Simulating Panic Amplification in Crowds via Density-Emotion Interactions

Erik van Haeringen
Vrije Universiteit
Amsterdam, The Netherlands
e.s.van.haeringen@vu.nl

Charlotte Gerritsen
Vrije Universiteit
Amstedam, The Netherlands
cs.gerritsen@vu.nl

ABSTRACT

A considerable number of agent-based models have been introduced to study the spread of emotions in crowds. Since these studies often aim to simulate collective behaviour driven by emotional escalation, like during stampedes and riots, amplification of emotion is a key aspect in these models. However, the biological processes underlaying emotion amplification in these models often remain unclear, preventing validation and accurate parameter setting.

The aim of the present study is to explore whether density-emotion interactions can theoretically explain events of panic amplification in dense crowds. Specifically, we extend the model DECADE, of which the process that drives emotional convergence is rooted in psychological and neurological literature, while support is lacking for the amplification process. Therefore, in this study we propose an alternative amplification mechanism that operates on the desire to maintain a personal space. A minimum distance is kept from others under normal conditions, but under stress other goals are prioritised, like escape. This results in personal space violations, where serious violations induce emotional stress in others. Additionally, pushing behaviour is considered when a stressed agent is prevented from escaping.

The proposed model is validated with video of an evacuation incident, that was previously used to validate emotion contagion models. We conclude that the proposed amplification mechanism offers a plausible alternative that is biologically falsifiable, as it resembles emotion amplification in a dense crowd, while incidents in less dense crowds do not escalate. Further empirical study is necessary to establish whether such a mechanism indeed contributes to real-world stampedes.

KEYWORDS

Crowd simulation; Emotion contagion; Agent-based; Emotion amplification

ACM Reference Format:
Erik van Haeringen and Charlotte Gerritsen. 2023. Simulating Panic Amplification in Crowds via Density-Emotion Interactions. In *Proc. of the 22nd International Conference on Autonomous Agents and Multiagent Systems (AAMAS 2023), London, United Kingdom, May 29 – June 2, 2023*, IFAAMAS, 8 pages.

1 INTRODUCTION

Emotion contagion has frequently been named as an important contributing factor or cause for incidents that involve the rapid rise of collective negative emotions, like during stampedes and riots [5, 20, 38]. Following this view, a number of agent-based models have been developed, where the process of emotion contagion itself includes a positive feedback loop at the level of the group. That is to say that in these models, group emotion escalates through the act of emotion exchange alone. However, in psychological literature, emotion contagion is commonly described as the process of emotional exchange that converges the emotional state of the group [8, 31]. Thus, if the effect of emotion contagion drives towards an average emotional state, this begs the question how these emotional spirals exactly arise.

In examining various proposed models of emotion contagion that contain a mechanism for amplification, we found that the biological foundations for the amplification process are commonly missing. One type of contagion models that is widely used in the field, is based on modelling infectious diseases [30]. In these types of models, with the Durupinar model as a prime example [5], having an emotion is compared to carrying a disease, taking a categorical approach to emotion contagion. If one is infected with an emotion, they can infect others that are in a susceptible state. The amplification comes from the directional nature of the process, where the infected affects the susceptible, but not vice versa. This differs markedly from the description in psychological literature where the exchange of emotion in groups is commonly described as a bidirectional process [31].

A second prominent type of contagion mechanism is based on bidirectional exchanges in dyads that draws from thermodynamics [30]. In these types of models, agents take up some of the emotional state of others via a dyadic exchange that is mediated by individual, social and environmental factors. An influential example is the ASCRIBE model [3]. In ASCRIBE, this process is called absorption and is supported by the authors with neurological literature on mirror neurons and somatic markers. This form of exchange results in the convergence of emotions in groups, similar to the description in psychological literature. However, absorption by itself does not result in an emotional spiral at the level of the group. To simulate such a spiral, like the sudden spread of panic during a stampede, ASCRIBE proposes another process called amplification. Through this process the emotional state of an agent is amplified if it is similar to the combined emotional state of its neighbours. However, the underlying mechanism for this process is not made clear by the authors, detracting from the biological plausibility of the model. The missing biological foundation for this process makes it difficult to deduce a value for the parameter that controls the degree of amplification in the model from real crowds, and to reason on its relation to other factors, such as the personality of the agent.

We propose that the mechanism underlying amplification may depend on scenario-specific environmental and social factors that

Proc. of the 22nd International Conference on Autonomous Agents and Multiagent Systems (AAMAS 2023), A. Ricci, W. Yeoh, N. Agmon, B. An (eds.), May 29 – June 2, 2023, London, United Kingdom. © 2023 International Foundation for Autonomous Agents and Multiagent Systems (www.ifaamas.org). All rights reserved.

work in tandem with emotion contagion. For example, the mechanism that leads to amplification during an escalated protest may be different from that during a stampede. In this study, we propose a link between density and emotion as the underlying mechanism for sudden emotional amplification during stampedes. We hypothesise that emotional amplification occurs when agents violate the personal space of others, which is kept under normal circumstances, motivated by a strongly negative emotion that makes them prioritise escape over keeping a social distance. Since people are known to react emotionally if others violate their personal space [4, 32, 33], this may incite sufficient emotional stress in the other to propagate the desire to flee. Under the right circumstances this could then result in a positive feedback loop that brings collective panic and flight behaviour.

To test this, the density-emotion mechanism is implemented in an extension of the ASCRIBE model, called DECADE [29]. In DECADE emotional exchange takes place via the process of absorption, amplification or dampening (negative amplification) by adjusting a single parameter. We compare the proposed model with absorption and a link between density and emotion against the original DECADE model with amplification, as well as the epidemiological-based Durupinar model [5]. For this we follow the methodology that was previously used to empirically validate the ASCRIBE and Durupinar model in the context of an incident where a sudden panic broke out in a crowd that had gathered for a memorial ceremony in the Netherlands [3, 27]. While ASCRIBE was found to resemble the trajectories of real people to a higher degree than the other models in this previous work, the authors concluded the navigation model likely formed a significant limitation. To improve upon this navigation model, we combine the contagion models with an adaptation of the RVO2 model for collision free navigation [28], which we extended with the tendency for agents to keep a social distance from others depending on the emotional state of the agent and a directional preference for less dense areas. Also, instead of only simulating the 35 agents that were traced [3], we simulate almost the entire crowd to give a more realistic medium for emotion to spread to the traced agents and allow for competition with the non-traced agents during escape.

2 RELATED WORK

Besides more traditional approaches to simulating crowds, that for example describe groups as fluids, potential fields, collections of particles, or as sets of strictly rational individuals, in recent years increasing attention has gone to the role of individual sentiment and other psychological traits in collective behaviour [17, 36]. Agent-based models are a type of model that is particularly suitable to simulate the effects of diversity in psychological factors on crowd behaviour [25]. This is due to the bottom-up nature of this type of model, where the individual properties and perception of an agent determine its decision making.

Emotion contagion is a term used for a collection of processes via which emotions spread in groups, with the result that individual emotions tend to converge towards a collective emotion [11]. For an overview of agent-based models of emotion contagion in groups we refer to a recent literature review by van Haeringen et al. [30]. This review finds that current research of emotion contagion in crowds is mostly focussed on (preventing) collective emotions that are strongly negative, and concludes that despite large theoretical progress, empirical validation is lagging behind.

Particularly related to the present study, is work that simulates the rapid amplification of panic in large crowds, triggering evacuation behaviour with the potential for crowd crushes and collisions. The following are recent examples of this. Xu et al. [35] combine epidemiological contagion of emotion, based on the Durupinar model [5], with local and global path planning algorithms to simulate evacuations in environments with multiple sources of danger. Mao et al. [21] present a contagion model that extends the ASCRIBE model [3] with the effect of leaders and followers in subgroups to simulate the evacuation from schools and stadiums. Zhou et al. [39] simulate the evacuation of a train station, stadium and museum, by combining path planning with epidemiological contagion in a cellular automaton, based on the model of Fu et al. [7]. Xiao and Li also extend the Fu model, by considering the effects of visual and non-visual perception on emotion contagion in crowds during evacuations [34]. Finally, while this work does not focus on an evacuation scenario, Lv et al. recently introduced a novel approach by combining epidemiological contagion of emotions among agents with deep reinforcement learning to assess the role of antagonistic emotions in riots [19].

3 METHODS

3.1 The proposed model

3.1.1 Emotion contagion. The spread of emotions among the agents is simulated by the DECADE model [29]. DECADE is an extension of the ASCRIBE model [3], where instead of a categorical emotion like fear, emotion spreads via two continuous dimensions, valence and arousal. The absorption and amplification mechanisms of DECADE are similar to that of ASCRIBE, but are adjusted to operate in the range (-1 1), where 0 is the emotionally neutral state. For brevity, we refer to [29] for further details and the mathematical implementation.

3.1.2 Personality. The personality of the agents is implemented using the OCEAN model of personality [22], also known as the Big Five. We chose this as the OCEAN model is commonly used in crowd modelling as well as in psychological literature [30]. The DECADE and Durupinar model define three parameters with a similar meaning in the contagion mechanism based on the personality of the agent, namely the susceptibility of the receiving agent, the expressivity of the sender and the ability to regulate emotion. How these are derived from the OCEAN model however differs for two of the three parameters. In both the proposed model and the Durupinar model, the susceptibility of the agent to emotions of others (δ) is determined via the empathy scale by Jolliffe and Farrington [15]. The emotional expressivity of the agent (ε) in the proposed model is determined from the personality of the agent based on the correlations found by Gross and John between the traits of the OCEAN model and emotional expressivity [10]. The ability to regulate emotion (λ) in the proposed model is based on a study by Baranczuk [1]. We used the average slopes found by Baranczuk among OCEAN personality traits and three out of the six strategies of emotion regulation that were deemed effective in regulating emotion by the author. For an explanation of how expressivity and regulation effectiveness are determined in the Durupinar model, we refer to [5].

$$\delta = 0.35\varphi^O + 0.18\varphi^C + 0.14\varphi^E + 0.31\varphi^A + 0.02\varphi^N \tag{1}$$

$$\varepsilon = 0.14\varphi^O - 0.02\varphi^C + 0.32\varphi^E + 0.11\varphi^A + 0.29\varphi^N \tag{2}$$

$$\lambda = 0.17\varphi^O + 0.22\varphi^C + 0.19\varphi^E + 0.45\varphi^A - 0.23\varphi^N \tag{3}$$

3.1.3 Emotion regulation. Emotions are generally short-lived, decaying over time [9]. Previously this was implemented as an exponential decay in DECADE, where strong emotion decreases at a faster rate than mild emotion. A recent study by Ojha et al. however remarks that emotions typically do not decay immediately, but instead are maintained for some time and then decrease rapidly [23]. Inspired by the work of Ojha et al., we have changed the decay function of DECADE to a hyperbolic tan function to approach this description. When regulation time (τ_i) is low, decay is minimal, but as the regulation time approaches decay time T, a rapid decay occurs following an s-shape to approach zero, the neutral state. The regulation time T of an agent is drawn from a normal distribution, the mean and variation of which are determined by the ability of the agent to regulation emotion (λ) modulating a maximum time for emotion regulation that applies to all agents (τ_{max}). Regulation time τ_i increases every simulation step if emotion is above a minimum threshold, otherwise it resets to zero. This allows for emotion (re)activation after the previous emotion has passed.

$$\Delta E_r = -E_r * \frac{1 + \tanh(\tau_i - T)}{2} \tag{4}$$

$$\tau_i = \begin{cases} Dist(E_r) > 0.1 & \tau_{i-1} + \Delta t \\ else & 0 \end{cases} \tag{5}$$

$$T = NORM\begin{pmatrix} \mu = \tau_{max} - \tau_{max} * \lambda_r \\ \sigma = \tau_{max}/10 \end{pmatrix} \tag{6}$$

3.1.4 Perception and navigation. Perception in crowd models is a complex problem, as sight and hearing are for example affected by dynamic obstacles and environmental sound. For the present study, we simplify this to a viewing range of three metres and a hearing range of ten metres in all directions. The agents use sight to select the nearest ten agents as their neighbours. Since more than ten agents may fit in the maximum viewing area, this approximates the narrowing of the viewing distance in a high-density crowd. In the case that is used to validate the proposed model, the event that triggers an emotional response that sets of the stampede occurs via hearing, as it was caused by a screaming person [3].

The navigation of the agents is based on the RVO2 (Reciprocal velocity obstacles) model [28]. This model starts from the assumption that pedestrians take the same collision avoidance strategy, from which the model calculates the optimal global solution using linear solver algorithms (Figure 1A). As input the RVO2 model takes a preferred velocity for each agent. To simulate emotion driven evacuation behaviour, the preferred velocity in the proposed model depends on the valence-arousal state of the agent. In its normal state, an agent acts in accordance with its long-term goal (Figure 1B). In the examined case study of a memorial, that goal is to remain in place to attend the ceremony. On the other hand, when the agent has a strongly aroused and negative emotional state, it will attempt to flee from the threat. This threshold is set as an Euclidean distance of 0.5 from the most negative and aroused point in valence-arousal space (Figure 1B). The exact value is arbitrary as we did not find literature about at what level of emotion people decide to act in an evacuation scenario.

Velocity can be described as two components, a direction and a speed. The preferred speed with which an agent flees ranges between 0 and 12km/h, and positively depends on its emotional negativity and arousal (Figure 1B).

$$V_{pref} = \left(1 - \frac{E_{dist}}{\sqrt{0.5}}\right) V_{max} \tag{7}$$

The preferred direction of the agent in a calm state is set as the angle towards the event, as any unexpected commotion is likely to draw attention. When the agent is stressed, its direction is determined first by taking the opposite angle towards the source of the threat. Next, since the intention of the agent is to flee, it makes sense to modify this preference slightly to the left or right when the density is lower than in front (Figure 1C). For this the local densities of three areas in the field of view are observed by the agent by counting the number of agents.

To ensure the agents do not collide, the minimum distance in the RVO2 model that an agent keeps to other agents is defined as two times the radius of the agent, with the assumption that the radii of the agents are equal. Instead, we extended the RVO2 model such that agents keep an additional distance to others that represents their personal space. A study by Hecht et al. measured the shape of personal spaces using various approach tasks and found the shape in all conditions approximately circular [13]. Therefore, we chose to implement the personal space that agents like to keep to others, as a minimum distance between the outer edges of agents. This distance was set to 30 centimetres, which is derived from a report by the US Federal Emergency Management Agency, that states that with a personal space below 0.3 metres^2 motion is severely restricted and the chance of contact with others becomes high and is normally avoided in crowds with the exception of elevators and buses [6]. However, we propose that this changes when someone is in a panicked state, driving people to prioritise escape over the requirement for their own personal space or respecting that of others. Thus, above the panic threshold the minimum distance that is kept by agents between its outer edges and that of other agents was set to zero.

3.1.5 Density-emotion link. The proposed link between density and emotion is twofold. The first is that people tend to maintain a personal space and may react emotionally to others that violate this personal space [12]. However, as Beermann and Sieben remark in a recent study, while the general assumption is that high density situations induce stress and discomfort, research of how emotion is affected by different densities and circumstances is scarce [2]. We found that the same applies for the related effect of personal space violations in crowds. Beermann and Sieben conducted an experiment where they placed participants in a box of 1 m^2 and measured the arousal response via skin conductance, both with and without verbal interaction between the participants. The authors however find that the results with regard to arousal are inconclusive.

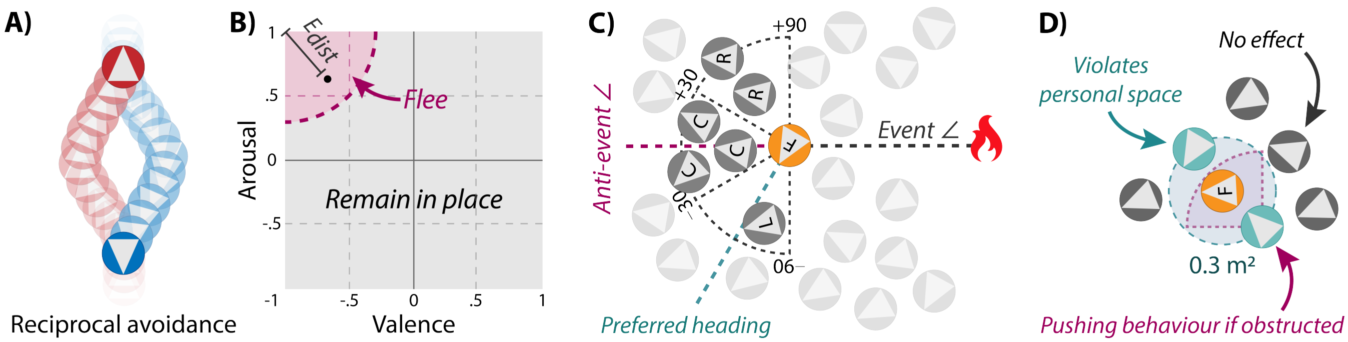

Figure 1: A) Reciprocal avoidance by the RVO2 model. B) Agents only prefer to move when emotionally aroused and negative, with a preferred speed that depends on the strength of the emotion. C) Agents flee in the opposite direction of the event or 60 degrees to the left or right of this direction, depending on which area has the least neighbours. D) Agents are emotionally affected if the local density is high, measured in a 1 m^2 area surrounding the agent (green area). If agents are prevented from fleeing when stressed, they will exert force against other agents within arm's reach that are in their way (pink area).

Although not aimed at groups, a study by Welsch et al., conducted various approach experiments in a one to one encounter with a stranger, where they tested the relation between proximity and the level of discomfort in participants, that was indicated using a joystick [32]. They concluded that intrusion of personal space occurred relatively abrupt where an intrusion of 15 centimetres already lead to a clear increase in discomfort. Making use of virtual reality, Dickinson et al. place participants in virtual groups with varying densities and find that high densities induced negative affect in participants [4]. Nevertheless, since clear empirical guidance is currently lacking, we chose to implement a simple linear function for the decrease of valence and increase of arousal when the personal space of an agent is violated (Figure 1D), where the opposite of the distance between agent i and intruder j relative to the maximum distance of the personal space determines the impact on emotion, scaled by parameter ω for tuning purposes.

$$\left.\begin{array}{l} E_{val\,j} = E_{val\,j} - \\ E_{aro\,j} = E_{aro\,j} + \end{array}\right\} \omega \left(1 - \frac{D_{ij}}{D_{persSpace}}\right) \tag{8}$$

The second link is via the use of force during congestion in high-density situations. Stampedes often involve collisions and pushing, where asphyxia as the result of collective pushing has been named as the largest contributor to casualties from stampedes [14]. Under normal conditions in the model, agents do not push each other. However, when an agent in a panic state is hindered in its escape, the agent will exert a force in the direction that it wants to travel (Fig. 1D). This happens when its actual speed is less than half of its preferred speed. To mathematically express the emotion-driven pushing behaviour, we use a simplified kinetic description. Specifically, Newton's second law of motion is used to calculate the impact of pushing behaviour by agent i on agent j. The acceleration of the victim j equals the maximum pushing force F_{max} in the direction agent i is facing, modulated by the degree of panic, divided by the mass of agent j (M_j). The net acceleration vector A_j is determined by summing all the forces from the neighbours (N_j) that are applied to the agent during a simulation step. This is translated to the potential displacement of agent j. Agent j will only move in this direction as far as there is space with respect to other agents and obstacles. Note that therefore the personal space of an agent is not only violated by panicked individuals, but potentially also by victims of pushing behaviour.

$$\frac{\Delta \overrightarrow{v_j}}{\Delta t} = \overrightarrow{A_j} = \sum_{i \in N_j} \frac{(1 - \frac{E_{dist\,j}}{\sqrt{0.5}})\overrightarrow{F_{max}}}{M_j} \tag{9}$$

Further, we assume that being pushed always negatively affects valence and positively affects arousal, since being pushed from opposite directions is unpleasant even if one is not displaced. For this the sum of the pushing accelerations of the neighbours is taken and modified by parameter ϑ that controls the impact of physical forces on emotion. The result is detracted from the valence of agent j and added to its arousal.

$$\left.\begin{array}{l} E_{val\,j} = E_{val\,j} - \\ E_{aro\,j} = E_{aro\,j} + \end{array}\right\} \theta \sum_{i \in N_j} \frac{\left(1 - \frac{E_{dist\,i}}{\sqrt{0.5}}\right) F_{max}}{M_j} \tag{10}$$

3.2 Simulation set-up, measures and analysis

To test the proposed model with density-emotion interactions, which includes emotion contagion via the absorption mechanism of DECADE, it is compared against the same absorption model without the proposed density-emotion link. Further, as this study aims to provide a biologically explainable alternative to the amplification mechanism in DECADE/ASCRIBE, the proposed mechanism is also compared to DECADE with amplification mechanism. Lastly, also the epidemiological-based Durupinar model [5] was included, as it is one of the most used models of epidemiological emotion contagion [30].

In the first part of the results, the effect of different densities on amplification of panic is measured. This is done by placing agents in a 38 by 38 metre space at the centre of an open world, where for the densities of 0.6, 1.2, 1.8 and 2.4 people/m^2, 900, 1750, 2750 and 3625 agents were generated respectively in this space. The agents begin with an emotionally neutral state. After 60 simulation steps (2 seconds) a trigger event induces a strong negative aroused state for the agents within 3 metres from the centre coordinate. The locations of all agents were recorded and subsequently analysed with the use of density plots.

In the second part of the results, we examine the May 4th case study that was previously used to validate and compare the ASCRIBE, Durupinar, ESCAPES, Hatfield and Social Force models [3, 27]. This incident occurred during a memorial in The Netherlands. During a minute of silence, a man screamed, after which panic spread through the crowd. In the present study we make use of the paths of 35 individuals in the crowd that were traced from video footage of the incident that was broadcast on Dutch television [3], but we found this material is currently only available in lower quality on YouTube [37]. Since these paths were tracked from a side-viewing camera, the distortion was too large to exactly trace the layout of the square from satellite pictures on top of the paths. Therefore, we approximated the layout of the buildings and other obstacles by hand. We did not include the fences as obstacles as people can be seen jumping over or toppling the fences during the incident. After this we placed 17750 agents, the majority by generating them at random locations with a minimum distance from other agents, and some by hand to approximate details observed in the video, like the row in the centre aisle. The scream that triggered the evacuation was implemented as a brief event of a single time step that induced a strong negative and aroused state in agents within ten metres of the source location reported by Bosse et al. [3]. The exact radius within people were heavily affected is a common-sense estimation, as we did not find literature to set this more precisely. Since all models contain stochastic factors, ten repetitions were simulated for each condition.

To tune the models, we ran simulations with the May 4th scenario with a range of settings for one parameter per model. For the proposed model that was the constant ω that determines impact of personal space violations on emotion. For DECADE with the amplification mechanism parameter β was adjusted that controls the degree of amplification. For the Durupinar model the mean dose size was adjusted. We then selected the setting that gave the combined lowest error for the distance and speed of the 35 traced paths in the real crowd. Further details for the tuning process and the reasoning behind the other parameter settings can be found in Appendix 2.

The models were implemented in C++ using Microsoft Visual Studio, where the majority of the calculations are performed on the GPU using the CUDA framework. These, as well as the supporting software, scripts and data are available in the supplementary materials, see Appendix 1. The model output was analysed using RStudio.

4 RESULTS

4.1 Effect of crowd density

Figure 2 presents the comparison of the different models at different starting densities of the crowd in an open world. First of all, for the proposed mechanism (labelled Density), it shows that there is strong amplification of emotion when the starting density of the crowd is high, but not when it is at 1.2 people/m^2 or lower. Most clearly visible at a density of 1.8 people/m^2 is that the fear spreads unevenly, possibly indicating that the agents have chosen the path of the lowest resistance. Also visible is that when agents reach the open space outside the crowd, they calm down relatively quickly. Next, with only emotion contagion via absorption, the strong emotion of the few at the centre is not amplified through the crowd. Instead, the emotion of the triggered agents quickly converges toward the average emotion of the crowd, which is neutral. In contrast, emotion contagion with the amplification mechanism of the DECADE model strongly spreads emotion throughout the entire crowd. This occurs even if the density is low. Similarly, it is visible that agents remain panicked longer than in the proposed model after they have escaped from the main crowd. Finally, while the Durupinar model appears not to amplify the strong panic behaviour throughout the crowd, closer examination learns that fear does spread to all the agents, albeit at a relative low intensity, causing them to move at a slow pace.

The right half of Figure 2 shows the emotional spiral of the proposed model over time at a starting density of 1.8 people/m^2, that is most comparable to the case study discussed in the next subsection. After the trigger event at second two, a ring is formed in the crowd where density is relatively high, the fear of the agents is strongest and pushing behaviour takes place. The high-density ring expands over time through the crowd, leaving behind agents that have calmed down.

4.2 Empirical validation

Figure 3 shows the simulation results for the May 4th incident in two ways. First, in the form of the individual paths of the 35 agents that were traced during the simulations in the present paper, as well as from the real incident. Second, as the simulation output of all agents at the end of the simulation, six seconds after the incident started. The crowd state before the incident and six seconds after is shown as a qualitative reference. The proposed density mechanism and the amplification mechanism in DECADE perform similarly, producing a large wave of panic with elevated density, that spreads through the crowd in a circular manner away from the incident. While this approximates the length of the paths, indicating traveling speed, the direction of paths does not match well for all agents, resulting in a relatively large position error compared to the real paths (Figure 4). Also, the spread is limited to only the right side of the centre aisle, whereas in the real crowd people become infected on the left side at the end of the clip as well. Similar to the density experiment, when the density mechanism is turned off (Absorption) the emotion is not amplified throughout the crowd. In the Durupinar model the emotion spreads through the majority of the crowd on the right side of the aisle, but in a less intense form, causing large scale slow movement. The small displacement in the absorption and Durupinar models resulted in a lower position error, but a larger error in speed.

5 DISCUSSION

The present study introduces a biologically-plausible model for mass amplification of emotions in crowds. This is based on a tendency to react emotionally to the violation of one's personal space or being pushed. In our view, innovation is necessary because amplification mechanisms in current models of emotion contagion are not well supported by psychological literature, nor can they be

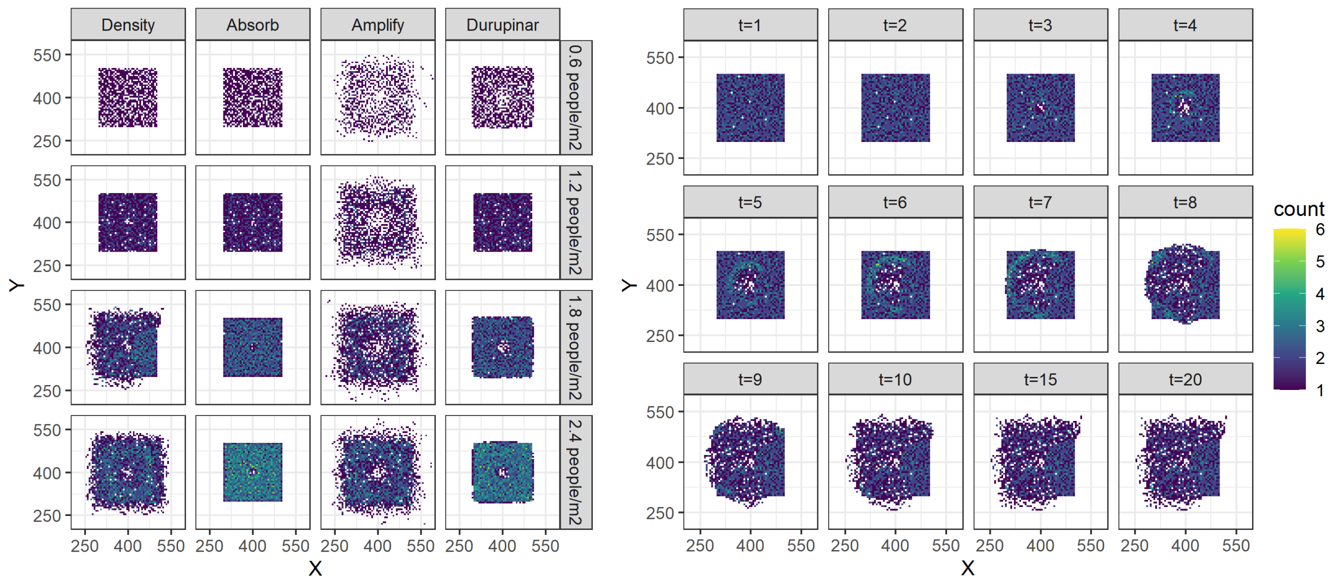

Figure 2: Density plots of the different models at various start densities after 20 seconds (left), and a time series of the proposed model with a start density of 1.8 m^2 (right). See supplementary materials for the video.

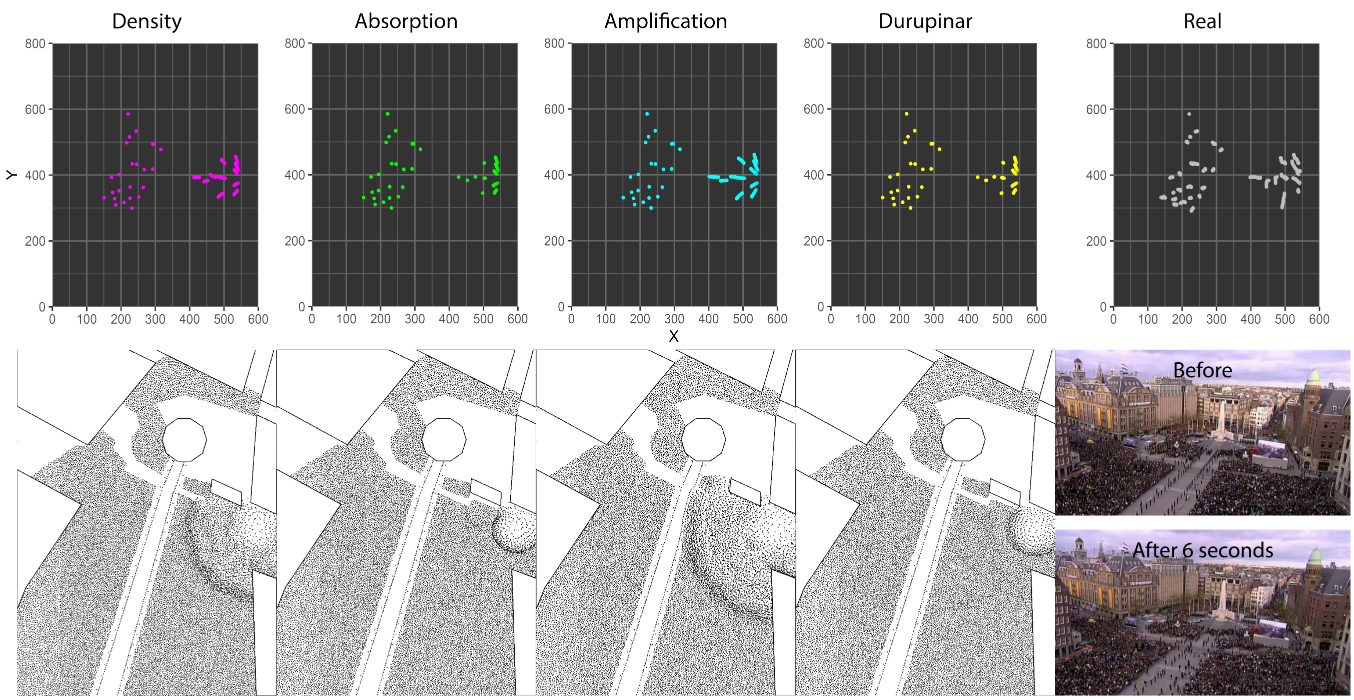

Figure 3: Simulation result after 6 seconds for the paths of the 35 tracked agents (top) and view of all agents (bottom). The paths of the real people that were tracked and the video from which these paths were extracted by Bosse et al. [1] is shown on the right. See supplementary materials for videos.

validated or tuned empirically. Yet, while the proposed mechanisms could be measured empirically, we found that current knowledge is lacking on the exact emotional impact of personal space violations and pushing behaviour. Therefore, the findings of this study may contribute to the field by motivating empirical research of these processes in the future, which is more resource demanding than computer simulation and often has steeper practical and ethical

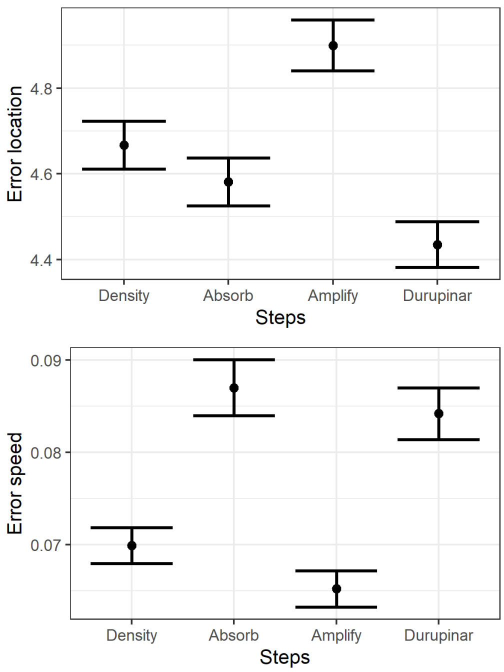

Figure 4: Average deviation in the position (left) and speed (right) for each model compared to the traced data in the May 4th incident (mean ± SE).

challenges to overcome. At the same time, we recognise that research involving crowds and emotions is highly challenging. and involves many interwoven processes that are difficult to study in isolation [16].

Specifically, our findings show that the combination of emotion contagion in the form of absorption with the proposed links between density and emotion is capable of producing a negative emotional spiral, with a similar result in the validation scenario as the contagion-based amplification in the ASCRIBE and DECADE models. A notable difference is that the occurrence of amplification in the proposed model depends on the density of the crowd. This aligns with crowd literature that identifies density as an important risk factor for the occurrence of stampedes [26]. We therefore hypothesise that the proposed model is more suitable to also simulate normal crowd conditions and small-scale incidents that do not result in mass panic, whereas the amplification mechanism of DECADE would be unstable, driving the emotional state of the crowd to escalate when any amount of emotion is introduced into the system.

The simulations with the Durupinar model also resulted in wide spread of fear throughout the crowd, yet in a much weaker fashion. This resulted a slow general retreat, instead of a panicked escape. We found the same unexpected pattern even when the dose parameter was set ten times higher than the value used by Durupinar et al. [5] (see Appendix 2). A possible explanation for this pattern is that when the cumulative dose for a susceptible agent, calculated from the doses stored in a limited memory, passes the threshold for infection, the increase in the panic value is relatively low, as the infection threshold defined by Durupinar et al. [5] is relatively low. Since doses can only pass from infected agents to susceptible agents, the panic value does not rise further. Moreover, when the agent infects subsequent agents farther away from the origin of the emotion, these will receive a lower dose, as this is modulated by the degree of panic of the infected individual. Therefore, it takes more time for emotion to spread, during which the emotion regulation process in the model has a larger impact. Another contributing factor that was not present in simulation of the May 4th incident in prior studies [3, 27] is that the highly emotional agents near the trigger event are blocked by the surrounding crowd, limiting their sphere of influence. However, it should be noted that only the contagion mechanism of the Durupinar model was implemented with a single categorical emotion. It is possible that introducing multiple emotions as well as the regulatory system in the form of the Pleasure-Arousal-Dominance model that is used to mitigate between emotion and behaviour by Durupinar et al. [5] would produce different results.

A significant deviation from the real incident, that was found for all simulations, is that panic did not spread across the centre aisle. In the video it can be observed that once the escape behaviour is observed near the aisle, it also spreads over the aisle to the crowd on the other side. This seems an example of the effect of emotion contagion, as it is not a change in density or being pushed that spreads the panic across the gap in the crowd. That this is not observed in the simulations follows from the limitations of the perception model that was used, where an agent only perceives other agents within a certain range. This range is set to three metres to represent the limited perception within a dense crowd. However since the centre aisle is empty, the actual perception distance across the aisle is likely much larger. It could be that with a more realistic perception model, emotion would jump this gap. However, the immediate response of people accross the centre aisle suggests that some preparatory process may have preceded it. A possible explanation is that, while the man's scream in a silent crowd starting the stampede was only severe enough to trigger escape behaviour in those close to him, a large portion of the crowd was still affected by it and prepared to escape upon further sign of danger. Future work could therefore also examine in more detail how the trigger event affects people in space, as well as consider the implementation of preparatory or freeze behaviour that raises the alertness of agents.

Finally, data sets of emotional crowd behaviour are currently rare. The validation scenario used in the present study was chosen because it is one of only a few available examples that was used to compare both the ASCRIBE and Durupinar-type of contagion models to empirical data. Therefore we believe that the recent rise of an open-data culture in science also has the potential to significantly further the field of crowd simulation [18, 24]. Moreover, the data sets that are currently available are often not suitable to directly validate psychological processes of crowd models, such as emotion contagion, because these do not contain measures of psychological traits. Instead, the prevailing method is to validate a model as a whole, by comparing behaviour (often in the form of movement) of agents to that of real people[30]. Thus, even though the present results give a positive indication to further explore whether density-emotion interactions underlay emotional escalation in crowds, these points underscore that the presented results are preliminary, and that there is a pressing need for future work to gather richer data of emotional groups, and to share data sets from a broad variety of environments and scenarios, to determine the generalisability of models of emotional crowds.

SUPPLEMENTARY MATERIALS

The supplementary materials can be found at: https://osf.io/5kcj4

ACKNOWLEDGMENTS

We would like to thank Tibor Bosse for providing the data set of the May 4th incident. This work is part of the research programme Innovational Research Incentives Scheme Vidi SSH 2017 with project number 016.Vidi.185.178, which is financed by the Dutch Research Council (NWO).

REFERENCES

[1] Urszula Barańczuk. 2019. The five factor model of personality and emotion regulation: A meta-analysis. *Personality and Individual Differences* 139 (mar 2019), 217–227. https://doi.org/10.1016/J.PAID.2018.11.025
[2] Mira Beermann and Anna Sieben. 2022. Waiting Behavior and Arousal in Different Levels of Crowd Density: A Psychological Experiment with a "tiny Box". *Journal of Advanced Transportation* 2022 (2022). https://doi.org/10.1155/2022/7245301
[3] Tibor Bosse, Mark Hoogendoorn, Michel C.A. A. Klein, Jan Treur, C. Natalie van der Wal, and Arlette van Wissen. 2013. Modelling collective decision making in groups and crowds: Integrating social contagion and interacting emotions, beliefs and intentions. *Autonomous Agents and Multi-Agent Systems* 27, 1 (jul 2013), 52–84. https://doi.org/10.1007/s10458-012-9201-1
[4] Patrick Dickinson, Kathrin Gerling, Kieran Hicks, John Murray, John Shearer, and Jacob Greenwood. 2019. Virtual reality crowd simulation: effects of agent density on user experience and behaviour. *Virtual Reality* 23, 1 (mar 2019), 19–32. https://doi.org/10.1007/S10055-018-0365-0/TABLES/8
[5] Funda Durupinar, Ugur Gudukbay, Aytek Aman, and Norman I. Badler. 2016. Psychological Parameters for Crowd Simulation: From Audiences to Mobs. *IEEE Transactions on Visualization and Computer Graphics* 22, 9 (sep 2016), 2145–2159. https://doi.org/10.1109/TVCG.2015.2501801
[6] Federal Emergency Management Agency. 2005. *Special Events Contingency Planning*. Technical Report. 257 pages.
[7] Libi Fu, Weiguo Song, Wei Lv, and Siuming Lo. 2014. Simulation of emotional contagion using modified SIR model: A cellular automaton approach. *Physica A: Statistical Mechanics and its Applications* 405 (jul 2014), 380–391. https://doi.org/10.1016/j.physa.2014.03.043
[8] Amit Goldenberg and James J. Gross. 2020. Digital Emotion Contagion. *Trends in Cognitive Sciences* 24, 4 (apr 2020), 316–328. https://doi.org/10.1016/J.TICS.2020.01.009
[9] James J. Gross and Hooria Jazaieri. 2014. Emotion, emotion regulation, and psychopathology: an affective science perspective. *Clinical Psychological Science* 2, 4 (dec 2014), 387–401. https://doi.org/10.1177/2167702614536164
[10] James J. Gross and Oliver P. John. 1995. Facets of emotional Expressivity: Three self-report factors and their correlates. *Personality and Individual Differences* 19, 4 (oct 1995), 555–568. https://doi.org/10.1016/0191-8869(95)00055-B
[11] Elaine Hatfield, Megan Carpenter, and Richard L. Rapson. 2014. Emotional contagion as a precursor to collective emotions. *Collective Emotions* (apr 2014), 108–122. https://doi.org/10.1093/ACPROF:OSO/9780199659180.003.0008
[12] Leslie A. Hayduk. 1978. Personal space: An evaluative and orienting overview. *Psychological Bulletin* 85, 1 (jan 1978), 117–134. https://doi.org/10.1037/0033-2909.85.1.117
[13] Heiko Hecht, Robin Welsch, Jana Viehoff, and Matthew R. Longo. 2019. The shape of personal space. *Acta Psychologica* 193 (feb 2019), 113–122. https://doi.org/10.1016/J.ACTPSY.2018.12.009
[14] Dirk Helbing and Pratik Mukerji. 2012. Crowd disasters as systemic failures: Analysis of the love parade disaster. *EPJ Data Science* 1, 1 (jun 2012), 1–40. https://doi.org/10.1140/EPJDS7/TABLES/6 arXiv:1206.5856
[15] Darrick Jolliffe and David P. Farrington. 2006. Development and validation of the Basic Empathy Scale. *Journal of adolescence* 29, 4 (aug 2006), 589–611. https://doi.org/10.1016/J.ADOLESCENCE.2005.08.010
[16] Petros Kefalas and Ilias Sakellariou. 2017. The invalidity of validating emotional multi-Agent systems simulations. *ACM International Conference Proceeding Series* Part F130953, 1–8. https://doi.org/10.1145/3136273.3136290
[17] Yang Li, Maoyin Chen, Zhan Dou, Xiaoping Zheng, Yuan Cheng, and Ahmed Mebarki. 2019. A review of cellular automata models for crowd evacuation. *Physica A: Statistical Mechanics and its Applications* 526 (jul 2019), 120752. https://doi.org/10.1016/J.PHYSA.2019.03.117
[18] Julia S.Stewart Lowndes, Benjamin D. Best, Courtney Scarborough, Jamie C. Afflerbach, Melanie R. Frazier, Casey C. O'Hara, Ning Jiang, and Benjamin S. Halpern. 2017. Our path to better science in less time using open data science tools. *Nature Ecology & Evolution 2017 1:6* 1, 6 (may 2017), 1–7. https://doi.org/10.1038/s41559-017-0160
[19] Pei Lv, Qingqing Yu, Boya Xu, Chaochao Li, Bing Zhou, and Mingliang Xu. 2022. Emotional Contagion-Aware Deep Reinforcement Learning for Antagonistic Crowd Simulation. *IEEE Transactions on Affective Computing* (2022). https://doi.org/10.1109/TAFFC.2022.3225037
[20] Pei Lv, Zhujin Zhang, Chaochao Li, Yibo Guo, Bing Zhou, and Mingliang Xu. 2019. Crowd Behavior Evolution with Emotional Contagion in Political Rallies. *IEEE Transactions on Computational Social Systems* 6, 2 (apr 2019), 377–386. https://doi.org/10.1109/TCSS.2018.2878461
[21] Yan Mao, Shanwen Yang, Zuning Li, and Yongjian Li. 2020. Personality trait and group emotion contagion based crowd simulation for emergency evacuation. *Multimedia Tools and Applications* 79, 5-6 (may 2020), 3077–3104. https://doi.org/10.1007/s11042-018-6069-3
[22] Robert R. McCrae and Paul T. Costa. 1989. The Structure of Interpersonal Traits: Wiggins's Circumplex and the Five-Factor Model. *Journal of Personality and Social Psychology* 56, 4 (1989), 586–595. https://doi.org/10.1037/0022-3514.56.4.586
[23] Suman Ojha, Jonathan Vitale, and Mary-Anne Williams. 2020. EEGS: A Transparent Model of Emotions. (nov 2020). arXiv:2011.02573 http://arxiv.org/abs/2011.02573
[24] Chris Paton and Shinji Kobayashi. 2019. An Open Science Approach to Artificial Intelligence in Healthcare. *Yearbook of medical informatics* 28, 1 (aug 2019), 47–51. https://doi.org/10.1055/S-0039-1677898/ID/JRPATON-51
[25] Nur Siyam, Omar Alqaryouti, and Sherief Abdallah. 2020. Research Issues in Agent-Based Simulation for Pedestrians Evacuation. *IEEE Access* 8 (2020), 134435–134455. https://doi.org/10.1109/ACCESS.2019.2956880
[26] Lee Soomaroo and Virginia Murray. 2012. Disasters at Mass Gatherings: Lessons from History. *PLoS Currents* 4 (2012). https://doi.org/10.1371/CURRENTS.RRN1301
[27] Jason Tsai, Emma Bowring, Stacy Marsella, and Milind Tambe. 2013. Empirical evaluation of computational fear contagion models in crowd dispersions. *Autonomous Agents and Multi-Agent Systems* 27, 2 (2013), 200–217. https://doi.org/10.1007/s10458-013-9220-6
[28] Jur van den Berg, Stephen J. Guy, Ming Lin, and Dinesh Manocha. 2011. Reciprocal n-body collision avoidance. *Springer Tracts in Advanced Robotics* 70, STAR (2011), 3–19. https://doi.org/10.1007/978-3-642-19457-3_1
[29] Erik van Haeringen, Charlotte Gerritsen, and Koen Hindriks. 2021. Integrating Valence and Arousal Within an Agent-Based Model of Emotion Contagion. In *Advances in Practical Applications of Agents, Multi-Agent Systems, and Social Good. The PAAMS Collection*, F Dignum, J M Corchado, and F De La Prieta (Eds.). Springer, Cham, 303–315. https://doi.org/10.1007/978-3-030-85739-4_25
[30] Erik van Haeringen, Charlotte Gerritsen, and Koen Hindriks. 2022. Emotion contagion in agent-based simulations of crowds: a systematic review. *Autonomous Agents and Multi-Agent Systems 2022 37:1* 37, 1 (nov 2022), 1–41. https://doi.org/10.1007/S10458-022-09589-Z
[31] Gerben A. van Kleef, Marc W. Heerdink, and Astrid C. Homan. 2017. Emotional influence in groups: the dynamic nexus of affect, cognition, and behavior. , 156–161 pages. https://doi.org/10.1016/j.copsyc.2017.07.017
[32] Robin Welsch, Christoph von Castell, and Heiko Hecht. 2019. The anisotropy of personal space. *PLOS ONE* 14, 6 (jun 2019), e0217587. https://doi.org/10.1371/JOURNAL.PONE.0217587
[33] Stephen Worchel. 1978. Reducing Crowding without Increasing Space: Some Applications of an Attributional Theory of Crowding. *Journal of Population* 1, 3 (oct 1978), 216–230. http://www.jstor.org.vu-nl.idm.oclc.org/stable/27507573
[34] Q Xiao and J Li. 2021. Evacuation model of emotional contagion crowd based on cellular automata. *Discrete Dynamics in Nature and Society* 2021 (2021). https://doi.org/10.1155/2021/5549188
[35] Mingliang Xu, Xiaozheng Xie, Pei Lv, Jianwei Niu, Hua Wang, Chaochao Li, Ruijie Zhu, Zhigang Deng, and Bing Zhou. 2021. Crowd Behavior Simulation With Emotional Contagion in Unexpected Multihazard Situations. *IEEE Transactions on Systems, Man, and Cybernetics: Systems* 51, 3 (2021), 1567–1581. https://doi.org/10.1109/TSMC.2019.2899047
[36] Shanwen Yang, Tianrui Li, Xun Gong, Bo Peng, and Jie Hu. 2020. A review on crowd simulation and modeling. *Graphical Models* 111 (sep 2020), 101081.
[37] Yourdutch Media Productions. 2010. Paniek Dodenherdenking 2010. https://www.youtube.com/watch?v=0cEQp8OQj2Y
[38] Guijuan Zhang, Dianjie Lu, and Hong Liu. 2020. Strategies to Utilize the Positive Emotional Contagion Optimally in Crowd Evacuation. *IEEE Transactions on Affective Computing* 11, 4 (oct 2020), 708–721. https://doi.org/10.1109/TAFFC.2018.2836462
[39] Rui Zhou, Yi Ou, Weichao Tang, Qian Wang, and Bao Yu. 2020. An Emergency Evacuation Behavior Simulation Method Combines Personality Traits and Emotion Contagion. *IEEE Access* 8 (2020), 66693–66706. https://doi.org/10.1109/ACCESS.2020.2985987