

COLLECTIVE PATTERNS UNDER EMERGENCY CONDITIONS: LINKING NON-HUMAN BIOLOGICAL ORGANISMS TO PEDESTRIANS

SHIWAKOTI, Nirajan*
SARVI, Majid*
ROSE, Geoff*
BURD, Martin⁺

*Institute of Transport Studies, Department of Civil Engineering, Monash University, Melbourne, Victoria 3800, Australia

⁺School of Biological Sciences, Monash University, Melbourne, Victoria 3800, Australia

ABSTRACT

Lack of complementary data under emergency conditions has hindered the progress of quantitative theories and models to simulate the collective dynamics of pedestrians. Previous studies have been limited in this way, but this study attempts to address that gap in data for model development and validation by using empirical data from non-human biological organisms. Experiments with panicking Argentine ants were performed to study collective pedestrian traffic. The experiments were the first to use non-human biological organisms to study the effect of geometrical structures to the collective movement patterns. Based on the experiments, a conceptual framework to model collective forces are presented. The practical applications of the experiments are also discussed. The proposed novel approach suggests a new direction in applying knowledge of the collective dynamical patterns of non-human entities to the collective dynamics of humans, in order to devise sound strategies to aid evacuation.

Keywords: Collective dynamics, Emergency/panic, Pedestrians, Ants, Egress/Evacuation

1. INTRODUCTION

Collective movement is important during emergencies such as natural disasters or terrorist attacks, when rapid egress is essential for escape. Although several models exist to describe normal pedestrian dynamics (see Shiwakoti et al. 2008 for review), quantitative theories capable of predicting such collective patterns under panic/emergency conditions are scarce due to lack of complementary data to validate model predictions (Helbing et al. 2000). That

difficulty has led researchers to explore alternative means to aid in the development and validation of pedestrian models. Shiwakoti et al. (2009) highlighted the use of non-human biological organisms in this capacity. Collective movements involving animals are mechanisms for migration, defense, or escape from potential dangers such as predators (Okubo 1986). Commonly observed patterns among animals such as herding, flocking, schooling and swarming (Okubo 1986, Charlotte 2005) can help reveal the fundamental principles of collective pedestrian dynamics (Shiwakoti et al 2009). In this study, role of non-human biological organisms to understanding collective dynamics is discussed, drawing on observations from experiments with panicking Argentine ants (*Linepithema humile*). Based on the experiments, a conceptual framework to model collective forces is presented. The potential applications of those experiments are also discussed.

2. COLLECTIVE PATTERNS: PEDESTRIANS AND ANIMALS

One of the interesting aspects of collective dynamics of various non-human biological organisms is that they are emergent systems. Emergent systems or self-organized systems arise from ‘the emergence of order on a global scale through interactions on a local scale (Charlotte 2005). For example, an ant colony exhibits emergent order where each individual ant, following a simple rule of pheromone deposition as it travels, contributes to the establishment of a complex interactive communication system. The concept of emergent systems becomes pronounced in human, especially under emergency conditions, when individuals with limited intelligence /information (due to high crowd density and short time for egress) interact locally, thereby producing group behavior on a global scale. In collective animal motion, it is important to consider whether individuals are “close to” or “far from” from their neighbors, since those distances ultimately dictate the patterns of the collective motion. For example, the critical distance that fish in schools maintain from each other varies within 16 to 25% of their mean body length, while attractions start at a distance beyond their body length (Okubo 1986). There is a zone of attraction and a zone of repulsion that maintain the collective patterns. Okubo (1986) mentions that a wave of agitation propagated through schools of fish exposed to frightening stimuli in an experiment. The formation of “shock waves” was due to a rapidly shifting zone in which the fish reacted to the actions of their neighbors by changing their own positions. The speed of wave propagation reached 11 to 15 m/s, which is much higher than the maximum forward speed of individual fish (about 1 m/s). Similarly, when predators attacked bird flocks, formation of a “ball” of birds has been observed along with an increase in their flight speed. At times, the flock “pulsated” (expanding and contracting in a spatial sense) as inter-bird distance varied. Kholshchevnikov & Samoshin (2008) reviewed studies on pedestrian evacuation carried out by researchers in Russia and elsewhere in the world and identified the identical structures of collective pedestrian flow. They mention that the distance between people constantly changes and causes local squeezing which later on disappears and appears again. An increase in desired speed (of up to 5 m/s) has also been associated with panic in pedestrian crowds, which can lead to effects such as the “faster is slower effect”, “pushing / trampling”, and “herding” phenomena (Helbing et al 2000). Thus there appears to be striking similarities in the structure and behavioral rules of the collective dynamics of several non-human organisms, such as schools, swarms, flocks, and also human groups.

3. COLLECTIVE FORCES: ROLE OF ANIMAL DYNAMICS

Previous studies on collective animal dynamics (Okubo 1986, Matuda & Sannomiya 1985) and limited studies on collective human dynamics (Helbing et al. 2000) have been based on Newton's law of Motion. Hence it can be assumed that Newtonian mechanics can be a platform for modeling collective dynamics. Newtonian mechanics state that a temporal change of the momentum of an individual occurs in the direction of the net force \vec{F} which is the product of mass (m_i) and acceleration (\vec{a}_i) as shown below by Equation 1 and 2

$$m_i \vec{a}_i = \vec{F} \quad (\text{E.Q. 1})$$

$$m_i \frac{d^2 x}{dt^2} = \vec{F} \quad (\text{E.Q. 2})$$

For a number of individuals (N), the forces (\vec{F}_{ij}) acting on individual (i) from another individual (j) and from the surrounding environment (\vec{F}_{wi}), such as number of obstacles and walls (N_w), would be

$$\vec{a}_i = \sum_{j=1(i \neq j)}^N (\vec{F}_{ij}) / m_i + \sum_1^{N_w} \vec{F}_{wi} / m_i \quad (\text{E.Q. 3})$$

If one specifies \vec{F} , the motion of an individual is uniquely determined as the position $\vec{x}(t)$ and velocity $\vec{v}(t)$ of each individual could be updated in each time step (Δt) from the integration of the Newton's equation of motion. The important issue here is to identify and represent those forces that would be able to produce the collective dynamics of the individuals under emergency situations. To understand the nature of these forces, real data of human panic under emergency conditions are required which are rare. Most experiments with humans crowd (Daamen & Hoogendoorn 2003) aim to understand the behavior and characteristics of pedestrian flow under non-panic conditions. Although such experiments are of fundamental importance in understanding the behavior of people under emergency conditions, comparisons with real life data are necessary to validate any model's prediction. To provide data for model validation, evacuation exercises have been carried out by some researchers. These trials have been conducted in public buildings (Proulx 1995, Olsson & Regan 2001), industrial premises (Ko 2007), and passenger vessels (Galea & Galparsoro 1994). However, a problem with such evacuation trials is the high number of repetitions required for statistical significance. Also, there are ethical and safety concerns that prevent creating a real panic. Hence experiments with Argentine ants were conducted by the authors to study the commonalities of the dynamics of pedestrians as well as other non-human biological organisms under panic conditions.

3.1 Experiments with Argentine ants

Ants offer several advantages in the study of collective movement (Burd 2006). Ants naturally form collective traffic and follow physical or chemical paths in ways that resemble human crowd movement. The experiments were conducted to study the effect of presence

Collective patterns under emergency conditions: linking non-human biological organisms to pedestrians

SHIWAKOTI, Nirajan; SARVI, Majid; ROSE, Geoff; BURD, Martin

or absence of an obstacle (a column) near the exit of an enclosed test chamber, analogous to a room in the built environment of humans. Although there has been limited study of panics in non-human organisms that made qualitative comparisons with human escape (Saloma et al 2003, Altshuler et al 2005), these experiments with/without a partial exit obstruction were first to study the effect of geometrical structures to the collective movement patterns of non-human entities during rapid egress. Before conducting experiments with/without column, preliminary experiments with multiple exits were carried out to confirm previous findings of asymmetric use of the available exits under panic conditions (Altshuler et al 2005). The motive for confirming that phenomenon with Argentine ants was to develop confidence in the appropriateness of the model organism and the experimental setup for the intended study. Hence, the number of repetitions is low for the preliminary experiments with multiple exits while the repetitions for with/without column near the exit are sufficient.

Each experimental trial involved a group of 200–250 ants nesting naturally in a chamber made from a transparent plastic petri dish lid 35 mm in diameter and 4 mm deep. The exit width and depth were 2.5mm and 2mm respectively. We ran experimental trials under two experimental treatments (30 repetitions each), one with no obstruction on either side of the nest exit, and the other with a partial obstruction (a column 5 mm in diameter and 4 mm high, to correspond to the depth of the nest chamber) placed inside the nest chamber 2 mm in front of the exit, slightly asymmetrically to the main axis of the exit. To study the effect of multiple exits, chambers with two exits and four exits were created. Panic was created by injecting 10 μ l of citronella oil (an insect repellent) into the nest chamber. With the introduction of citronella, ants rushed toward the exit, in a manner reminiscent of people in a crowd panic.

Figure 1 shows the experimental setup with multiple exits. In the two-exit experiments, the average difference in exit usage was 28% (based on 3 repetitions), while in the four-exit experiment, the relative use of two exits out of the available four exits was 74% (based on one experiment).

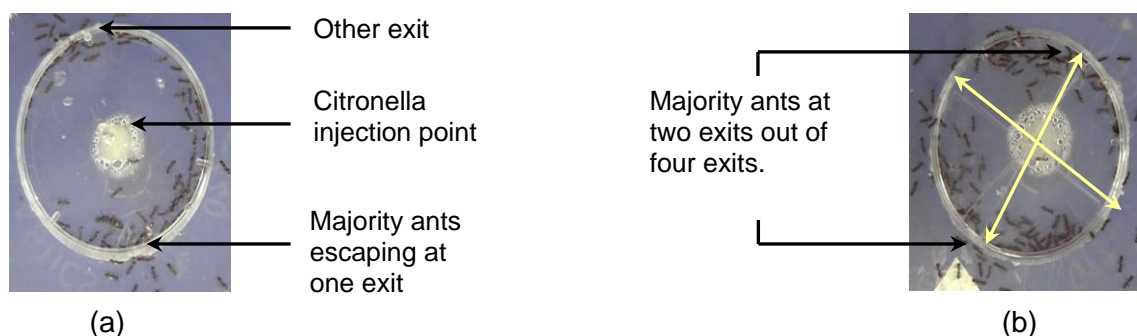


Figure 1– Experimental setup for multiple exits: two exits (a) and four exits (b)

Experiments with two exits and four exits pointed to ineffective use of available exits, as predicted for humans escaping under panic (Helbing et al. 2000). Still (2000), with a simple calculation based on a network, reveals that network analysis as followed in building guides

Collective patterns under emergency conditions: linking non-human biological organisms to pedestrians

SHIWAKOTI, Nirajan; SARVI, Majid; ROSE, Geoff; BURD, Martin

for crowd control is oversimplified. Still highlights that when a network offers alternatives for egress, the impact of losing some of these in an emergency has to be part of the safety calculations. This symmetry breaking phenomena is not only observed in non-human entities and pedestrian traffic but also have been a notable problem in vehicular evacuation. In mass vehicular evacuation such as New Orleans, unbalanced use of the available escape routes has lead to inefficient evacuation (Wolshon, 2002).

Figure 2 shows the experimental setup with and without column at the exit. The average evacuation time for the first and second cohorts of 50 ants was measured by manual counting during playback of digital video recordings. The presence of a column at the exit generally enhanced the flow of panicking ants as compared to absence of a column. A similar increase in flow due to a column or partial barrier at exit has been predicted for human crowds escaping from a room (Helbing et al. 2002). However, this theoretical prediction could not be confirmed with empirical data, owing to the lack of data on human behavior under panic. Thus, experiments such as the one reported here have huge potential for evaluating design solutions for safe egress of pedestrians. Figure 3 shows the average escape time for 50 ants in experimental trials with and without a column. The average escape time for 50 ants was 19.4 seconds without the column but only 13.3 seconds when the column was present, a reduction of 32% in average evacuation time with the presence of column near the exit. The two means are significantly different as determined by a t-test, with p value being less than 0.05.

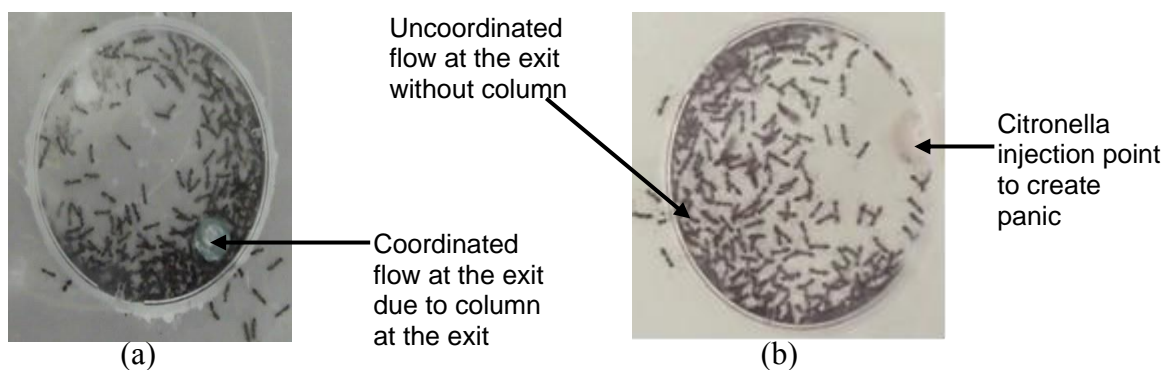


Figure 2 – Panicking ants experiment: (a) column near exit facilitating the flow of ant traffic and (b) uncoordinated ant traffic without column at exit.

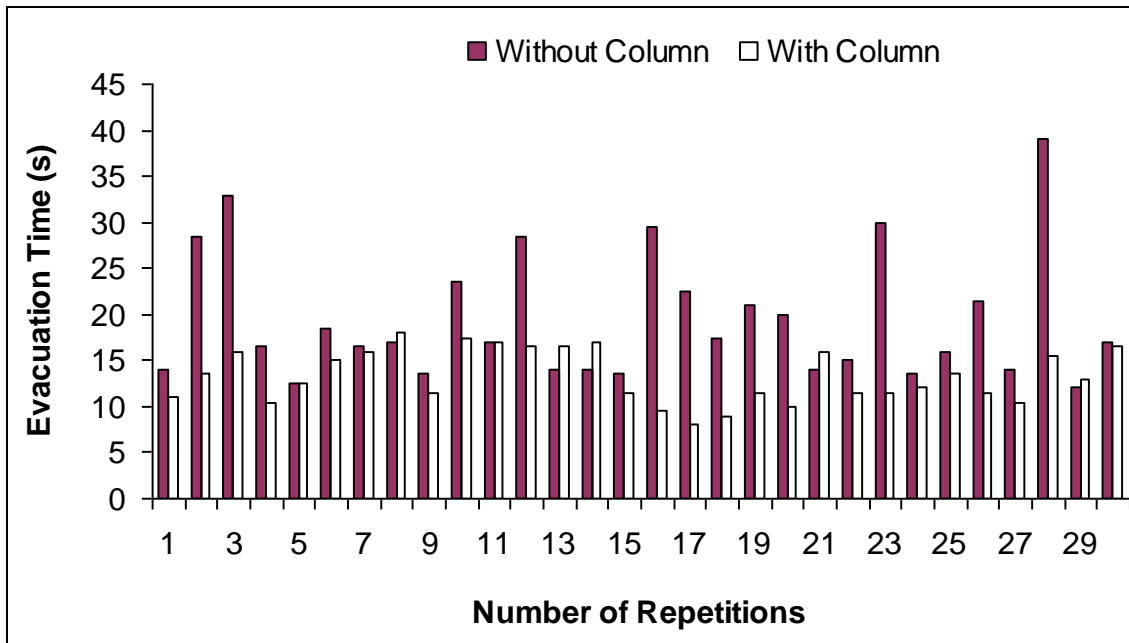


Figure 3 – Comparison of average evacuation time for 50 ants based on 30 repetitions of the experiment with and without column

The reaction time (pre-evacuation time) of the ants before they start evacuating the nest was also measured. The reaction time was considered the time that elapsed between the injection of the citronella to the chamber and the time when ants began to evacuate the chamber (benchmarked by the escape of the first 3 ants from the chamber). Figure 4 shows the distribution of the pre-evacuation time of the ants based on 60 observations. The majority of the reaction times (85%) were below 10 seconds with the average being 6.5 seconds.

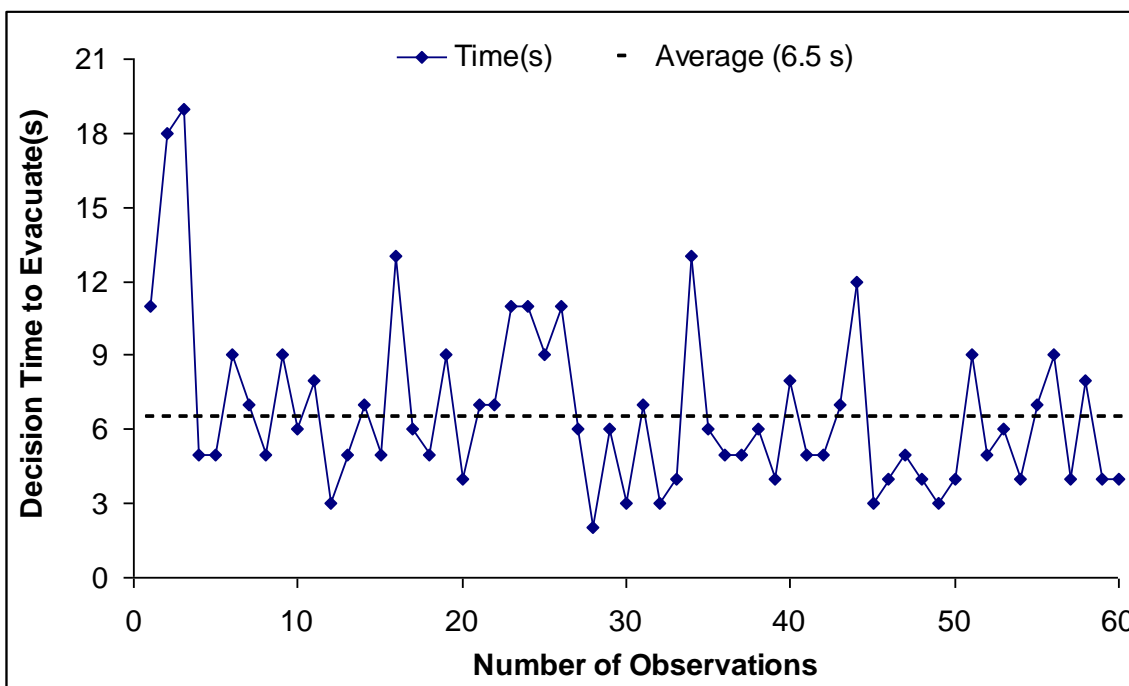


Figure 4: Distribution of pre-evacuation time of the ants

It was observed that the ants which were near to citronella injection point pushed the ants that were nearby and those nearby ants then pushed the other surrounding ants continuing like a chain reaction until the ants began to leave the chamber. The chain-reaction mechanisms of communicating the danger conditions among ants may provide an insight on possibility of developing such mechanisms in case of human panic. In human evacuation, total evacuation time consists of sum of the pre-evacuation time and the evacuation time (to leave the exit or enclosed area). However, limited data exists on pre-evacuation times for humans. Usually consideration of pre-evacuation time is ignored (due to difficulty in estimating its value) or assumed (usually between 0 and 120 seconds) in simulation based on modelers' experience (Daamen 2007). From ants experiment, the observations suggest that inclusion of higher pre-evacuation time (at least more than 10 seconds) is justifiable for estimation of pre-evacuation time for simulation in human case. This is supported by the fact that even the ants, who are generally seen to be co-operative and non-selfish, took on average 6.5 seconds to react to the event (citronella) and began to evacuate. In one study relating to human evacuation trials (Tavares et al. 2007), pre-evacuation times were collected from the experiments and these ranged from 5 to 98 seconds with a mean pre-evacuation time of 46.7 seconds (based on two trials). That study also supports the above stated hypothesis of using higher pre-evacuation time based on ant experiments. However, it is to be noted here that in evacuation drills, researchers have to confine themselves to small numbers of participants with no control on level of panic, which then does not represent the true scenario for crowd panic. The pre-evacuation or evacuation time obtained from these evacuation exercises can be different than those in real panic. Hence, there is potential on such empirical data from biological organisms to compensate for the scarcity of data on human panics.

3.2 Insights from ants experiment for modeling collective forces

Based on the experiments following nature of collective forces are hypothesized along with conceptual modeling framework. The proposed framework is expected to be able to simulate the collective dynamics of individuals with body mass difference across a size gap as large as ants and pedestrians.

3.2.1 Motivational force:

Panic in the experiment was associated with an increase in fleeing speed from 3mm/s (normal) to 9mm/s (panic), similar to human and other non-human organisms as discussed earlier. This increase in fleeing speed could be viewed as the consequence of motivational forces on the part of individuals to move towards a safe place or exit as quickly as possible. The motivational force for each individual (\vec{F}_m) could be thus modeled as proportional to its desired velocity (\vec{v}_d).

$$\vec{F}_m \propto \vec{v}_d \quad (\text{E.Q. 4})$$

3.2.2 Interactive forces:

When panic was created, the density of ants became quite elevated near the nest exit, resulting in frequent contacts. However, they tried to avoid colliding with each other when they were very close (<1mm) or when contact actually occurred. Between 1mm to approximately 8mm inter-individual distance, the density of ants was not great as it was near the exit, so that more ants were trying to occupy the available space. Beyond 8mm, the ants were attracted to the exit on random basis. The existence of these different zones can be conceptualized as the zone of attraction and repulsion, as observed in the collective dynamics of schooling and flocking by other organisms. Hence, it can be assumed that the regulation of collective patterns of individuals exposed to frightening stimuli results directly from a change in interaction range (attraction and repulsion range). These behavioral rules, is proposed conceptually as a relationship between interpersonal distance and the resulting repulsive and attractive forces, as shown in Figure 5. The repulsive forces depend on the proximity of individuals. Their magnitude is large when interpersonal distance is small, and decrease with increasing distance until a point where the interpersonal distance exceeds the repulsion range. At that point, attractive forces begin to act on pedestrians to draw them together, until the maximum point of attraction is reached. At even greater separation, the attractive forces would start decreasing and eventually have negligible effect. It can therefore be assumed that, as in animal dynamics, these zones of attraction and repulsion maintain the collective movements of pedestrian crowds. The repulsive and attractive forces (\vec{F}_I) can be modeled as proportional to the inverse of the square inter-personal distance (D) as below:

$$\vec{F}_I \propto \frac{1}{D^2} \quad (\text{E.Q. 5})$$

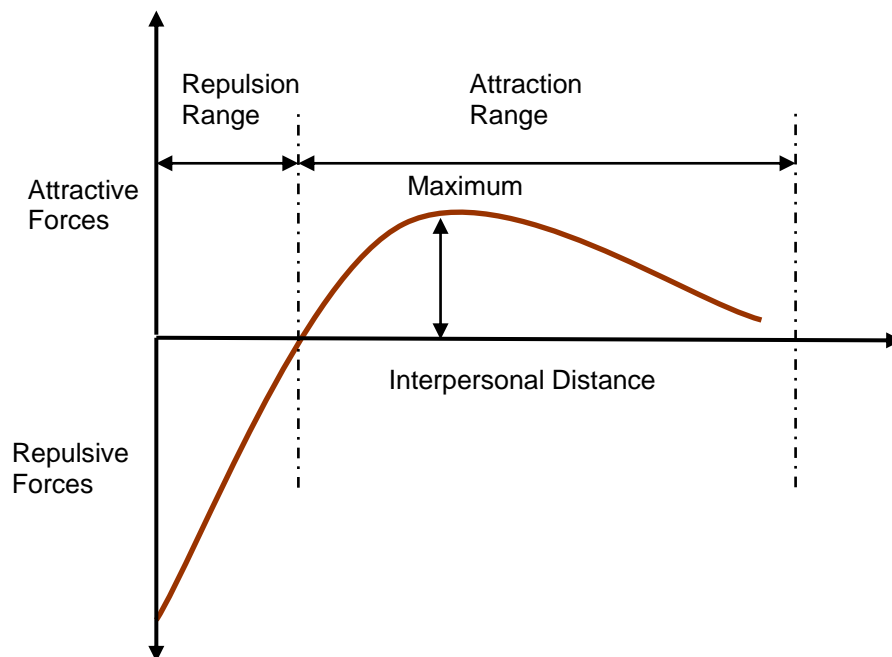


Figure 5 – Conceptual diagram showing repulsive and attractive forces based on interactive range of interpersonal distance

3.2.3 Collision / Pushing forces:

When ants were moving at high speed, frequent collisions with mutual interactions occurred near the exit. It is necessary to model these collision and pushing forces. Similar issues arise in the study of rigid spherical body collisions in molecular dynamics (Rapport 1995). An analogous approach can be taken for representing pushing forces for collective traffic as shown in Figure 6. The problem is usually addressed by incorporating strong normal forces (\vec{F}_n) as well as shearing forces (\vec{F}_t) between the colliding particles. As shown in Figure 6, the initial velocity (dashed arrow) gets diverted to a new direction due to a normal force and a shear force. Hence pushing forces (\vec{F}_p) can be modeled as:

$$\vec{F}_p = \vec{F}_n + \vec{F}_t \quad (\text{E.Q. 6})$$

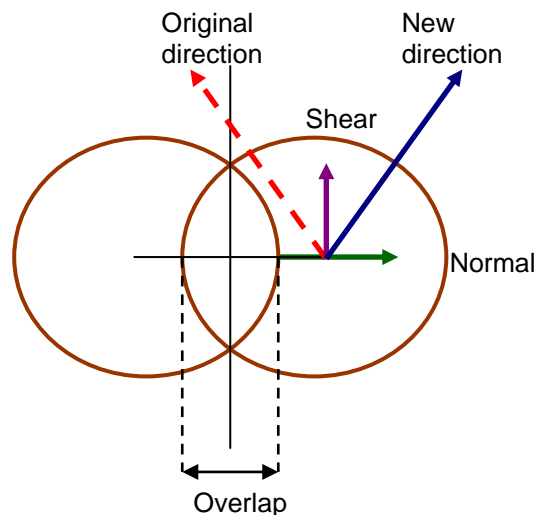


Figure 6 – Components of pushing forces to avoid collision based on inelastic sphere collision concept of molecular dynamics

3.2.4 Random forces:

As mentioned in section 3.2.2, beyond 8mm inter-individual distance, the ants were attracted to the exit on random basis. Hence random forces are necessary for modeling collective dynamics to include disturbances due to exogenous factors as well as the psychological state of the individuals. This could be function of difference in speed (v), size (r), orientation of the individuals (θ) and other biological, environmental details (ξ). Thus random force (F_r) is given by

$$F_r = f(v, r, \theta, \xi) \quad (\text{E.Q. 7})$$

With the forces as defined in section 3.2.1 to 3.2.4, there is potential to parameterise the developed model to reproduce the collective dynamics of ant traffic and then scaled it up for human case. That is to say, if one organism were built to the same design as another, but on a different scale, it would be useful to discover how the various parameters must scale with body size, up or down, to produce a working model. With that one can directly compare the behavior of biological entities and pedestrians in order to devise good strategies of evacuation.

4. PRACTICAL APPLICATIONS

The proposed framework has the potential in devising strategies and solutions that enhances the safety of pedestrian crowds. Experiments with ants can be carried out to imitate the dynamic escape of panicking pedestrian crowd at the egress point of a room or an enclosed area like a stadium, transfer station, theatre, etc., with different architectural adjustments. The layout of physical geometrical structures at the exit point has an important role in determining the efficiency of evacuation processes and developing strategies to aid evacuation as observed from the ants' experiments. The practical application could be in changing building designs and the layout of open public spaces, by providing supporting evidence that architectural adjustment would actually be effective and improve safety. One of the possibilities is to test different design solutions (double column, funnel shaped barrier, triangular separator etc.) intended to facilitate pedestrian flow under emergency conditions.

Ants might also be used to simulate pedestrian crowds in an intersection during panic. The study of collective ant movement under panic conditions might illuminate how pedestrian traffic at intersections becomes organized. Although some studies have been conducted to study pedestrian traffic at intersections under normal conditions (Helbing et al 2002, Hughes 2003), but pedestrian traffic at intersections, with regard to panic traffic, has not been well addressed in the literature to date. The authors have conducted some preliminary experiments with panicking ant traffic to simulate the collective traffic at intersection. Preliminary results show that ants enhance their escape patterns by minimizing the mutual interactions at the central part of the intersection as shown in Figure 7 (a). Figure 7(b) shows the schematic diagram of the direction of the flow of ants in the experiment presented in Figure 7(a). As it can be seen in Figure 7(b), most of the ants turn towards nearby intersection leg (indicated by bundle of arrows) rather than moving across each other at the central part of intersection (indicated by single arrow). However, further experiments and analysis are necessary to understand their peculiar way of avoiding the conflicts and integrating it into pedestrian traffic model. Owing to the lack of complementary data of human panic during emergency/panic situations, such empirical laboratory experiments as explained above can be important tools to study collective crowd dynamics both from model development and validation perspective.

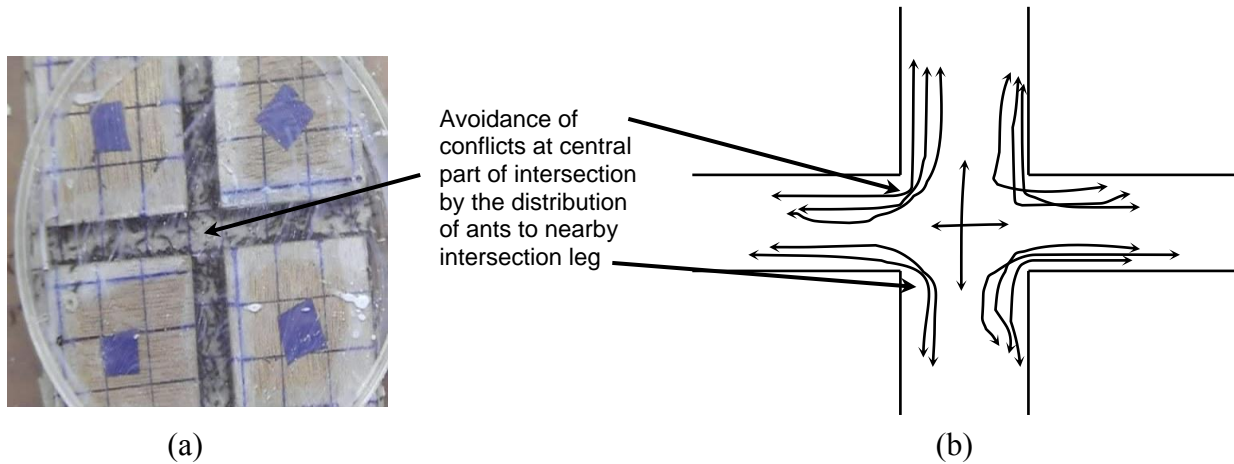


Figure 7 – Preliminary experiments showing organization of ants traffic at intersection under panic conditions (a) and schematic diagram showing the detailed organization of ants traffic in the experiment (b)

5. CONCLUSION

This paper investigated the use of non-human biological organisms to understating the collective pedestrian traffic under emergency conditions. It was shown that simple rules, such as those employed in collective animal dynamics, are applicable for modeling collective pedestrian dynamics. The existence of general rules for dissimilar agent may indicate that collective dynamics are emergent systems where entities with limited intelligence interact locally to produce emergent group behavior on a global scale. The proposed approach has provided a new direction in applying the knowledge obtained from collective movement patterns of biological entities to the collective human dynamics in order to devise sound strategies to aid evacuation. The experiments with Argentine ants, which were first of its kind to study the effect of geometrical structures to the collective movement patterns, contributed in the advancement of knowledge on using biological entities as an alternative experimental system, to compensate for the scarcity of data on human panics. It also provided reassurance that a developed model correctly identifies the essential features of solutions that are efficacious and improve the safety of pedestrian crowds. The approach also contributed in considering both attractive and repulsive interactive zone and forces as observed in ants experiment and other non-human biological organisms in modeling collective pedestrians' crowd dynamics. We also illustrated practical scenarios in which experiments with panicking ants can be used to assess design solutions for safe egress in future.

Future work would continue to use of empirical data from non-human biological entities in understanding the collective dynamics as well as capturing the complexities of the collective dynamics which might have not been fully addressed in mathematical models. Such a novel framework, which integrates complementary expertise of traffic engineering and biology, has

Collective patterns under emergency conditions: linking non-human biological organisms to pedestrians

SHIWAKOTI, Nirajan; SARVI, Majid; ROSE, Geoff; BURD, Martin

the potential in devising strategies and solutions that enhances the safety of pedestrian crowds.

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Collective patterns under emergency conditions: linking non-human biological organisms to pedestrians

SHIWAKOTI, Nirajan; SARVI, Majid; ROSE, Geoff; BURD, Martin

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