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Experimental evidence of the "Faster is Slower" effect in the evacuation of ants

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ABSTRACT

The *faster is slower* effect is a self-organized phenomena first described for pedestrian dynamics. Although it has been obtained in computer simulations, it has not been observed in real systems yet. To achieve this goal, we carried out experiments with ants, which are self-propelled biological agents. The ants were placed inside a bidimensional chamber with a narrow exit, and a paper imbibed with repellent was placed in the opposite wall of the chamber. Using different concentrations of citronella, which produced different degrees of repellency, the ants were forced to egress from the chamber and the evacuation time was measured. A minimum evacuation time is observed for intermediate concentrations of citronella, compatible with the *faster is slower* effect. However, this effect was not generated by the occurrence of blocking clusters right before the exit as the ants did not display a selfish evacuation behavior.

1. Introduction

The system made up of people and crowds in motion is a complex system which should be studied from an interdisciplinary approach including physical, biological, psychological and social aspects. Some of these aspects are more suitable than others to be studied directly on a human system.

There are certain states of the system, such as emergency evacuation of a crowd through a narrow door, for which an adequate experimental characterization is difficult. A realistic experiment should include high density of people and at the same time, behaviors related to individual survival instinct. Under these conditions there may be high pressure zones which can cause blockage of exit, choking, or other fatal injuries.

This is the main reason why computer simulations are the state of the art to study this kind of phenomenon. However, given the lack of information of how real systems behave in extreme conditions, computational and physical models are not properly validated, and one should be very careful when drawing conclusions for real systems.

1.1. The "Faster is Slower" effect

In the present work we are interested in the experimental study of the so-called *faster is slower* (FIS) effect. This refers to the increase of the evacuation time when the degree of hurry of a crowd to get out through a narrow exit is high.

The FIS effect was first described by Helbing et al. (2000) by using computational simulations of the social force model and it was studied by Parisi and Dorso (2005, 2007). One important assumption in these simulations is that all the particles present a "*selfish evacuation behavior*". This means that once the evacuation begins every single agent tries to escape as soon as possible by following a direct path to the exit, at all times. This behavior produces a jam right before the exit containing all the agents that still could not get out, and this jam lasts the whole evacuation.

In this context, the FIS effect can be observed in a plot of *evacuation time* vs. *desired velocity* (representing the degree of hurry or anxiety to escape) as a curve that presents a minimum at some intermediate value of the desired velocity (v_d).

Necessarily, the evacuation times must be measured for several values of v_d, so that the minimum can be observed. In this curve, each evacuation time corresponding to each v_d is the average of a certain number of realizations of the evacuation process under the same v_d.

Although this curve has not still been measured for any real system of any kind of particles or agents, it is established as a self-organized characteristic of pedestrian dynamics. Even new models are sometimes validated trying to display this effect. A possible justification to this acceptance can be the empirical observation of exit blockage in real emergency egress through a narrow door as in *The Station* nightclub fire, USA, 2003 (http://en.wikipedia.org/wiki/The_Station_nightclub_fire).

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It must be noted that the observation of this kind of event is not enough to obtain even one point on the curve of evacuation time vs. v_d mentioned above, because each point on that curve is an average of several realizations. Moreover, a single blockage event does not allow one to calculate the probability of occurrence of this blockage, or how this probability varies with the door width. Summarizing, a single blockage, for a given system configuration (geometry, number of pedestrians, etc.), does not confirm the existence of the FIS effect.

Another important remark is that the FIS effect could be present or not in a system of real physical particles (biological or inert), and in case it does exist, the microscopic mechanisms can be explained or not by the configuration and behavior assumed when the room evacuation problem is studied with the social force model. That is, we would like to state a lack of dependence between the possible existence of the FIS effect in a real system and the social force model predictions and explanations about it.

1.2. Human systems vs. simplified models

When a system is complex, as in the case of emergency egress of humans, it is useful to study simpler systems having some key ingredients of the complex one. In this sense, our master plan consists in looking at different systems with an increasing degree of complexity and with an increasing degree of likeness to the human system.

A first step to experimentally study some physical aspects of competitive egress would be to consider granular matter. Experiments with granular materials are currently being carried out (Gago et al., unpublished results). The next steps would be the competitive egress of social insects, nonsocial insects and finally mammals.

In the present work we focus on social insects. In particular, ants share certain characteristics with humans, namely: (a) they have some communication mechanisms between individuals: pheromones, vibration, tactile contact, etc. (Detrain and Pasteel, 1987; Holldobler, 1999; Mc Cabe et al., 2006); (b) they have sensors that allow them to perceive the surrounding environment; (c) they are able to react behaviorally to harmful or dangerous stimuli from the environment; and (d) they are biological self-propelled entities. However, the results obtained in the experiments with ants should not be directly extrapolated to humans because they have different evacuating behavior as we will show in Section 3.

Here, we study the FIS effect in a system of evacuating ants. The idea is to generate an increasing level of escaping behavior by increasing the concentration of a chemical repellent. This would be equivalent to increasing the *desired velocity* in the curve where the FIS effect was measured by means of computer simulations.

Experimentation with animals has arisen as a new approach in the pedestrian dynamics field. For example, Saloma et al. (2003) studied the egress of 60 mice through an exit of variable width. The competitive or panic egress was generated by putting the mice in a water pool. It was found that the mice escaped in bursts of different sizes that obey exponential and power-law distributions depending on the exit width.

More recently, at least two studies reporting experiments with ants have been published: Altshuler et al. (2005) studied the symmetry breaking in the use of two exits when ants are in a "panic" state. Shiwakoti et al. (2009) investigated the influence of placing an obstacle before the exit and found that it could reduce the egress time of ants. It must be noted that the FIS effect was not analyzed in any of these previous experiments with animals.

Finally, it is also worth emphasizing that we warn not to directly extrapolate conclusions drawn from experiments with ants to the field of pedestrian dynamics, as if both systems were equivalent because they are not.

1.3. Research goals

The main goal of the present work is to find out whether the *faster is slower* effect exists in a system of biological agents, in this particular case, ants stressed with citronella.

By doing this, we expect to advance in the road that will lead, in the future, to experimentally validated and reliable models of pedestrian evacuations in competitive state.

2. Materials and methods

2.1. Insects

We used two different colonies of the carpenter ant *Camponotus mus* (Roger). The colonies were captured in Santiago del Estero province (Argentina; 27° 49′ S, 64° 03′ W) and transported to the laboratory. Each colony – composed of around 1000 workers and one or more queens –was placed in an artificial nest consisting of a plastic box (20 × 30 cm and 30 cm high) with fluon painted walls to prevent animals from escaping. The bottom of the nest was made of plaster with a hollow covered by a glass. Nests were maintained in the laboratory for 1 year under natural light/dark cycles and nearly constant temperature (25 ± 3 °C). Animals could move freely within the nest and had access to freshwater. For each nest, the time elapsed between two consecutive experiments was a week. During these periods ants were fed with honey–water and chopped insects.

2.2. Experimental device and protocol

We developed an arena (Fig. 1) which consisted of two acrylic chambers (12.2 × 9 cm): the complementary chamber (A) and the punishable chamber (B). Both chambers were connected by a narrow corridor (0.6 cm wide × 1.6 cm long).

As can be seen in Fig. 1, chamber A has a squared shape and chamber B has a conical hopper shape to induce the flow of ants to be directed towards the door when evacuating this chamber (B).

The entire device was covered by an acrylic lid (28 × 14 × 0.8 cm) leaving a chamber high of 0.5 cm to avoid ants climbing ones over the others.

In both chambers, the walls opposite to the exit were mobile pistons allowing change in the size of the chambers independently.

In order to force the evacuation of the chamber *B* evoking a competitive situation, we punished this chamber with a repellent substance (a solution of citronella oil in water in several concentrations). A filter paper imbibed with this repellent solution was placed below the piston of chamber B (piston B).

The protocol for each realization of the experiment was the following:

- 100 ± 3 ants of similar size were carefully taken from one of the nests and placed within a circular flask container (7.5 cm diameter) with fluon painted walls to transport the whole group of ants from the nest to the arena in one step.
- At the beginning of each experimental session, both chambers had their biggest sizes (i.e. with the pistons at 12 cm away from the exit).
- The ants were placed in chamber A by emptying the circular flask container. Immediately the arena was covered with the lid.
- Piston of chamber A (piston A) was gently pushed until it reached the opposite wall, forcing the ants to exit through the corridor to chamber B and preventing them to return to chamber A. This ensured that all ants had passed through the door at least once before the beginning of the recording.
- When all ants were in the punishable chamber, the filter paper was imbibed with 3.5 ml of citronella solution. Then, piston B

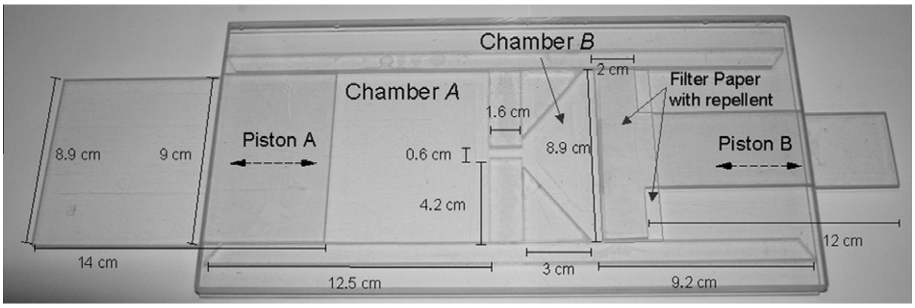

Fig. 1. Photo of the experimental device built in transparent acrylic.

was gently pushed until it reached the configuration shown in Fig. 1, where only the conical section of the chamber was available for the ants.

- Then, piston A was moved backwards and removed from the device leaving the exit opened and hence the chamber A was made accessible from chamber B. At this step, the evacuation started. A metal mesh was placed at the free side of chamber A preventing both, animals from escaping and the accumulation of citronella odor in this non punishable chamber.
- The evacuation of ants from the punishable chamber (B) was recorded with a video camera (Sony HDR- SR11, 1920 × 1080 pixels, at 30 fps). From the videos, evacuation times were obtained.
- After each assay the acrylic device was washed with water and alcohol and it was left to dry in the air, so the arena was free of citronella solution for the next experiment.

2.3. Experimental series

As stated above, the filter paper was imbibed with 3.5 ml of repellent solution. To produce several degrees of repellency in the ants, we used citronella essential oil solutions in different concentrations. Citronella is a popular botanical ingredient in insect repellent formulations (Chris and Coats, 2001), and it was also used to generate panic-like behavior in other ants experiments (Altshuler et al., 2005; Shiwakoti et al., 2009).

Forty (40) realizations of the experiment divided into four (4) sets of ten (10) runs were performed. Each set corresponds to one of the following citronella concentrations: 25% (0.9 ml of citronella plus 2.6 ml of water), 50% (1.75 ml of citronella plus 1.75 ml of water), 75% (2.6 ml of citronella plus 0.9 ml of water) and 100% (3.5 ml of citronella).

Additionally, two control experiments were performed:

2.3.1. Control Experiment 1

Two experimental trials using only water instead of the citronella solution were performed.

2.3.2. Control Experiment 2

The goal of this experiment was to evaluate the possible emission of formic acid during the assays.

Camponotus ants commonly spray formic acid when they are perturbed or in an alarm situation. This substance could be harmful or also repellent for the ants in a small and crowded space as it is the case of the experimental device. Therefore, it could interfere or mask the influence of the citronella odor on the ants' behavior.

The pH of the formic acid emanation is 1, so it can be clearly recognizable on pH paper (Df universal test paper). One single ant can produce a visible color spot of ~0.5 cm of diameter when it is disturbed.

We covered the entire floor of the arena with the pH paper and performed the whole experimental trial twice with a 100% citronella concentration.

3. Experimental results

More than 40 realizations of the experiment were performed following the protocol described in Section 2.2. As an example, in Fig. 2, a snapshot of a representative evacuation process can be observed.

3.1. Control experiments

In the "Control Experiment 1" the citronella solution was replaced by water. In this condition, ants displayed low mobility and only about 30% of the ants had evacuated after 600 s in both trials. This represents a very long time compared to the ones obtained in the experiments with citronella, as it will be seen later. Thus, this control confirms the repellent effect of citronella. In practical terms the evacuation time is infinite in the absence of the repellent.

"Control Experiment 2" (described in Section 2.3) was carried out to explore the possible emission of formic acid by ants, which may also have a repelling effect during the essays. The pH paper did not show any secretion of formic acid in any chamber. Hence, the citronella is the only cause of repellency in the experiments. We conclude that no release of formic acid was generated by the procedure at any step, i.e. neither during the initial placement of the ants on the device nor even when they sense the presence of citronella in its highest concentration.

3.2. Evacuation experiments

From the analysis of the videos recorded, the evacuation times of the first 70 ants were measured.

Fig. 2. A frame of the recorded video from an evacuation of ants with a 75% concentration of citronella when about 20% of the ants were already evacuated. The snapshot displays the typical distributions of ants during the evacuation.

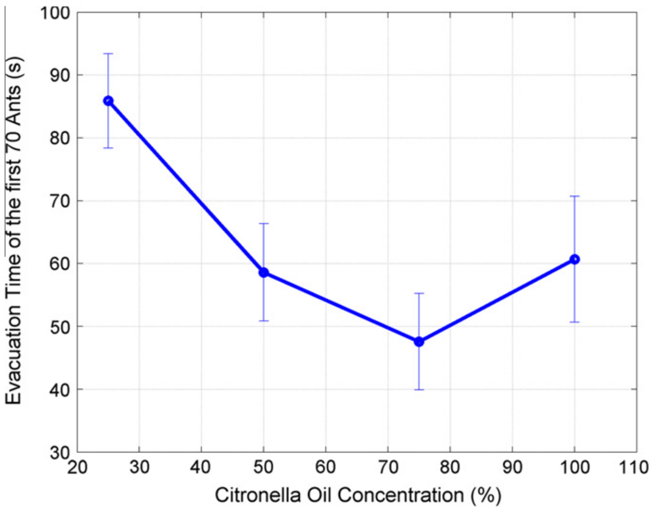

Fig. 3. Mean value and one standard deviation of evacuation time for each of the four citronella concentrations. This curve shows the *faster is slower* effect for the ant system.

The relationship between these evacuation times and the citronella concentration (which is directly related to the degree of repellency in ants) is shown in Fig. 3.

The evacuation time for 0% citronella (Control Experiment 1) is out of scale, so it cannot be included in this plot.

The results shown in Fig. 3 indicate that as repellent concentration increases, the evacuation time decreases up to a concentration of about 75%. Beyond this value, the evacuation time increases and consequently, the evacuation performance gets worse. This phenomenon is known as the *faster is slower* effect.

During the experiments performed using citronella as repellent, it was observed that ants do not follow the "*selfish evacuation behavior*" (see Section 1.1) in any trial. Instead, they do some exploratory trajectories that rarely produce a high density zone near the exit. This fact can be seen in the sequence displayed in Fig. 4 for a typical trial with 100% concentration of citronella.

3.3. Discussion

The observation of exit blockage in catastrophes suggests that, under very extreme circumstances, people head straight for the exit trying to save their life as individuals. Thus, it is reasonable to assume the "*selfish evacuation behavior*" for the simulations where the FIS effect is displayed (Helbing et al., 2000; Parisi and Dorso, 2005, 2007).

On the contrary, ants do not display the same behavior, neither in normal conditions (Fourcassie et al., 2010) nor in our experiment as seen in Fig. 4. Ants are social insects that live in a self-organized colony and perform all tasks and behaviors for the benefit

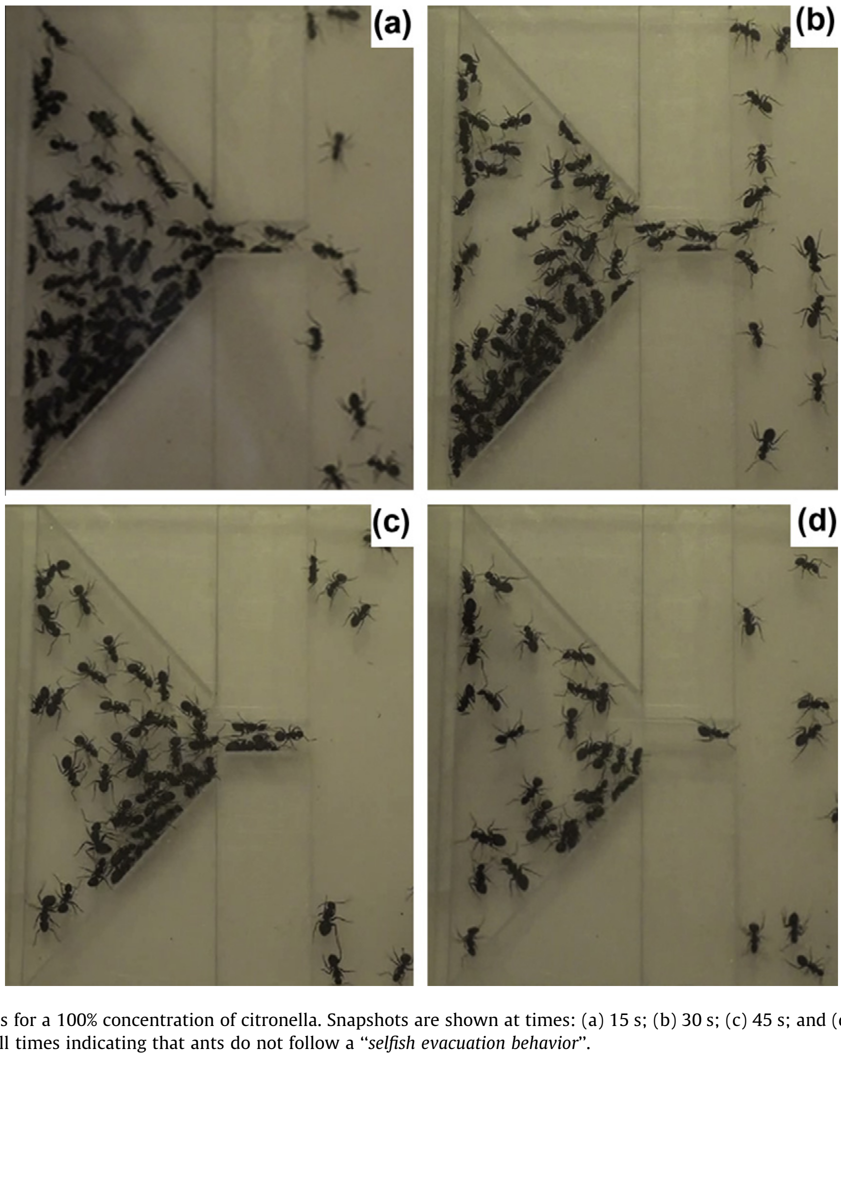

Fig. 4. Typical evacuation process for a 100% concentration of citronella. Snapshots are shown at times: (a) 15 s; (b) 30 s; (c) 45 s; and (d) 60 s. It can be observed that the density near the door is low at all times indicating that ants do not follow a "*selfish evacuation behavior*".

of the group rather than the individuals. Thus, a possible explanation is that the ants maintain their cooperative traffic rules and circulation organization patterns even in such harmful circumstances as in our experiment with the presence of a repellent.

Because of this difference between ants and other animals, we conclude that the egress of ants under the repellency of citronella cannot be directly related to the emergency egress of humans. This important finding indicates that, either other stimuli to generate panic (rather than citronella) or other animals, should be used to have a system more similar to people in a state of competitive egress.

Ants avoid intense contact near the exit, which prevents the arch-like formations or blocking clusters responsible for the FIS effect in the computer simulations. Nevertheless, the FIS effect is present, but for different reasons.

A possible explanation of why higher values of citronella concentration produce an increase in the evacuation time is the following: regardless of the mechanism used by the ants to find the exit, this mechanism might be affected by the high concentration of the repellent reducing the evacuation efficiency. Verifying this possibility and discovering which mechanism produced the FIS effect in the present experiment will be performed in the near future by image processing of the recorded videos.

Another possible explanation is the following: even though all individuals have had the experience of going through the door before the egress begins (as described in Section 2.2), we are not able to assure whether they know the way out. If this were the case, it may resemble a panic situation with humans in which, either by lack of light, the presence of smoke or any other reason, individuals cannot readily identify the egress location, and even factors such as smoke can also affect their responsiveness and escape reaction.

4. Conclusions

In the present work the first experimental evidence of the *faster is slower* effect was found in a system of escaping biological entities stressed with increasing levels of repellency.

The causes of the *faster is slower* effect in the present experiment are not the same as in the case of computer simulations, basically because ants do not push other ants in a straight line toward the exit. In order to reproduce this behavior with biological agents, new experiments will be conducted either with other stimuli to generate panic (rather than citronella) or with other animals. Also a detailed analysis of the images recorded will be performed in future work to reveal the causes of the *faster is slower* effect observed in ants under the aforementioned conditions.

Finally, because of the different behavior of evacuating ants when compared with humans, we advise not to apply the results of experiments with ants directly to human systems.

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