Using non-human biological entities to understand pedestrian crowd behaviour under emergency conditions

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ABSTRACT

Models of collective movement have been developed for both human crowds and animal herds and other aggregations but these models have not been used to test whether panicked crowds display generic features of dynamical behaviour regardless of species, and in particular whether a single model can explain panic behaviour in organisms of vastly different body size. We use a single modelling framework to examine crowd behaviour in ants and humans, which differ by 8 orders of magnitude in body mass. We assess whether simple allometric scaling of model parameter values, based only on the body mass difference, allows the model to describe the collective behaviour of the two species under panic conditions. We verified the model against experimental data from panicking Argentine ants (*Linepithema humile*) and then rescaled the parameter values to human body size. The predictions of rescaled model correspond to the quantitative data available for crowd panics, suggesting that the same kinds of interactions among individuals and with the physical environment govern crowd behaviour. We tested the effects of partial obstruction and the homogeneity of body sizes on the escape rate and found that appropriate selection of size and location of obstruction and homogeneity of body sizes can increase the outflow of pedestrians by more than double. Broader comparisons of crowd behaviour among species with different forms of locomotion and body size can enhance our theoretical understanding of crowd panics and potentially has applications in handling of agricultural animals as well as human public safety.

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1. Introduction

Collective movement of large numbers of pedestrians is important in many situations, such as the evacuation of public buildings in emergencies or panic situations. Here, we consider panic or emergency as situations in which individuals have limited information and vision (due to high crowd density and short time for egress), and which result in physical competition and pushing behaviour (Helbing et al., 2000; Lee and Hughes, 2006; Shiwakoti et al., 2009). This is different than the orderly evacuation or normal pedestrian dynamics where the bulk of literature is restricted (Okazaki and Matsushita, 1993; Still, 2000; Olsson and Regan, 2001; Hoogendoorn and Bovy, 2002; Klüpfel, 2003; Hughes, 2003; Kretz, 2007; Asano et al., 2009).

Understanding how crowds behave during collective displacement is at the heart of both 'movement ecology' (Holden, 2006) and pedestrian traffic engineering (Helbing et al., 2000; Shiwakoti et al., 2009). Collective patterns of crowd behaviour arise whenever organisms, including humans (Helbing et al., 2000; Shiwakoti et al., 2009) and other species (Okubo, 1986; Camazine et al., 2001; Couzin and Krause, 2003) aggregate in large numbers. Speed and interaction rates among individuals in a crowd are typically elevated under panic or emergency conditions. Models of collective movement have been developed for both human crowds (Helbing et al., 2000; Lee and Hughes, 2006) and animal herds and other aggregations (Okubo, 1986; Couzin and Krause, 2003) but these models have not been used to test whether panicked crowds display generic features of dynamical behaviour regardless of species, and in particular whether a single model can explain panic behaviour in organisms of vastly different body size. Also, current understanding of pedestrian crowd panic is limited by the scarcity of complementary data to develop and validate explanatory models (Helbing et al., 2000; Shiwakoti et al., 2009; Shiwakoti and Sarvi, 2013). It might be possible to improve the predictive ability of models by comparing human crowds to social animal groups, such as ant colonies, providing the model can be scaled appropriately (Altshuler et al., 2005; Burd, 2006; Shiwakoti et al., 2009; Shiwakoti and Sarvi, 2013; Soria et al., 2012).

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We have previously developed a mathematical model of crowd dynamics for emergency situation based on Newtonian mechanics (Shiwakoti et al., 2010, 2011) in which individual motion is governed by both internal driving forces and external forces that come into play when individuals come into contact with each other or with objects in their environment. Here we test whether this single model can accurately describe the behaviour of both humans and Argentine ants (*Linepithema humile*). These two species differ in the manner and speed of locomotion, in chemical, visual and aural perception and communication, and in the nature of the social organization, yet we account only for body mass differences in the model. To rescale the model from ants to humans, we used a known scaling pattern for maximum locomotion speed to infer all other parameter values that we could not directly measure.

2. Microscopic model

Here we summarize the main essence of the microscopic model developed to study the crowd behaviour under emergency situations; while the additional details can be found in the literature (Shiwakoti et al., 2010, 2011). Movement in the model is governed by Newtonian mechanics; in particular, the motion of each individual i follows the direction of the net force,

$$m_i \vec{a}_i = \vec{F}_i. \tag{1}$$

The net force acting on an individual is the summation of several component forces. Our model identifies two kinds of internally generated forces. The first is a global impulsive force that defines an intended path, such as toward a food source or away from an enemy. The second is a local force whose strength and direction varies with the proximity and arrangement of other individuals in the crowd. The local force is attractive when an individual becomes too isolated (a "follow the crowd" or "safety in numbers" effect) and repulsive at close range when collisions are imminent. Since an individual in a crowd may be near some individuals and far from others, the complete local force acting on a focal individual is the summation of its interactions with all other individuals in the crowd and with physical obstacles in its environment. A final component force arises when individuals in the crowd come into contact with each other or with features of their environment (e.g., walls and obstacles), as occurs in any contact between bodies in physical mechanics. Thus, the net force on individual i is given by

$$\vec{F}_i = \vec{F}_I + \vec{F}_L + \vec{F}_C, \tag{2}$$

in which $\vec{F}_I$ is the impulsive force, $\vec{F}_L$ the local interaction force, and $\vec{F}_C$ the contact force.

The impulsive force is defined by an acceleration vector composed of a characteristic speed, v_f, a unit vector $\vec{p}$ that points from an individual's current position towards its goal point, and a relaxation time σ^{-1} that is necessary for accelerative equilibrium of impulsive forces and resistive forces. Thus, the impulsive force is given by

$$\vec{F}_I = m_i \vec{a}_I = m_i v_f \sigma^{-1} \vec{p}_i. \tag{3}$$

We model the local effects as an interplay of attraction and repulsion governed by the distance X_{ij} between individuals. Organisms moving in a given direction are more likely to be attracted and repulsed by those in front of them than by those to the side or rear. We model this effect by a weighting factor, $W(\theta_{ij}) = 1 - [(1 - \cos\theta_{ij})/2]^2$, that depends on the angle θ_{ij} between i's current direction of motion and the direction from i to j. The weighting is

greatest for individuals directly in i's path and falls to zero for individuals directly behind. Finally, if we account for the body size of individuals by assigning a radius r_i, we can define the local force as

$$\vec{F}_L = \phi W(\theta_{ij}) \left(\frac{X_{ij} - (r_i + r_j) - \lambda_R}{[X_{ij} - (r_i + r_j) - \lambda_R]^2 + \lambda_A^2} \right) \vec{n}_{ij}, \tag{4}$$

in which $\vec{n}_{ij}$ is a unit vector normal to the ij axis, and the parameter ϕ can take on one of two values depending on whether $X_{ij} - (r_i + r_j) - \lambda_R$ is positive (and the attractive force is in play) or negative (for the repulsive force). Should the "intentional" forces $\vec{F}_I$ and $\vec{F}_L$ fail to prevent collisions, perhaps due to an extremely high local density of individuals, we must account for the forces generated by contact. The problem is addressed by invoking strong normal forces as well as frictional (shearing) forces acting tangentially between the colliding particles as below

$$\vec{F}_C = \vec{F}_n + \vec{F}_t = \alpha_1 \vec{v}_n + \alpha_2 \delta \vec{n} + \mu_1 \vec{v}_t + \mu_2 \delta \vec{t}. \tag{5}$$

The normal force ($\vec{F}_n$) pushes two individuals apart much like a compressed spring would do. Dissipation of the collision energy by the "spring" is determined by a damping coefficient, α_1, and the normal component of the impact velocity, $\vec{v}_n$. The rebound in the normal direction $\vec{n}$ is governed by the compression δ (the overlap between the colliding bodies) and an elastic restoration coefficient α_2 that reflects the stiffness of the particles in contact. The tangential force ($\vec{F}_t$) is similarly governed by friction coefficients, μ_1 and μ_2, the tangential component of the impact velocity, $\vec{v}_t$, and the compression δ. Avoidance of physical obstacles in the environment and the effect of contact between individuals and stationary obstacles is modelled by an expression analogous to $\vec{F}_L$ and $\vec{F}_C$.

3. Empirical data on ants

The first step in examining the generality of our crowd model was to verify the model performance against empirical behaviour in ants. We previously conducted experiments with Argentine ants, collected from the campus of Monash University (37°54′S 145°07′E) in Melbourne, Australia and the details of experimental setup can be found in the literature (Burd et al., 2010; Shiwakoti et al., 2011). We observed the escape rate of around 200 ants from enclosed areas of four different configurations that are expected to affect passage through exits. One configuration is based on the counterintuitive prediction that escape rates from enclosed areas will be enhanced if there is a partial obstruction or barrier on the 'upstream' side of an exit (Helbing et al., 2000). The counterintuitive performance of obstruction in terms of outflow has recently been predicted for granular flow in a hopper as well (Alonso-Marroquin et al., 2012; Lozano et al., 2012). We tested this with ants escaping from a circular chamber (i) with or (ii) without a small column located in front of an exit, creating a partial obstruction. We also tested two other exit configurations: a square chamber with an exit situated either (iii) at the corner of two walls or (iv) in the middle of a wall. Panic was created by injecting citronella oil (an insect repellent) into the chamber.

For this study, we extracted the exit times (to the nearest 0.04 s) of the first 50 ants to leave the chamber, when the crowd pressure at the exit was greatest. From these data, we plotted the number of ants that had escaped as a function of the elapsed time since the onset of panic, i.e., the cumulative escape pattern. Frequency distributions of headway times were determined for the experimental and simulation escapes from the combined data of replicates for the various treatments. The time interval between the exits of successive ants is known as a "headway."