Physica A xx (xxxx) xxx–xxx

Contents lists available at ScienceDirect

Physica A

journal homepage: www.elsevier.com/locate/physa

Effect of exit locations on ants escaping a two-exit room stressed with repellent

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HIGHLIGHTS

- We explored ant evacuation efficiency from a chamber with two exits.
- Ants under stress demonstrated the phenomenon of "symmetry breaking."
- The efficiency of ant escape was greatest when the exits were furthest apart.
- There were important differences between ant and the prediction of the Social Force Model of pedestrian behavior.
- Unlike humans, ants did not show jamming at the exit.

ARTICLE INFO

Article history:
Received 15 October 2015
Received in revised form 8 February 2016
Available online xxxx

Keywords:
Dynamic process
Evacuation
Stress conditions
Ant behavior
Symmetry breaking

ABSTRACT

In order to investigate the effect of the distance between two exits on ant evacuation efficiency and the behavior of ants escaping from a two-exit room, we conducted ant egress experiments using *Camponotus japonicus* in multiple situations. We found that the ants demonstrated the phenomenon of "symmetry breaking" in this stress situation. It was also shown that different locations for the exits obviously affected the ants' egress efficiency by measuring the time intervals between individual egress and flow rate in eight repeated experiments, each of which contained five different distance between the two exits. In addition, it is demonstrated that there are differences between the predictions of Social Force Model of pedestrians and the behaviors of ants in stress conditions through comparing some important behavioral features, including position, trajectory, velocity, and density map.

1. Introduction

The problem of pedestrian escape from a crowd has been addressed by computer models such as the Social Force Model [1]. The model incorporates some behaviors that are characteristic of pedestrians, such as the "faster is slower" effect, a consequence of jamming [2]. Garcimartín et al. [3] also conducted experiments with students to demonstrate the "faster is slower" effect.

The priority among humans is individual safety [4,5], so they tend to walk straight to an exit to save their own lives. This behavior was also found in some animals under stress conditions, for example, mice and sheep.

1.1. Experiments in mammals

Evacuation experiments were conducted using mice by guiding them to swim through an exit of variable width to reach a safety platform [6]. Mice made urgent efforts to reach the exit. Their behavior was in accordance with the results of numerical

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http://dx.doi.org/10.1016/j.physa.2016.03.083
0378-4371/

simulations [7]. In order to describe the behavior of mice evacuating from a two-exit chamber more accurately, the element of copying was added to correct a disadvantage of the previous model [8].

Experiments using sheep [9,10] revealed that sheep rushed to a barn where food was placed. Sheep chose a direct path to the door and clogging was observed. Subsequently, clogging was quantified on the basis of the data from the sheep experiments. The effects of varying exit size and placing an obstacle near the exit on evacuation were also explored.

1.2. Experiments in ants

Ants are typical eusocial insects and are generally tractable in experiments, and so, many researchers have focused on their behavioral features. We will first discuss ant behavior under normal conditions [11–20].

Studies have shown that foraging ants use a single trail when traffic density is low but build a second trail when traffic density is high to maintain optimal traffic organization. In addition, pushing behavior played a role in optimizing traffic organization [16]. A subsequent ant experiment on unidirectional trails focused on the fundamental aspects of ant traffic organization. The jamming phase was not observed in the experiments [18].

Ant traffic can reveal the behavioral evolution of social insects and also provide new insights into the study of traffic systems [19]. Oettler et al. [14] experimented with foraging ants to determine whether they follow Fermat's principle when they move on two different surfaces and reported that they show interesting self-organization behaviors. The behavior of ants very much depends on the precise species. Tandem running during foraging was a common behavior in the Australian ant, *Camponotus consobrinus*. In a tandem pair, the follower ant was typically an experienced forager [20].

Some researchers focused on the effects of different environmental geometry on the ants' evacuation from an area, in order to learn more about the influence of stress conditions on their behavior. Experiments have evaluated how the nest design affected collective movements. In one study, the average rate of ant egress was enhanced when there was a partially obstacle near the exit [21]. Shiwakoti et al. [22] tested the effects of different structural features on ant egress under stress conditions. They evaluated egress efficiency with and without a partial obstruction at the exit and in various situations with different exit locations. Geometrical adjustments played an important role in ant egress. Moreover, complex configurations affected ant evacuation [23,24].

Some researchers have studied the dynamic characteristics of ant egress under stress conditions. The dynamic "faster is slower" phenomenon in ant egress was shown by Soria et al. [4]. They used different concentrations of citronella oil to change the degree of stress in ant evacuation experiments. Intermediate citronella oil concentrations produced the shortest evacuation times. The "faster is slower" effect during evacuation differed between ants and humans [25]. This phenomenon was not exhibited during ants' egress under temperature stress conditions [5].

Although studies have revealed some interesting phenomena related to ant egress, the behavior of ants under stress situations deserves further investigation. For example, it is not clear how ants evacuate without jamming at the exit. Few studies have explored how ants evacuate from a two-exit room. In the present work, we explored the behavior of *Camponotus japonicus*escaping from a room with two exits that were separated by varying distances. The study focused on investigating the features of ant evacuation behaviors in this scenario. Ant evacuation behavior has been proposed as a model for human evacuations [26], but the ants' egress behaviors differed from those of humans in important ways [4,5,25,27]. Our aim in the present work is to further compare behaviors between ants and humans to test their similarity in a stress situation.

2. Materials and methods

2.1. Ethics statement

The study was approved by the Animal Research Committee of the University of Science and Technology of China. All efforts were made to minimize suffering.

2.2. Ant experiments

We captured multiple colonies of *C. japonicus* in Shaanxi Province of China and transported the colonies to the laboratory. The ants were placed in plaster nests, the tops of which were covered by glass. Nests experienced natural light/dark cycles in the laboratory. Ants were fed fruit and honey when they were not participating in experiments. In order to provide an appropriately sized chamber, the body length and head width (i.e., the largest lateral dimension of the individual's head) of 50 randomly selected ants were measured using a ruler to the nearest 0.1 cm, and the chamber was sized accordingly.

A rectangular chamber (7.0 cm wide $\times$8.5 cm long $\times$0.6 cm high) made of polymethyl methacrylate (PMMA) was built (Fig. 1). The height was chosen to prevent ants from climbing on top of each other. One side of the chamber contained two exits 0.5 cm wide, separated by a varying distance (1.0, 2.5, 4.0, 5.0, or 6.0 cm). A filter paper soaked in citronella oil, a repellent substance, was placed on the other side to induce stress in the ants and drive them to the exit.

The experiment was carried out in two parts: first, an evacuation experiment that used the repellent substance, and second, a control experiment that used pure water rather than the repellent substance. In experiment 1, about 30 similar-size ants from the same nest were placed in the chamber, with the exits blocked. After the ants had been introduced into the

Please cite this article in press as: S. Wang, et al., Effect of exit locations on ants escaping a two-exit room stressed with repellent, Physica A (2016), http://dx.doi.org/10.1016/j.physa.2016.03.083