Self-Organization in the Movement Activity of Social Insects (Hymenoptera: Formicidae)

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Abstract. Social insects present behavioral, morphologic and social variation, which bring ideal situations to study emergent temporal-spatial patterns. In this study, we observe the self-organization in the movement activity of social insects in different species and densities. In our preliminary results, all the species observed present a pattern more complex in higher densities and with structural differences between them.

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INTRODUCTION

Among complex biological systems, social insects are ideal model systems to study emergent temporal-spatial patterns resulting from interactions among individuals. In particular, ants, which are more diverse than all the other social insects together (bees, wasps and termites) \cite{1}, show considerable variation among species in colony-level behavioral integration. Indeed, there are several algorithms inspired by models of ant colony behavior, culminating in an increasing success among researchers in computer science and operations research \cite{2}. In ants, there are empirical evidences for collective synchronization in group activities \cite{3, 4, 5, 6, 7, 8, 9, 10, 11}. The activity of entire colonies of \textit{Leptothorax allardycei} (Mann) yields an integer dimension that is consistent with periodicity in activity. On the other hand, the attractor of the movement activity of single, isolated \textit{L. allardycei} has a small, non-inter dimension characteristic of low-dimensional chaos \cite{6}. However, the relation between how the chaotic behavior of single ant relates to the self-organizing and foraging behaviors of the ant colony has received little attention \cite{12}. The presence of chaos in the animal behavior can bring profound consequences in the interpretation of behavioral evolution and natural selection itself. Through the study of social complex behavior, we can investigate ways in which complexity emerges and the factors that could determine chaotic or periodic behavior in the self-organization in animal societies. The technological breakthrough of the last decade was enormous and permits the use of computational programming and mathematical tools for animal behavior analysis. In particular, the tracking of individual movement offers new ways of dealing with collective behavior in a spatial-temporal context. In this study we observe the movement activities presented by three species that differ with respect to their morphological, behavioral and social traits. Through this approach, we could infer the influence of different density, species and castes in self-organization behavior, aperiodic behavior in single individuals and how the periodic behavior emerges in the system.

METHODS

We used digital video recordings to extract x-y coordinates of single individuals moving along a two-dimensional plane. Two ant species were studied: the ant species \textit{Gnamptogenys striatula} Mayer 1884 and \textit{Linepithema micans} (Forel). \textit{Gnamptogenys striatula} is a well succeed ant species with some primitive behavioral and morphologic characteristics. \textit{Linepithema micans} is a diverse and potential invasive species with more advanced behavioral and morphologic characteristics. Lastly, for comparison with non-social animals, we used the beetle \textit{Tenebrio molitor} Linnaeus 1758, a well know beetle’s species that presents a gregarious behavior.
Observations and Arena

Three colonies of each species were placed in laboratory and maintained with equal conditions of temperature and humidity (20°C±3; 50% UR). The individuals were removed from the colonies and placed in the arena (Figure 1) for at least one hour, during daylight time (8:00 am to 5:45 am). The arena was brightly lit (~1500 lux) with fluorescent daylight bulbs spots in each corner, inside a box (51 x 51 cm) for elimination of external influences (wind and light inconsistence). The arena consists of a Petri dish (92 x 92 mm), the ants stayed between a specific substract and a top glass above the Petri dish. The subtract arena was opaque white, with a series of white rubber silicon (RTV), promoting specific adjustment inside the Petri dish for each species. Before the experiments, both the Petri dish and the substract were cleaned, dried and not used for at least five hours before a new experiment. The experiments were recorded during two hours (N=144,440 frames) with a camcorder (JVC GZ HM-320) at 20 cm height from the petri dish by 20 frames per second. In these preliminary results were used 1, 4 and 16 individuals with 30 replies for each species population, during the first 30 minutes of the videos resulting in 1890 individual time series with 36110 frames.

FIGURE 1. The arena overview. The general vision of the arena disposition of the fluorescent bulb light spots (gray boxes), the camcorder (black rectangle), with the Petri dish (circle) in the center of the arena.

Data Analysis

The position x-y in the 2-dimensional coordinates of each ant’s and beetle (visual) center of mass and its body orientation in each frame were extracted using the Ctrax software, Caltech Multiple Fly Tracker (version 0.3.3; http://ctrax.berlios.de/) and the associated FixErrors toolbox for MATLAB (MathWorks, Inc., Natick, MA, USA) [13]. Besides the fact that the Ctrax was primarily made for track flies, it is able to track large groups of different animals while maintaining their individual identities [14, 15]. In particular, Ctrax software is open source and thus freely available, it is accurate and requires only simple available equipment. The recurrence analysis a priori will be used to quantify the number and duration of recurrences in the time-space of each time series. Recurrence analysis has been successful used to observe, interpret and correlated complex patterns in different systems, under vastly circumstances and situations [16, 17, 18]. In our preliminary results here exposed, we used an important tool of recurrence analysis, the Recurrence Plot or RP [19], an advanced technique of nonlinear data analysis, it is a visualization (or a graph) of a square matrix, in which the matrix elements correspond to those times at which a state of a dynamical system recurs. The RP reveals all the times when the phase space trajectory of the dynamical system visits roughly the same area in the phase space. The recurrence plot is an array of dots in an $N \times N$ square, where a dot is positioned at $(i, j)$ whenever $x_j$ is close enough to $x_i$. In order to create a recurrence plot, an m-dimensional orbit of $x_i$ is created. The ball of radius $r$ centered at $x_i$ in $\mathbb{R}^m$ contains a suitable amount of other points $x_j$ of the orbit. Lastly, a dot is plotted for every point $(i, j)$ for which $x_j$ is in the ball of radius $r$ centered at $x_i$. These graphic representations of recurrence points within a system permit to observe and interpret the general overview pattern of each individual time series. The RPs were made in the package tChaos for R software [20, 21]. The presence of recurrence in dynamical systems can indicate, among other information, the degree of determinism of the underlying mechanism. For example, the density of diagonal lines in the recurrence plot is a direct evidence of determinism. Moreover, a recurrence quantification analysis provide a characterization of the type of dynamics present (periodic, chaotic, etc.) [22].

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RESULTS

The preliminary results show differences in the systems patterns of the threes species and in each density (Fig. 2). It is clearly observed that the elevation in the density of the individuals make the recurrence plots show a more complex pattern.

![Figure 2](image)

**Figure 2.** Examples of recurrence plots for each species in the considered densities. The recurrence plots for each species are highlighted inside each column, from the right to left, *Gnamptogenys striatula*, *Linepithema micans* and *Tenebrio molitor*. The rows (a), (b) and (c) corresponds to the densities, in the same order, 1, 4 and 16 individuals. In the RPs, white is maximum distance and black is minimum. A total of 333 points were used, the time is 1800 seconds and embedded dimension is two.

Probably, due to the fact that the species have evolutive differences (between the ant’s species) and even of social organization (beetle’s species) some differences can be noted, particularly in each species. *Gnamptogenys striatula*, the more primitive ant species, show peculiar behavior in the system in the first and last density (respectively, 1 and 16 individuals). *Linepithema micans* show a more elaborated pattern, increasing its puzzling design with higher density. *Tenebrio molitor* show a progression more similar in the behavior of the system, in relation to the different densities, the presence of several and paced clusters lines probable indicates no change in
state or slowly changes, the presence in different parts of the RP also could indicate periodicity, this could be linked with it more gregarious behavior in presence of others individuals. In all the three species is observed a change of pattern between the first density (one individual) and the other ones, becoming more complex. One of the mainly results of this first overview of the time series is the observed difference of RP patterns in the species. This indicates the possibility of achieving complex patterns and behaviors in different ways, and could be linked to the evolutionary differences presented by each species. Besides the existence of chaotic behavior in the movement of single ants [6], here we see a glimpse that indicates chaotic behavior in higher densities, and how the process in each species to achieve its complex pattern could be different.

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