Motion perception of biological swarms

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Abstract

Biological swarms are collections of many independent agents who are motivated to remain clustered in a large group. The motion of swarms, then, is complex, with the influence if independent members within a coherent structure of the group. We investigated whether human perception of biological swarms was sensitive to this internal complexity of the group motion, as has been observed for biological motion of single objects, such as the limbs of a walking person. In two experiments, we tested motion detection and discrimination of biological swarm motion compared with scrambled, unstructured spiral and rigidly-structured rotational motion. The results showed that discrimination of swarms was superior to perception of scrambled swarms that contained no structure, but was worse than discrimination of the motion of rigid structures. These results suggest that perception of swarms does not engage a specialized mechanism for detecting internal structure, as is found with other types of biological motion, but instead reflects the properties of perception of a coherent global motion. These results have implications for the design of human-machine interfaces. The majority of existing human-robot swarm interaction visualizations presents the human user with each individual swarm member. The presented results imply that an abstract visualization representing the general swarm structure will perform as well, or better than visualizations of each individual.

Keywords: Cognitive Science; Vision; Perception; Experimental research with adult humans; motion perception; biological motion; structure from motion; swarm

Introduction

Biological swarms are a distinctive phenomenon created by the common needs and desires of a collection of individuals who associate with one another. Be they flocks of birds, schools of fish or herds of cattle, swarms have characteristic motions based on each individual's desire to remain with the group combined with their basic needs, such as finding food and avoiding predators (Attanasi et al. 2014; Couzin & Krause, 2003; Couzin, 2009; Sumpter, 2010). Self-organizing principles bring about the emergence of global motions that have distinct patterns, even while each individual member of the swarm retains independence (Couzin et al, 2002; Wood & Ackland, 2007; Cavagna & Giardina, 2010). The motion of swarms can be defined as a type of biological motion, because swarms have characteristic patterns of motion that are defined by living organisms in locomotion (Johansson, 1973; Hiris, 2007).

Biological motion has been considered a special category of motion in perception research. The motion of living organisms, including people, animals, insects and even novel creatures, is perceived readily, even with sparse cues (Blake & Shiffrar, 2007; Mather & West, 1993; Pyles, Garcia, Hoffman & Grossman, 2007; Gold et al., 2008). Johansson (1973) discovered that a minimalist display showing only moving white dots was able to convey to an observer the accurate understanding of a person walking, as long as the dots reflected the location of the person's primary joints, such as elbows, shoulders, knees, and hips. Research has demonstrated that perception of human walking is effortless and automatic (Thornton & Vuong, 2004; Thornton, Rensink & Shiffrar, 2002), is possible by newborn babies (Simion, Regolin & Bulf, 2008) and activates specialized brain areas that are responsible for biological motion perception (Grossman et al, 2000; Grossman et al., 2005). Specialized perception to the motion of the human figure may reflect the fact that one of the most prevalent moving objects in our natural environment is other people.

The vast majority of research on biological motion has used motion of subparts of a single object, such as limbs of the body or features of the face (Blake & Shiffrar, 2007). Given the constraints of bone and joints, motion of subparts reflects a bounded set of possibilities that reliably reflect the underlying form. As such, it is perhaps not surprising that normal perception of biological motion seems to depend on both the motion detection system and the form recognition system (Thurman, Giese & Grossman, 2010). In fact, the superior recognition of biological motion over perception of other categories of motion has been attributed to the contribution of the form (Hiris, 2007; Gold et al., 2008).

The motion of swarms is a type of biological motion, because it is defined and constrained by the structure of biological entities. However, unlike biological motion of the human body, swarm motion has no underlying form that rigidly determines the relationship between parts. Individuals in a swarm behave similarly, but retain their independence creating a motion that is uniquely organized and free. At the same time, swarm motion is biological, based on the interactions between living organisms following basic rules of association that produce a coherent global motion that seems readily recognizable. This work investigated whether perception of swarm motion showed the sensitivity to the structure of moving swarms and whether this sensitivity was similar to the specialized system of biological motion perception of the walking human form. Developing a clear understanding of how humans perceive biological swarms directly impacts not only our understanding of human motion perception, but also can impact the design of swarm visualizations.

Experiment 1: Discrimination of Swarm motion vs Scrambled Swarm motion

To start our investigation of the perception of swarm motion, this experiment measured motion discriminability thresholds. If there is a specialized mechanism for detecting swarm motion, then observers should have lower threshold for discriminating swarm motions from one another than discriminating the same local motions with the global pattern of motion destroyed. Swarm motions were short movie clips (200 frames) of a school of 256 fish that were randomly selected from an extensive recording (over 10,000 frames) of fish schooling behavior (Couzin and colleagues, pers. comm). Scrambled control clips were made by randomly displacing each fish slightly, enough to destroy the global coherency of motion that is typical for biological swarms. In each block of eight trials, participants were asked to memorize one randomly-selected clip and discriminate it from another random clip in the subsequent trials across increases of motion noise. Swarm and scrambled motion were tested in separate blocks. This experiment tests the basic concept that organized motion of swarming fish is easily remembered and recognized by human observers.

Method

Following the traditional approach of cognitive science, this experiment tested several individuals in a repeated measures design testing the discrimination of swarm motion compared to the discrimination of scrambled motion.

Participants: Seventeen volunteers were recruited from the population of Vanderbilt University undergraduate students. Each participated for one hour in exchange for partial course credit or \$12 payment. Data from one participant was removed prior to analysis because the participant was unable to complete the session due to a schedule conflict. The protocol for this and all subsequently presented experiments was approved by the Institutional Review Board at Vanderbilt University and follows the Declaration of Helsinki and APA Ethics Code standards for the Protection of Human Participants in research.

Materials and Stimuli: Visual displays were constructed with Matlab and the Psychophysics Toolbox library (Brainard, 1997; Pelli, 1997) on an Mac mini with OSX 10.7.2 driving a DELL 1704FPT 17" flat screen monitor at a resolution of 1024X768 pixel and a refresh rate of 60 Hz. Participants viewed the stimuli from a distance of approximately 57 cm, such that stimuli subtending 1 cm on the screen were approximately 1 degree of visual angle.

The visual displays provided movie clips (200 frames) of white dots (0.25 cm diameter) inside a square white frame (22 cm X 22 cm) moving on a black background. The dots moved as a swarm in half of the clips. The motion of each dot was determined from an extensive recording (10,296 frames) of a school of 256 fish performing schooling behavior provided by Dr. Iain Couzin, Professor of Ecology and Evolutionary Biology at Princeton University (Couzin, 2009). Positions of each fish were extracted from the video recordings and rendered in the 2D visual displays as dots. Short clips were randomly selected without replacement from the recording. Scrambled control clips were generated by randomly displacing each dot. Displacements in both horizontal and vertical position were determined by adding or subtracting a random value between zero and one-quarter of the width of the display (5.5 cm). Displacements were enough to destroy the global coherency of motion that is typical for biological swarms, but maintained the motion path and speed of each dot. The fish motion throughout the school is variable, thus the speed of each dot varied widely with a mean speed of approximately 18 degrees per second (dps) (12.5 pixels per frame) and a standard deviation of 26 dps. Typically, dots near the center of the swarm, often near the center of the screen, moved slowly (0-2 dps), while those at the edges moved more quickly (30-50 dps). This pattern was not preserved in the scrambled condition, because each dot retained its trajectory, but was randomly displaced.

The swarm and scrambled motions were tested in separate blocks. At the beginning of each block of eight trials, participants memorized one randomly-selected clip and discriminated it from other random clips in each trial in a two-alternative temporal forced choice procedure (2ATFC). The trials varied by the number of randomly moving dots that were also present in the display – the motion noise. Noise dots replaced some subset of the moving dots at different proportions across trials. Noise was either 100%, 87%, 74%, 61% 48%, 35% 23% or 10% of the dots. Signal level was 100% minus noise level. Each noise dot moved in a random direction along a straight path at 1.5 dps, with a limited lifetime of 10 frames (0.167 sec), after which each was randomly displaced and moved in a new random direction. As such, the noise was dissimilar in speed, trajectory or lifetime to the moving dots.

Procedure: After providing informed consent, participants were shown a demonstration of the visual displays, including two swarm motions and two scrambled motions with no visual noise. After the task was explained, participants completed eight practice trials with either the swarm or the scrambled motion, counter-balanced across participants. The main experimental trials consisted of 18 blocks of eight trials. The blocks alternated between swarm motion and scrambled motion (counter-balanced across participants), so participants were always comparing swarm motion to swarm motion and scrambled motion to scrambled motion. Each block started with the exposition of one motion clip that was the *standard* motion to be memorized for that block of trials. Participants could press a key on the keyboard to repeat the video clip and see the standard multiple times, if they chose to do so. The subsequent eight trials each consisted of two motion clips, one presentation of the standard and one comparison clip with a 0.1 second blank screen between clips. Which clip appeared first was randomly determined for each trial. The comparison clip was chosen randomly on each trial. Both clips were presented at the same level of noise. All eight levels of noise were shown in a block of trials in random order. At the end of each trial, participants pressed one of two keys on the keyboard to indicate whether the standard was first or second in the trial. Feedback was immediately provided after the key press and the next trial advanced automatically after 1 second. Feedback was also given at the end of each block as a percentage of correct trials per block.

Results and Discussion

The percentage of correct responses across the motion types (Swarm and Scrambled) and the eight levels of motion noise for 16 participants were submitted to an ANOVA. Both main effects were statistically significant, showing that swarm motion was discriminated better than scrambled motion on average (Swarm M=89.3%; Scrambled M=80.5%, $F(1,15) = 56.1$, $p<.001$), and that higher noise produced worse discrimination performance than lower noise ($F(7,105)=44.36$, $p<.001$). The interaction was not statistically significant. These analyses indicate that participants were better able to discriminate swarm biological motion than their scrambled counterparts overall, but do not clearly indicate of how performance with the two motion types varied across levels of noise. Results are shown in Figure 1.

Discrimination thresholds for each participant were estimated separately in order to describe discrimination differences between motion types more clearly. The thresholds were set at the 75% correct discrimination level by fitting a 3rd-order polynomial to the accuracy data across

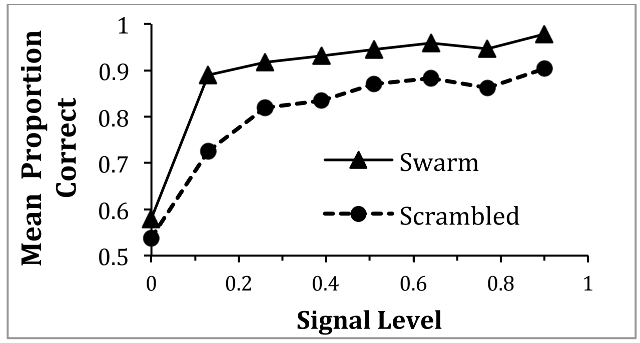

Figure 1: Proportion correct motion discrimination for swarm and scrambled swarm displays across signal level, averaged over participants.

noise levels for each motion type. The average threshold for the swarm motion was significantly lower than for the scrambled motion ($t(15)= -3.465$, $p<.005$). Interpolating from the fit functions, the results show that the swarm motion was discriminated at threshold with only 7% signal dots (93% noise), while scrambled motion was discriminated at threshold with 18% signal dots (82% noise). These analyses indicate that participants were able to discriminate swarm biological motion at higher levels of noise than the scrambled counterparts.

The results support the conclusion that the perception of motion of swarming biological agents is, as a whole, greater than the sum of its parts. As with previous research on the perception of biological motion of human figures (Thurman, Giese & Grossman, 2010), perception of biological swarms benefits from the coherent organization of the parts relative to the whole. These results are consistent with the subjective impression, expressed by the participants, that the swarm motion is a coherent, global motion with some deviant members, while the scrambled motion was much less coherent. Even though this experiment does not indicate whether or not perception of the swarm is achieved with a privileged mechanism, it indicates that people easily recognize swarm motion, even with substantial visual noise.

Experiment 2: Discrimination of Swarm motion vs Rigid and non-rigid rotation

Experiment 1 demonstrated that perception of swarm motion benefits from the presence of the spatial relationship between swarm members. Experiment 2 was designed to assess the extent of this benefit. Previous research has shown that the discrimination of biological motion, of a human walking figure, is better than discrimination of random motion (Hiris, 2007). This benefit to perception seems due, for the most part, to the internal structure of the biological form (Beintema & Lappe, 2002) as evidenced by the similar discrimination thresholds from walking figures and rotating geometric shapes (Hiris, 2007). If perceiving swarm motion is accomplished with a mechanism that readily detects structure, then observers will perform better when discriminating the direction of a swarm's motion as compared to a random arrangement of dots. Also, if swarm perception is similar to biological motion perception, then observers will perform just as well with swarms as with highly-structured figure motion. This experiment tests the notion that organized motion of swarming fish has structure that is readily perceived.

Method

Following the traditional approach of psychophysics, this experiment tested a few experienced individuals in an extensive measurement of motion discrimination thresholds. Motion discrimination thresholds were estimated for swarm motion, unstructured spiral motion and rigidly-structured rotation of a square.

Participants: Four experienced psychophysical observers were recruited from the Vanderbilt Vision Research Center. Each participated in 3-6 one-hour sessions of testing over a period of one week. Two observers (AES and MM) were collaborators and/or authors of this work. The other two observers (DM and YQ) were naïve participants who received partial course credit or payment.

Materials and Stimuli: Visual displays were constructed with the same materials as Experiment 1. There were three types of displays in this experiment: swarms, spirals and squares. Swarm displays were a subset of the same short movie clips of white dots. The selected subset of movies were based on the overall swarm's motion in the clip. Clips with distinct rotational or translational motion were selected and those with mixed or shearing motion were discarded. Spiral displays contained randomly-placed dots that moved on a spiral path. The position, speed and direction of the spiral was randomly varied across trials to span the same range of positions, speeds and directions as the swarm motions. Square displays contained dots that moved such that the arrangement of dots created a square that rotated about its center. The direction of the squares' rotation was randomly determined as clockwise or counter-clockwise for each trial. The position and speed of the square was randomly varied across trials to span the same range of speeds and positions as the swarm motions. Each dot in all displays has a limited lifetime (approx. 0.167 sec) before it disappeared and was replaced by another dot in a different location.

Procedure: After providing informed consent, participants were shown a demonstration of the visual displays, with no visual noise. Different display types were tested in separate blocks. The participants were asked to discriminate the direction of motion in each block of 24 trials. The participants responded with a key press on the number pad indicating counter-clockwise or leftward motion with the '1' key and clockwise or rightward motion with the '2' key. The trials within a block varied by the number of randomly moving dots that were also present in the display – the motion noise. The noise dots replaced some subset of the moving dots at different proportions across trials, which differed by participant. Each noise dot moved in a random direction along a straight path at 1.5 dps, with a limited lifetime of 10 frames (0.167 sec), after which each was randomly displaced and moved in a new random direction. Each participant completed 18-36 blocks of trials, or 6-12 blocks of each display type. Participants completed different numbers of trials, because the participants differed in the variability of their discrimination. Feedback was immediately provided after the key press and the next trial advanced automatically after 1 second. Feedback was also given at the end of each block as the percentage of correct trials for that block.

Results and Discussion

Discrimination performance for each participant was analyzed separately in order to describe discrimination differences between motion types more clearly. Figure 2 shows the accuracy of three participants for each condition across signal level. For every participant, swarm motion (blue curve) was discriminated at a level that was similar to discrimination of the spiraling random array of dots (red curve) and was not discriminated as well as the structured motion of dots moving as a square (green curve).

Figure 2: Proportion correct motion discrimination for swarm, spiral and square displays across signal level, shown separately for each participant (AES, DM, MM & YQ).

Discrimination thresholds were set at the 75% correct discrimination level by fitting a 3rd-order polynomial to the accuracy data across noise levels for each motion type and for each observer. The threshold for the Square motion was lower than for the Swarm motion for every participant. Interpolating from the fit functions, the results show that the rotating square motion was discriminated at threshold with only 6% signal dots (94% noise), while biological swarm was discriminated at threshold with 12% signal dots (88% noise). Spiral motion was discriminated at 14% signal dots (86% noise). These analyses indicate that participants were able to discriminate highly structured motion of the square at lower levels of noise than the unstructured spiral or the biological swarm.

These results do not support the hypothesis that swarm motion is perceived with support from an underlying form, similarly to the rotating square. Instead, these results indicate that swarm perception is perceived similarly to perceiving organized, but unstructured motion, such as spiral motion. Mechanisms of motion perception sensitive to complex global patterns (Freeman & Harris, 1992; Burr, Morrone & Vania, 1998; Barraza & Grzywacz, 2005) seem sufficient to explain the perception of biological swarms.

General Discussion

We investigated motion perception of biological swarms to determine whether the inherent structure of swarm motion was perceptible and specialized. Previous research has found that motion perception of biological agents, when defined as subparts of a body, is buttressed by the recognition of the underlying form. Having no rigid form, yet still conforming to some global regularities, swarm motion is a unique case of biological motion. Results of two experiments demonstrated that the spatial relations between members of the swarm are perceived in support of motion recognition, and, swarm motion is perceived similarly to unstructured global motions without the benefit of the perception of an underlying structure. These results suggest that motion perception of swarms is supported by a global motion system that is not specialized for the biological nature of the individual agents and their interaction, but instead, capitalize on the motion redundancy from multiple individuals to code the overall pattern.

Implications for Biological Motion Literature

This study has investigated the human perception of swarm motion to measure human sensitivity to the organized motion of a biological swarm. Although previous studies have investigated motion perception of biological groups, these have mainly focused on crowd perception in which the observer's viewpoint is from within the group, rather than as a distant vantage point (Sweeney, Haroz & Whitney, 2013; Gallup, et al., 2012). Here we investigated the perception of swarm motion where the observer oversees a display in which each individual is a single point moving amongst the others. Similar rendering of biological motion of the parts of a single human figure have been used to demonstrate that people are surprisingly good at seeing biological motion, likely because of the well-learned underlying form (Hiris, 2007; Gold et al., 2008; Thurman, Giese & Grossman, 2010). Swarm motion offers a unique opportunity to test motion that is biological, yet completely non-rigid, with freedom of each individual, and, at the same time, organized based on principles of group dynamics. Our conclusion that swarm motion is perceived similarly to other global motion patterns, without the benefit of an underlying form, indicates that biological motion as a category can be divided into form-based and non-form based. Form-based biological motion reaps the benefits of form perception supporting superior performance and surprisingly effortless perception. Non-form based biological motion, however, may be supported by mechanisms sensitive to complex global motions created from redundant local motions making a symmetrical pattern, as in optic flow (Koenderink, 1986; Freeman & Harris, 1992; Cavanagh, 1993). Future research on this topic is warranted to determine whether other types of swarms besides the fish used here, other types of tasks besides motion discrimination, or other display types might yield different results.

Implications for Human-Swarm Interaction

Perception of biological swarm motion has implications for the design of human-machine interfaces (e.g. computer displays), used when human operators are asked to direct robotic swarms. Biological swarms (e.g., fish (Couzin, 2009) and starlings (Attanasi et al., 2014)) consist of very large numbers of individual entities with limited intelligence and capabilities, but the collective demonstrates intelligent, complex behaviors. One promising direction in the design of robotic swarms is to create collectively intelligent groups by emulating their biological counterparts. Humans will be required to supervise such a swarm of robots, even while it is not within direct line of sight and while they are executing tasks for long durations, 8+ hours or days. The human supervisors (Scholtz, 2003) for these robotic swarm missions will be unable to continuously monitor the swarm and maintain vigilance levels. Additionally, it is highly probable that these human supervisors will be tasked with other duties, unrelated to their swarm supervision responsibilities that will diminish their attentional focus on the swarm. A known limitation of human-robotic interaction is limited number of individual robots that a single human can supervise, the human-robot ratio problem (Yanco & Drury, 2004). These constraints complicate the development of methods for human-swarm interaction.

Much of the current human-swarm interaction literature, related to the human supervising the swarm from a different location than the swarm's environment, focuses on providing a visualization of each individual robot. This rather basic visualization typically presents the robots as miniaturized robots (McLurken et al, 2006; Humphrey, Gordon & Adams, 2006), arrows (Kolling, Nunnally, & Lewis 2012), or circles (Nunnally et al. 2013). Though these displays do usually show additional information, like communication links (Kolling, Nunnally, & Lewis 2012) or influence vectors (Pajorová, Hluchý, & Masár 2013), they are relatively difficult to understand quickly. Occasionally, other visualizations are used, such as groupings of a small number of robots that do not show individual robots or show linkages between robots (Humphrey, Gordon & Adams, 2006). Thus, alternative visualizations are necessary to support the number of entities associated with swarms.

The presented research provides important insights in the human perception of biological swarms, which directly informs the design of robotic swarm visualizations. The results indicate that humans perceive the global motion of the swarm. If the movement of the individual swarm members can be abstracted to a single global motion visualization of the swarm, it may be easier for the human supervisor to monitor the overall swarm. It will reduce the complexity of the visualization, while allowing a single human to supervise a significantly large number of individual robots. Further, the results imply that such an abstract visualization, which is less computationally demanding than displaying individual robots, may be sufficient because perception of swarms occurs primarily at the level of global motion. This work is part of an ongoing investigation of several different visualizations and tasks which are being implemented and tested on observers to develop optimal human-swarm interaction.

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