns emerge. The latter, which we have chosen to pursue, has the advantage of simplicity, speed and, most importantly, allows more direct correlations between cause and effect. Thus, we sacrifice some realism but instead get a clearer look at the things that we do include.

2.2 Model description

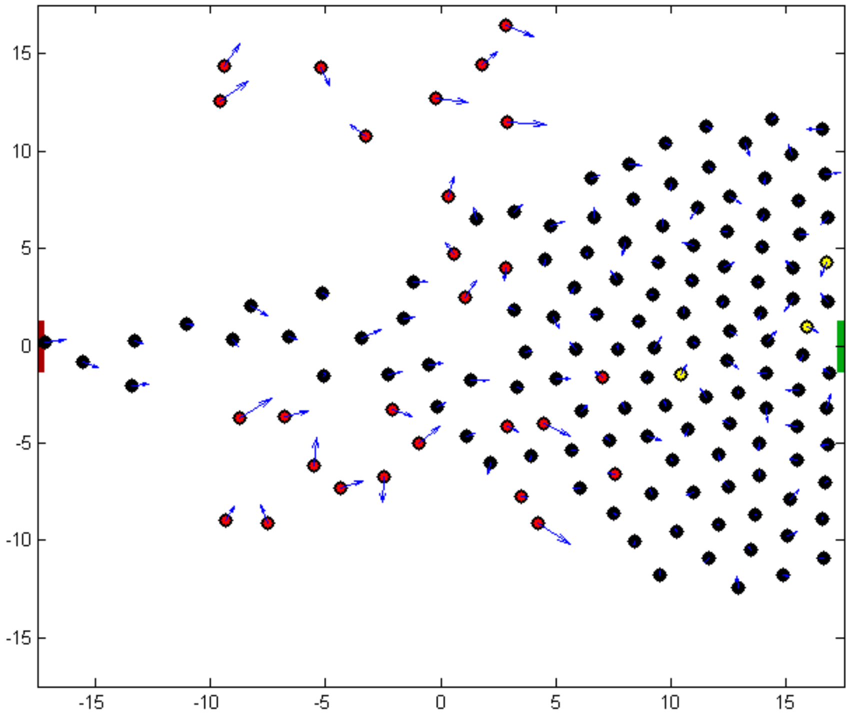

Figure 1: *Position of 200 MASHers, of which 20% panicked (red) and 80% calm (black). Some of the panicked MASHers have become aware of the exit this is indicated by the yellow markings. The MASHers are reseeded at the left side of the room upon exit at the right side making it a steady state simulation. The width of the doors are shown by the colored markings, red for entrance and green for exit.*

The model simulates an evacuation from a smoke-filled room of a crowd constituted by the two populations, panicked and calm. There are two traits that separate calm and panicked MASHers. Calm MASHers have low or no tendency to flock and know from the beginning about the exit location. Panicked MASHers have flocking behaviour and detect the exit when they come within a certain distance from it, the so-called visibility radius. Knowledge of the exit location adds a desired direction to the propulsion force, which otherwise only acts to maintain a certain speed in the MASHer's current facing direction. Individuals in the crowd are represented as N MASHers of radius r_0, each with a position $\boldsymbol{p}_i$ and a velocity $\boldsymbol{v}_i$. Interactions between MASHers are modeled using two forces:

Repulsion , which is a strong repelling force representing physical contact that comes into play when two MASHers intersect (i.e. at a distance less than $2r_0$).

Flocking , representing the panicked MASHers' tendency to follow other moving individuals in the near vicinity (less than $4r_0$ away).

Physical interactions between MASHers and the walls of the room are modeled using two forces:

Wall Repulsion , which is similar to the repulsion between MASHers and is applied to MASHers intersecting a boundary (i.e. at a distance less than r_0). This force is always perpendicular to the boundary.

Doorjamb Repulsion , which is identical to Wall Repulsion, except that the direction is dependent on the MASHer's position relative to a door. This force seamlessly joins with the Wall Repulsion force and acts on MASHers whose centers of mass are within the width of a door, but still have physical contact with a wall.

Lastly, there are two forces that act on individual MASHers independently:

Propulsion , a force that propels MASHers in a certain direction at the desired speed v_0. The force is directed towards the exit for all MASHers that have knowledge of it - otherwise it propels a MASHer forward in whatever direction it is currently moving. To exit aware MASHers a certain distance within the extension of the door frame, the propulsion force acts to move them straight through the opening rather than towards the center of it, allowing two or more MASHers to exit abreast when the door width allows. For our simulations, this "exit relaxation distance" has been $0.5r_0$.

Noise , the last force, is a weak random force with a normally distributed strength and uniformly distributed angle.

These forces are described in detail in equations (1) to (7) and are used to update the velocity at each time step according to equation (8).

Two different scenarios are simulated. In the first, hereby referred to as the "non-reseeded case", exiting MASHers are completely removed from the simulation, thereby gradually emptying the room. In the second, henceforth called the "reseeded case", exiting MASHers re-enter the room through an entrance on the opposite side, thus having a constant number of MASHers in the simulation at all times. To prevent discontinuous changes in force strengths, MASHers near the exit are subject to repulsion forces from MASHers near the entrance and vice versa. Figure 1 shows a typical situation where MASHers are reseeded in the room upon exiting.

$\boldsymbol{r}_{i,j}$ is the position of MASHer j relative to MASHer i ($\boldsymbol{r}_{i,j} = \boldsymbol{p}_j - \boldsymbol{p}_i$). $\boldsymbol{r}_{i,w}$ is the position of MASHer i with respect to wall w. $\boldsymbol{r}_{i,c}$ is the position of MASHer i with respect to doorjamb c. $\theta_{i,t}$ is a uniform random angle between 0 and π, and $\gamma_{i,t}$ is a random number from a normal distribution with mean 0 and standard deviation 1.

The constants ϵ, μ, α and σ represent the magnitude of each respective force, affecting the time scale at which the forces affect the simulation. Finding a good balance between these constants is necessary to have a fairly realistic simulation.

$$\boldsymbol{F}_{i,j}^{repulsion} = \begin{cases} \epsilon \left(1 - \frac{r_{i,j}}{r_0}\right)^{3/2} \hat{\boldsymbol{r}}_{i,j} & \text{if } r_{i,j} < 2r_0 \\ 0 & \text{otherwise} \end{cases} \tag{1}$$

$$\boldsymbol{F}_{i}^{flocking} = \alpha \sum_{j=0}^{N_i} \boldsymbol{v}_j \bigg/ \left| \sum_{j=1}^{N_i} \boldsymbol{v}_j \right| \tag{2}$$

$$\boldsymbol{F}_{i,w}^{wall} = \begin{cases} \epsilon \left(1 - \frac{r_{i,w}}{r_0}\right)^{3/2} \hat{\boldsymbol{n}}_{w} & \text{if } r_{i,w} < r_0 \\ 0 & \text{otherwise} \end{cases} \tag{3}$$

$$\boldsymbol{F}_{i,c}^{doorjamb} = \begin{cases} \epsilon \left(1 - \frac{r_{i,c}}{r_0}\right)^{3/2} \hat{\boldsymbol{r}}_{i,c} & \text{if } r_{i,c} < r_0 \\ 0 & \text{otherwise} \end{cases} \tag{4}$$

$$\boldsymbol{F}_{i}^{propulsion} = \mu \left(v_0 \boldsymbol{\xi}_i - \boldsymbol{v}_i\right) \tag{5}$$

$$\boldsymbol{\xi}_i = \begin{cases} \hat{\boldsymbol{v}}_i & \text{if not exit aware} \\ \hat{\boldsymbol{r}}_{i,exit} & \text{if exit aware and outside the door frame's extension} \\ \hat{\boldsymbol{n}}_{exit} & \text{if exit aware and within the door frame's extension} \end{cases} \tag{6}$$

$$\boldsymbol{F}_{i}^{noise} = \sigma\gamma \left[cos(\theta_{i,t}), sin(\theta_{i,t})\right] \tag{7}$$

$$\boldsymbol{v}_i^{k+1} = \boldsymbol{v}_i^{k} + \Delta t \left(\sum_j \boldsymbol{F}_{i,j}^{repulsion} + \boldsymbol{F}_{i}^{wall} + \boldsymbol{F}_{i}^{doorjamb} + \boldsymbol{F}_{i}^{propulsion} + \boldsymbol{F}_{i}^{flocking} + \boldsymbol{F}_{i}^{noise} \right) \tag{8}$$

2.3 Measures

After discussing and testing a number of different measures of crowd effects, we concluded that crowd density (MASHers per unit area, referred to as "density"), flux (of MASHers) and local body compression (sum of physical forces on MASHers, referred to as "compression") were most relevant to our particular scenario. These measures, described in detail below, are primarily applied to the stable states found in the reseeded case scenario, where we also count the number of MASHers leaving the room for each population. For the non-reseeded case, we primarily focus on measuring the time taken to evacuate certain fractions of the total population - primarily the 80% and 90% marks, as any less gives a very vague picture and approaching 100% produces very inconsistent results.

With density, flux and compression, we had the choice of measuring them as a continuous spectrum (previously done by Helbing [3]), or discreetly, by counting , for example, the amount of people within certain grid squares at every time step. We chose the continuous measure, since it produces useful values both at individual time steps and over longer periods of time, while also providing a natural smoothing of the data. To achieve this, we sum the contributions of nearby MASHers using a weighting factor $f(d)$, defined in equation (9), where d is the distance between the contributing MASHer and the measuring point. The "effective measurement radius", R, affects the coarseness of the results and was set to 2 for our simulations.

$$f(d) = \frac{1}{\pi R^2} exp(\frac{-d}{R^2}) \tag{9}$$

A side effect of this way of measuring is that points near the edges show lower values, since they always have fewer particles nearby. This is solved by introducing "ghost particles" outside the boundaries which are mirror images of actual particles inside the room. Density, flux and compression are measured in uniform grid points across the simulation space.

Using the weighting described in equation (9), the density $\rho(\boldsymbol{x})$ is calculated as the sum of the weighting terms of surrounding MASHers, as described in equation (10), where i iterates over surrounding MASHers and $d_{i,x}$is the distance between MASHer i and measuring point $\boldsymbol{x}$.

$$\rho(\boldsymbol{x}) = \sum_n f(d_{i,x}) \tag{10}$$

The flux, $J(\boldsymbol{x})$, is calculated as density times local speed, $V(\boldsymbol{x})$, see equation (11). Local speed is defined in equation (12), and is a measure of the average velocity of nearby MASHers, weighted in the same way as above.

$$M(\boldsymbol{x}) = \rho(\boldsymbol{x}) V(\boldsymbol{x}) \tag{11}$$

$$V(\boldsymbol{x}) = \sum_i v_i f(d_{i,x}) \Big/ \sum_i f(d_{i,x}) \tag{12}$$

The compression, $C(\boldsymbol{x})$, is defined as the total amount of physical forces applied on nearby MASHers, again weighted in the same way, where $\tilde{F}_i^{repulsion}$ is the sum of magnitudes of all physical contact forces on MASHer i:

$$C(\boldsymbol{x}) = \sum_i f(d_{i,x}) \tilde{F}_i^{repulsion}. \tag{13}$$

Lastly, the average escape time in the reseeded case, τ_p, of population p, where T is the total amount of time spent simulating and E_p is the total amount of evacuations during that time for that population, is calculated as:

$$\tau_p = \frac{N_p T}{E_p}. \tag{14}$$

3 Results

3.1 Evacuation time

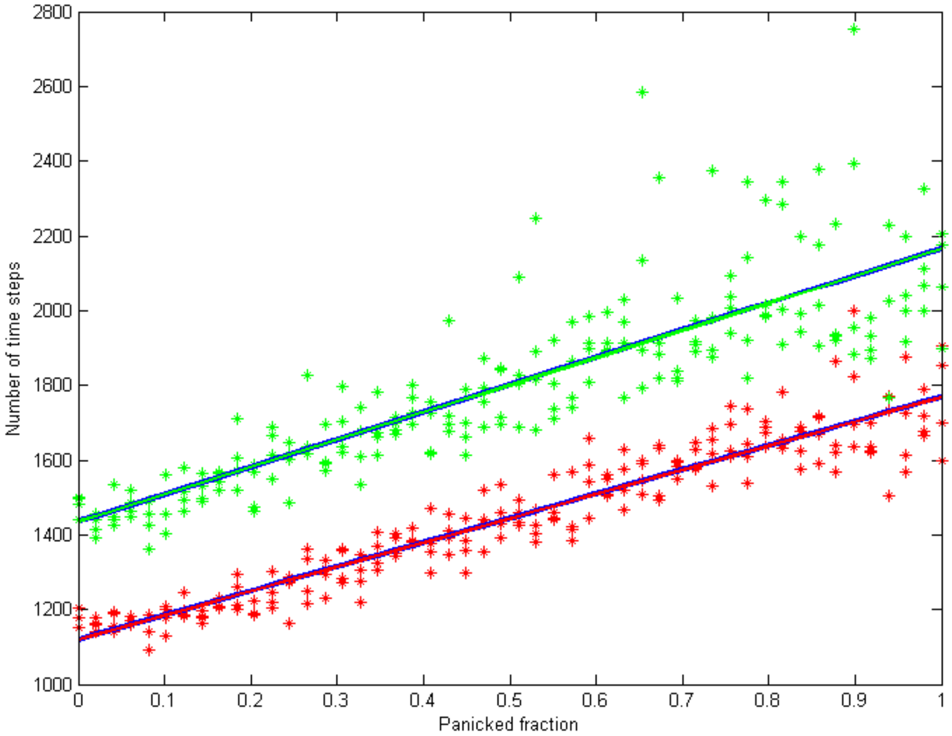

Figure 2: *Total evacuation time for 80% (red line) and 90% (green line) of the MASHers in a rectangular room. The dots are the data points from the simulation used to calculate the linear fit.*

In Figure 2 we see the time taken to evacuate 150 people in a non-reseeded scenario. The evacuation time increases close to linearly with the fraction of panicked MASHers. We also see a larger variation in the results as the fraction of panicked increases, indicating that panicked MASHers cause the flow of evacuation to become disorderly and erratic. Overall, we see about a 50% increase in evacuation time for both limits when having 100% panicked compared to 100% calm MASHers.

An interesting observation is that having a small fraction (0 - 0.2) of panicked people noticeably worsens the efficiency of the evacuation, even though the time measurement (for 80%) does not require them to reach the exit. This suggests some form of negative interaction between the two populations (or positive interaction among calm MASHers).

Looking at individual MASHers, it is clear that panicked MASHers are disadvantaged and on average leave the room much later than the average calm MASHer.

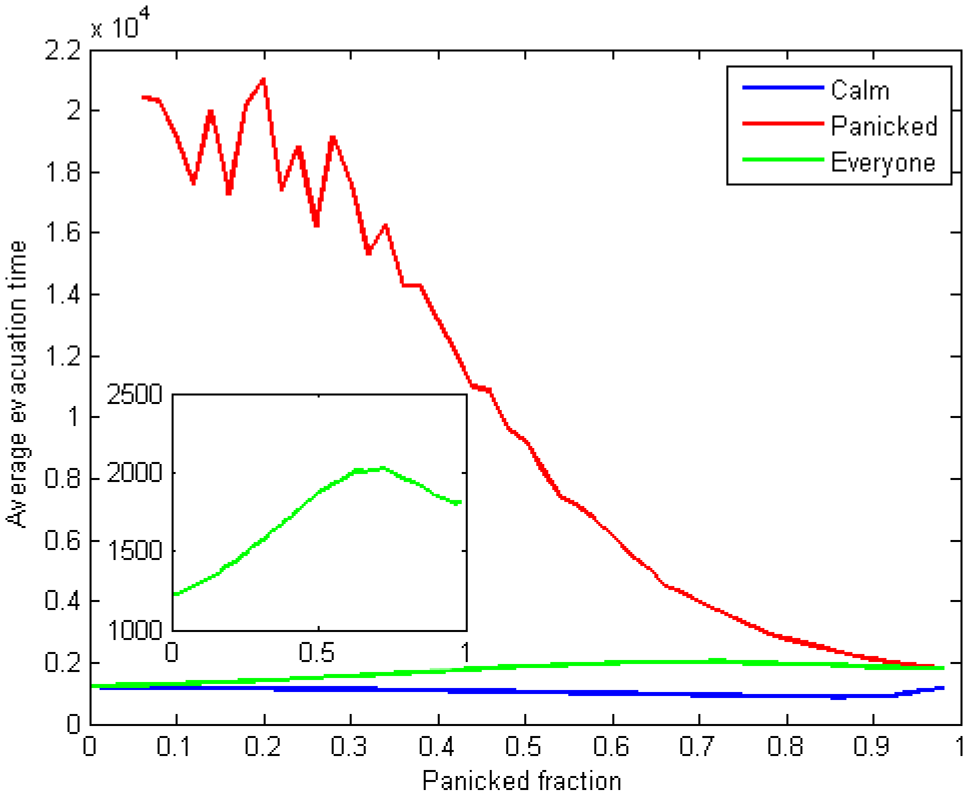

Figure 3: *Average evacuation time for MASHers during a steady state simulation for 20000 timesteps in a rectangular room. The interior subfigure shows the average evacuation time for all MASHers magnified on the y-axis.*

Next, looking at average escape times in a reseeded scenario with 200 MASHers simulated over a large amount of time steps (Figure 3), we see that calm MASHers generally escape more quickly when more panicked MASHers are introduced, likely due to a smaller crowd gathering around the exit. Interestingly, this trend breaks when getting near to a fully panicked room, where calm MASHers suddenly take slightly longer to escape. This appears to be due to them getting stuck at the back of the gathered crowd while panicked MASHers come in from the sides.

Surprisingly, there is a global maximum of the average evacuation time for the entire population at about 70% panicked, which means there are situations (say, 85% panicked) where average escape time can be improved by adding more panicked MASHers and, vice versa, worsened by adding more calm. This is a clear difference from the non-reseeded case where evacuation times increased linearly with the fraction of panicked MASHers.

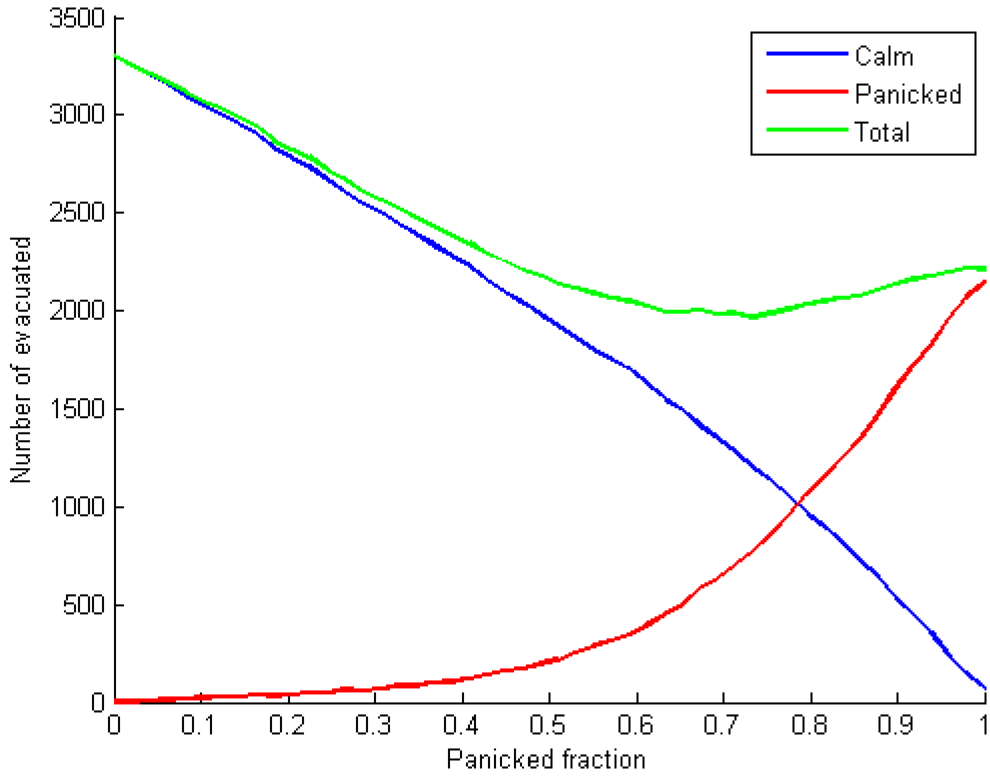

Figure 4: *Number of evacuated MASHers during a steady state simulation for 20000 time steps in a rectangular room.*

Looking instead at the total number of evacuated MASHers, Figure 4 shows the same worst case as for the average escape time, in this case as a global minima for the total amount evacuated. In some sense, more panic appears to help the efficiency of the evacuation in situations where panic is already widely present. There would appear to be positive effects associated with both panicked and calm crowds, and that these effects are most effective in pure populations of either kind.

The positive effect for calm MASHers could be that they form a large gathered crowd around the door, effectively forcing MASHers through the door. This effect would be lessened as soon as a few panicked people enter, which fits the data. For the panicked MASHers, a positive effect is that the (smaller) gathered crowd around the door will often oscillate slightly from flocking effects. This relieves jams and arches around the door. The global minimum correlates somewhat with when the gathered crowd just about covers the entire visible radius. This correlation is not strong enough to prove causation, but provides one possible explanation for the phenomenon.

We can also observe the general shape of the two population curves. The calm curve is very close to linear, suggesting very little dependency on the panicked fraction, whereas the panicked curve appears more like an exponential or power curve, showing that the panicked individuals are much more sensitive to the balance of populations in the system.

Still, by far the best case is when every single individual is calm.

3.2 Areas of danger

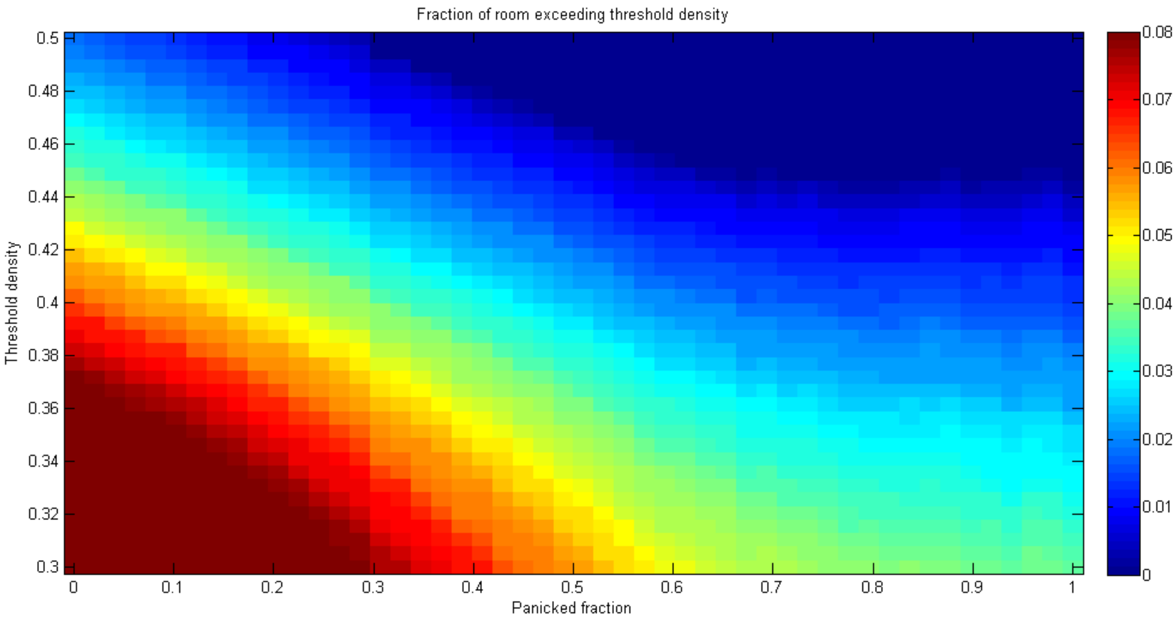

Figure 5: *The colorbar values shows the fraction of the room that is over a certain threshold density.*

However, slow evacuations may be better than fast ones if the fast ones entail people getting crushed on their way out. In Figure 5 we see a heat map showing the occurrence of areas within the room that exceed a certain threshold density. For reference, MASHers standing side by side equal a density of about 0.28, while a density of about 0.32 mean they fill the entire space. Densities above this signify increasing levels of compression, which quickly becomes dangerous. At a density of 0.4, or 20% body compression, we expect people to be almost completely asphyxiated, and spending an extended amount of time in these circumstances would almost certainly lead to severe injuries or death.

Regardless of speculations as to which densities are dangerous, we see that at any given threshold density, having a largely calm population produces more dangerous areas within the system, thus increasing the risk of harmful or lethal crushing effects. This is largely due to the extremely high values of density that arise when a lot of calm MASHers try to push towards the door at the same time.

The benefits of having more panicked people start to wear off at a fraction of about 0.7 (again, where the gathered crowd reaches its minimal size), but taking this together with the previous results (wherein a system with a fraction higher than about 0.7 benefited, in terms of speed, from having more panicked individuals), it may be that the optimal case when taking both time and safety into account surprisingly is having a completely panicked population.

3.3 Pathing

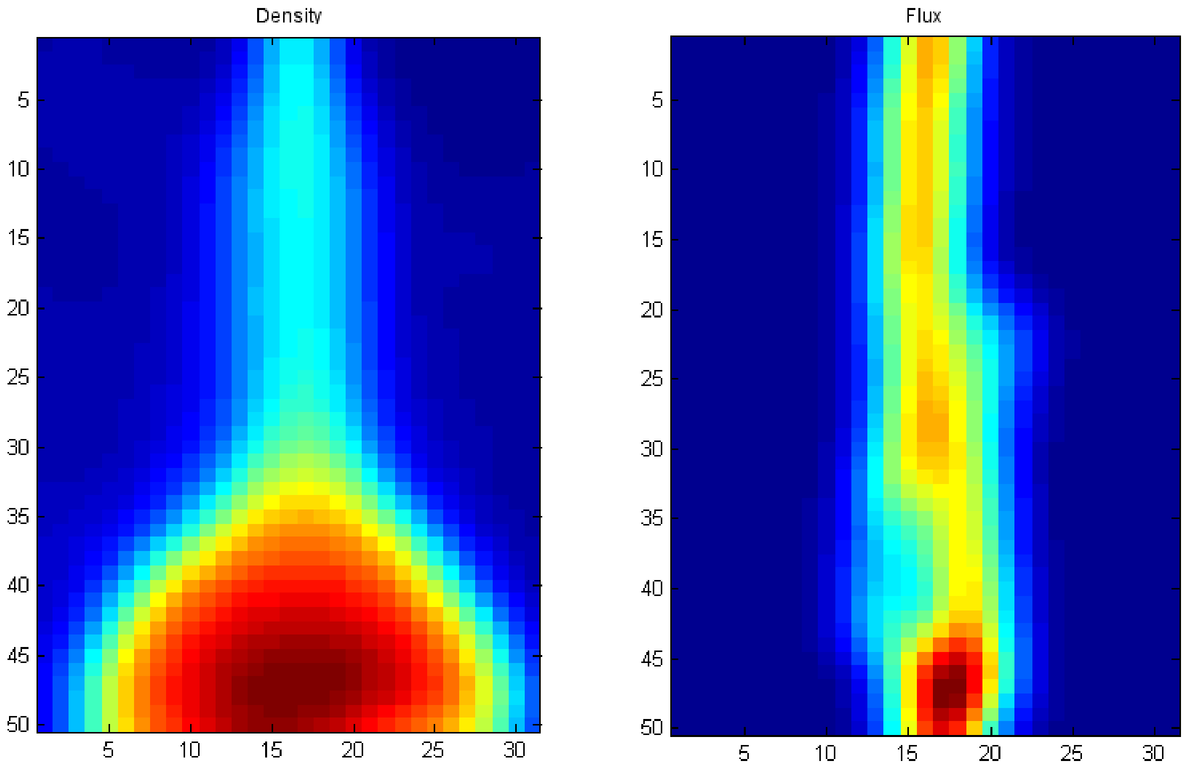

Figure 6: *A steady state simulation with 20000 time steps, 200 calm MASHers and no panicked MASHers, was used to produce the result seen in both images. The left shows the density averaged over time and the right image shows the flux.*

In reseeded scenarios, we often observe the formation of stable lanes through the crowd. This means that most movement in, and through, the crowd happens along a specific path, whereas MASHers in a location away from the path tend to be stuck for long periods of time (in Figure 6, compare the shape of the gathered crowd (left) and the flux patterns (right), where we see a path as a curved yellow area). Since all the MASHers try to push straight towards the exit, the space left by a MASHer leaving through the exit is most often filled by the one standing right behind it, thus forming a lane, similar to those found in pedestrian crowds in a street [5].

While interesting and pretty to look at, pathing is potentially dangerous in a situation where spending too much time in the same place may be harmful to an individual (due to smoke, pressure, etc) and people keep coming into the system, keeping the path stable.

Due to the increased randomness in their movements, panicked MASHers tend to approach the gathered crowd from different directions, thus increasing the amount of panicked MASHers decreases path stability and formation rate, helping relieve the problem of individuals being stuck in a bad spot.

4 Conclusion

From the analysis of panicked behaviour (moving around erratically), it seems that having a largely panicked crowd may actually be a good thing, as many of the crowd crush effects appear more strongly when a large amount of people are trying to reach the exact same spot at the same time (commonly mentioned in articles about the Hillsborough incident [6]), even though their individual actions seem rational. However, if escaping quickly is important, being a panicked person is generally a terrible idea (for you).

Also, if taking into account that people subject to crowd crush effects may actually slow an evacuation down (by becoming dead obstacles), the merits or panic may far outweigh the demerits.

In a broader scope, looking at collective motion with a particle-force model does produce interesting results without adventuring the lives of real test subjects. However, one must keep in mind that a force model is a very simplistic description of human psychology and behaviour, and such a model should realistically be tailored to look at one or a few particular effects, rather than the complete picture, in order to provide accurate results.

That said, even with our very simple model, we are able to find results that deviate from what was initially expected, from some of which we can draw parallels to real life phenomena.

The simplicity of force models is a major advantage compared to psychological models (like the visual navigation described by Moussaïd et al [4]) when looking at specific effects, and this alone is enough to keep them viable for research going forward. The interesting dynamics produced by mixing two or more populations produce emergent complexity and may be one of the things force models need to provide better descriptions of collective behaviour in the future, especially if allowing dynamic transitions between populations.

5 Onwards

If pursuing this model further, we suggest investigating the correlations between visibility radius and crowd size at worst escape time population balance, exploring dynamic changes between populations based on conditions on density, movement or others, adding threshold densities where MASHers “die” and become obstacles, or improving the model to handle a more general geometry and look at bottlenecks or rooms where several possible paths to an exit exists.

Acknowledgements

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