Human swarming behavior: multiple ordered states and inherent noises

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Abstract: Many animal groups display self-organized collective patterns of motion. Human crowds also offer various examples of self-organization, including flocking behavior similar to that seen in fish schools and bird flocks. While previous studies on human flocks or swarms have investigated the influence of individual vision on local interactions, the global properties and the change in interaction network at the group level remain elusive. Here, we show that human swarms can transition between multiple collective states, and their interaction networks are no fixed in time, similar to other animal groups. We tracked trajectories of participants walking together in an experimental arena and observed that they can exhibit well-organized collective behavior. In particular, human swarm composed of fifteen individuals showed transitions between two ordered states: polarized and milling groups. Individual noisy movements may contribute to these transitions. Indeed, we found that individual participants continuously change their relative positions with respect to their neighbors in a directed group, allowing for interactions with various neighbors. We expect that our findings provide insights to understand fundamental mechanisms underlying behavior in human crowds and nonhuman animal groups.

Keywords: self-organization, human crowd, pedestrian behavior, inherent noise

1. INTRODUCTION

Animal groups, ranging from insect and crustacea swarms, fish schools, bird flocks, and mammal herds exhibit global patterns of coordinated motion through self-organization. Human crowds are no exception. For instance, pedestrian crowds provide a wide variety of collective behavior, such as organizations of multiple unidirectional lanes in bidirectional pedestrian flows, stop-and-go waves, and crowd turbulence [1-3]. Even without transportation environments or situations (e.g., bottlenecks and crossings), people can also spontaneously walk together, perform swarming behavior, as do other animals. Understanding how people behave as a “human swarm” not only has important implications for help manage mass events and daily pedestrian transportation, but also provide a comparative perspective of collective animal behavior.

Collective behavior emerges from inter-individual interactions. It is therefore crucial to uncover characteristics of local interactions underlying collective human behavior. Previous studies on human swarms investigated the influence of individual vision on local interactions, mostly conducting virtual reality crowd experiments [4, 5]. For example, manipulations of movements of virtual crowds revealed that human participants alter their behavior depending on the number of virtual neighbors and their positions, in particular, the influence of neighbor is linearly combined and decreases with distance in agreement with the superposition hypothesis proposed by the most computational crowd models. Moreover, the importance of visual neighborhoods taking into account occlusion and view of walkers rather than just the use of physical distance has been investigated in human crowd studies, like in other animal group studies [6].

However, the global properties and statistical properties of the groups are still not elucidated. For instance, it is well known that animal groups such as fish school dynamically change geometry or form of the groups and sometimes transition between their global ordered states. These change in forms or ordered state can be triggered by inherent noise, i.e., internal movements of individuals on the inside of the group. Indeed, although animal groups appear to exhibit highly organized state (e.g., highly polarized and directed) at an instant in time, individuals travel in a group and perpetually replace their positions with neighbors in the long term. Internal structures in animal groups are not fixed in time, and hence enable interactions with various neighbors and smooth information transfer throughout the group. Would the same be true also in human crowds? In this paper, we introduce our human swarm experiments with real participants and investigate these global and statistical properties.

2. EXPERIMENTS

The experiment was conducted in May 2022 in the gymnasium of the Kyoto Institute of Technology, Japan (Fig.1). Forty-eight university students were recruited for the study (35 males, 13 females, mean (±SD) age = 21.08 ± 1.71 years). For ease of video analysis, each participant was asked to wear a black T-shirt a colored (red or yellow) cap. Written informed consent was obtained from all participants prior to the start of the study. The study was approved by the Ethics Committee of Kyoto Institute of Technology.

The floor of the experimental arena was covered with a green PVC gym floor cover so that the lines on the gym floor were concealed and participants could walk in their own outdoor shoes. For the purpose of efficient operation, we prepared two equivalent experimental arenas (10 × 8 m), where their boundaries were marked by blue tapes on the floor. We could thus carry out two experiments in parallel.

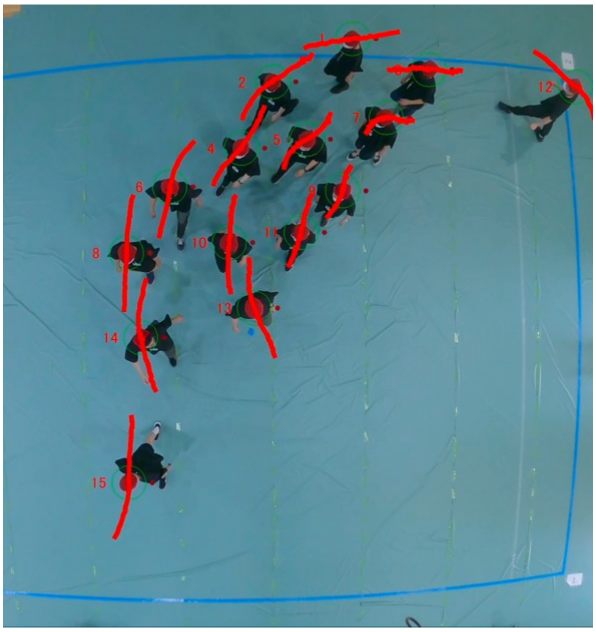

Fig.1 Human swarming experiment with fifteen participants.

Participants were randomly selected as a group with N participants for each trial, taking into account gender ratio. Before the trial, participants were instructed to take positions on the center of the arena. They were asked to walk throughout the experimental arena without lingering at any particular location, while staying together as a group. At a start signal, they started walking for 2 min, until a stop signal. A total of 10 replications were conducted, with N = 3, 7, 15 individuals (10, 6, and 4 replications, respectively). Note that in this paper, we mainly focused on 15 individual swarms.

The experiments were recorded from above with GoPro Hero 10 camcorders equipped with a linear digital lens (4K, 30fps) fixed at a height of 10 m. From the video images, we obtained time series pedestrian trajectory data using Petrack [7]. In this study, the time interval for velocity was dt = 1/3 s (10 frames).

3. RESULTS

4.1 Transition between collective ordered states

We observed that human walkers seemed to show well-organized collective behavior, walking together without colliding each other and lingering at any particular location. Regardless of N (the number of individuals), they basically exhibited polarized state movements as a group and turned collectively before reaching the border of the arena and collapsing their group. Only in one trial with N = 15, walkers seemed to show milling states, transitioning with polarized states (we call this as trial M).

To quantitatively evaluate the above observations about the collective structure of the human swarms, we employed two order parameters, identical to previous categorization in fish school [8]. First, we calculated the polarization parameter O_p to measure how individuals are aligned in a group,

$$O_p = \left(\frac{1}{N}\right) \left|\sum_{i=1}^{N} \boldsymbol{u}_i\right|,$$

where $\boldsymbol{u}_i$ is the unit vector of the velocity of individual i. It takes values of between 0 (no alignment) and 1 (strong alignment). Next, we used the rotation parameter O_r to describe a group's degree of rotation about its center of mass,

$$O_r = \left(\frac{1}{N}\right) \left|\sum_{i=1}^{N} \boldsymbol{u}_i \times \boldsymbol{q}_i\right|,$$

where $\boldsymbol{q}_i$ is the unit vector pointing from the group's center of mass toward individual i. It takes values of between 0 (no rotation) and 1 (strong rotation).

Fig. 2 shows some snapshots of reconstructed velocities of individuals within a group showing multiple ordered states (i.e., trial M). The walkers initially showed well-polarized movements (26 s) with high O_p and low O_r. Subsequently, they transitioned a somewhat disordered state (43 s), followed by structured milling movements (50 s) with low O_p and high O_r., which were maintained for about 20 s. The milling structure then collapsed (73 s) and re-organized again (106 s) via short term polarized state (90 s). In this way, in trial M, O_r occasionally maintains high values close to 1, despite O_p remaining low at times, while showing drastic changes of both parameters.

For comparison, we consider one representative trial with fifteen individuals, showing only polarized behavior (say, trial P). In trial P, O_p consistently reaches high values, approximately around 0.8, and generally surpasses O_r. In trial P and M, O_p exceeded 0.7 for 88% and 15% of the time, respectively, while O_r exceeded 0.7 for 1% and 64%, respectively. These results indicate that human crowds show multiple collective states at times.

4.2 Individual movements on the inside of the group

Next, we investigate individual movements within a group. It is well known that the internal structures of collective animal groups are not fixed in time [9, 10]. Rather, there are inherent noises generated within collective animal groups, where individuals continually replace their positions with neighbors. Is the same true in human crowds? To address this, we investigated diffusive behavior in a polarized group. The center of the mass reference frame is useful for observations of individuals' movements on the inside of the group.

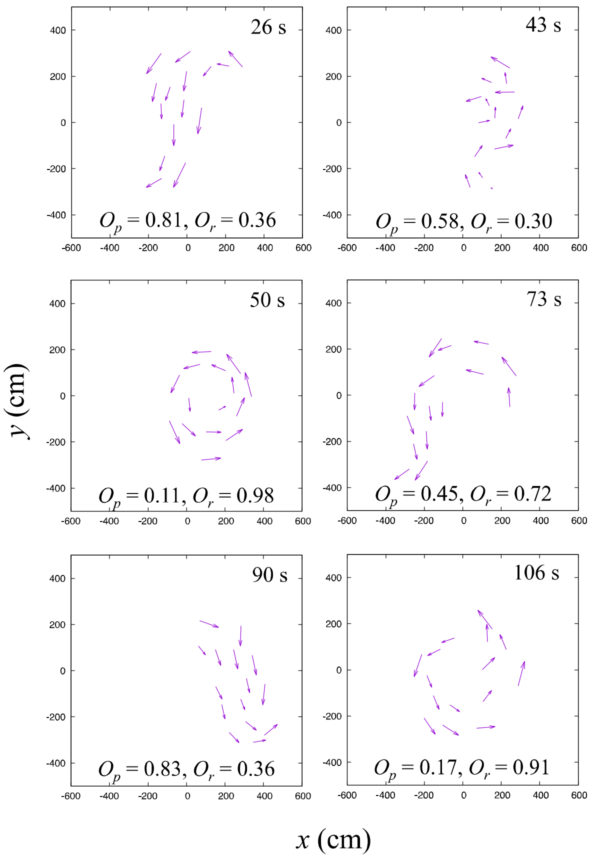

Fig.2 Time series of reconstructed individual velocities in trial M.

To measure how much individuals move on the inside of the group, we calculated the mean-square displacement (MSD) in the center of the mass reference frame as a function of time:

$$\delta r^2(t) = < |\boldsymbol{r}(s+t) - \boldsymbol{r}(s)|^2 >,$$

where $\boldsymbol{R}(s)$ denotes individual's position at time t, $\boldsymbol{R}_{CM}(s)$ is the position of the center of the mass of the group at time t, and $\boldsymbol{r}(s) = \boldsymbol{R}(s) - \boldsymbol{R}_{CM}(s)$ therefore represents the position of the individual in the center of mass reference frame. This quantifies the average distance travelled during time t. Many natural diffusion processes follow the power law:

$$\delta r^2(t) \sim t^{\alpha},$$

where the diffusion exponent α varies between 0 and 2. Brownian (normal) diffusion occurs when $\alpha = 1$. When $\alpha > 1$, the diffusion is faster than Brownian diffusion and is termed superdiffusion (the extreme case with $\alpha = 2$ is referred to as ballistic diffusion).

Fig. 3 shows an example of MSD as a function of time. We observed that, at relatively high elapsed time values (i.e., t), the slopes of the MSD trended either upward, downward, or exhibited undulating patterns, consistent with findings from a previous study [10]. This phenomenon can be attributed to the relatively lower sample count at these larger elapsed time values and/or the increased likelihood of walkers encountering borders of the group during longer movements. When we restricted the range of elapsed time from 0.03 to 3 s, we observed a diffusion exponent $\alpha = 1.80$. Although this value is slightly higher than that observed in fish school cases, it indicates that human walkers display super-diffusive behavior in the center of mass reference frame. Fig. 4 shows an example of an individual trajectory in the center of the mass reference frame. We can see that the individual visit various spatial location within the group, but not stays in a local region within the group. Also, there are step clusters separated by longer relocations, which was also observed in fish schools [10].

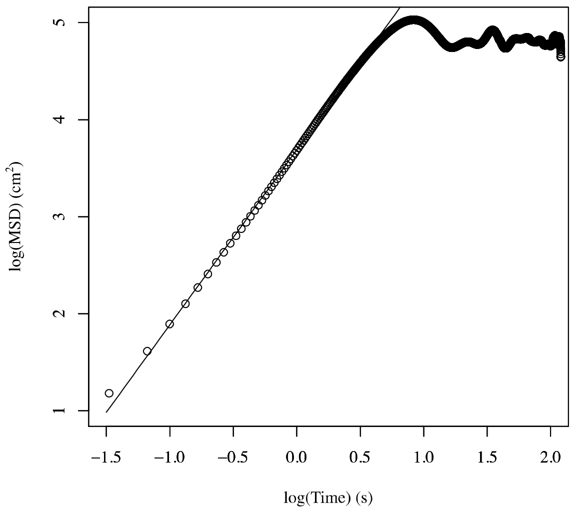

Fig.3 An example of MSD in the center of mass reference frame against time in human swarm.

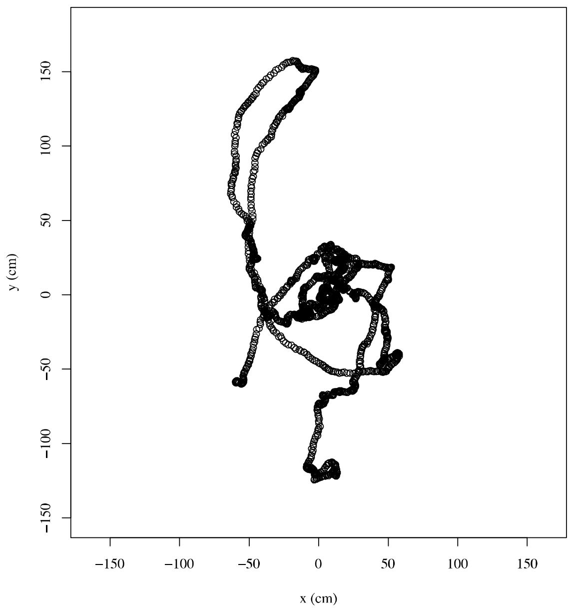

Fig.4 An example of individual trajectory the center of mass reference frame.

4. DISCUSSION

Previous studies on human swarms focused on the influence of individual vision on local interactions. We here investigated the global level behavior and showed that human walkers can show collective behavior similar to other animal groups such as fish schools. First, we observed that human swarms transition between polarized and milling states at times. We did not give participants detailed instructions how to move or gather each other. Therefore, the transitions spontaneously emerged through inter-individual interactions. Indeed, the milling structure appeared only in one trial with fifteen participants. In the other trials or other group sizes, only polarized structures were observed. It would be worth noting that at the time when the milling structure first organized during the experiment, laugher broke out among walkers participating in the structure, suggesting that the milling structure was unexpected even for the walkers.

What influences the milling state and its transitions to and from the polarized state? A previous study identified two factors: external factors (such as the boundary effect of experimental arena, which may be related to group size — the larger the group, the closer it tends to approach the border) and internal factors (such as changes in the motion of group members) [8]. It should be noted that in our experiment, the arena may have been relatively small compared to previous fish school experiments, causing human swarms to turn frequently. Approaching the border could lead to external perturbations for the swarms, potentially triggering transitions from polarized to milling states.

In relation to the internal factor, we also investigated internal individual movements on the inside of the group. We observed that human walkers exhibit superdiffusive movements within the group, as seen in fish schools [10], indicating that they move faster then Brownian walkers on the inside of the group. Visiting spatial location throughout the group would enables individuals to interact with various neighbors and form and maintain robust collective motions. Also, this inherent noise would have an important role to change collective structures. We are now investigating how the internal movements impact the transition between multiple collective states, taking into account the boundary effect.

We expect that our study provides insights to understand collective animal behavior from comparative perspective [1]. For example, we observed that human swarms also show the milling state, similar to those of fish schools. This result could give a hint to consider why fish schools (and human swarms) show the milling state, but not bird flocks. Comparing these three different taxa may capture researchers' attention toward their respective animals' medium or environments, such as air for birds and water for fish. In water, due to its higher resistance compared to air, more energy is required to obtain propulsion, but less energy would likely be needed for turning. In the case of human walkers, propulsion for movement is obtained through the frictional force between the ground and the feet, so it's likely that significant energy isn't necessary for turning as well. Therefore, in terms of ease of turning, it could be said that humans are closer to fish than birds. This turnability may be related to the emergence of the milling states. And this possibility may be more easily testable in human crowds than fish schools due to their ease of experimental manipulations. This is just an example. We consider that human swarm experiments could open the way for understanding collective behavior from alternative perspectives.

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