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Social integration of robots in groups of cockroaches to control self-organized choice

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Collective behaviour and decision-making based on self-organisation are demonstrated in eusocial insects¹⁻³, gregarious arthropods^{4,5} and vertebrates⁶⁻⁹. These biological findings have stimulated engineers to investigate novel approaches for the coordination of autonomous multi-robot systems based on self-organization¹⁰⁻¹².

Here we show that robots can be integrated into the collective decision-making process of cockroaches and used as social lures to modify their natural group behaviour.

This integration process is based on the acceptance of the robot by the cockroaches. Acceptance was achieved by conditioning the robots with the cockroach recognition pheromone while their core robotic behavioural module reproduces the cockroach reaction-decision mechanisms for shelter selection. Robots and cockroaches participate in

the collective choice leading them to select a common shelter. The presence of robots introduces new regulatory feedbacks that can be tuned to produce new global patterns that would not have been observed in their absence. The mixed cockroach-robot groups can be induced to mostly prefer a shelter that would be mostly avoided by the cockroaches alone. This form of global control is based on a small number of robots that modulate the underlying non-linear dynamics. These results demonstrate the possibility of using intelligent autonomous devices to study and to control self-organized behavioural patterns in group-living animals.

The use of lures has a long history, for instance the scarecrow in agriculture, or decoys for hunting. These lures are often the result of a tradition evolved from trial and error. Studies in ethology have highlighted the mechanisms underlying these traditions, showing that behaviourally meaningful objects can be abstracted to key sign-stimuli easily recognized and generating a strong response¹³⁻¹⁵. Isolating or reinforcing these key stimuli allows one to analyse their efficiency and better exploit their effects. However, most of these artefacts, including robotic lures mimicking bees, birds or mammals¹⁶⁻¹⁸, are neither reactive nor autonomous. This limitation makes them unable to respond to stimuli generated by the animals and therefore unable to induce responses leading to further stages of interaction sequences¹⁹⁻²¹. A key step in interacting with animals would be therefore to have robots able to respond, control and manage several related behavioural traits. Autonomous robots acting as interactive decoys are interesting research tools. By their ability to respond and adapt to animal behaviour they open perspectives for artificial intelligence and new ways to study individual and social animal behaviours. Robots, or any artificial agents, could then be used to implement new feedback loops leading to new collective patterns in these mixed natural-artificial systems.

In this research, self-organization is the central coordination mechanism exploited by both natural and artificial collective systems. Mechanisms based on self-organization are characterized by essential features such as non-linearity of response functions, incomplete information and randomness¹. Not all the forms of natural collective behaviour are self-organized - self-organization can exist in combination with other types of mechanisms including environmental templates, networks of privileged interactions among individuals and various forms of leadership or pre-existing individual specialization²²⁻²³. However, studies of animal societies¹⁻⁹ demonstrate that self-organization plays a crucial role in the coordination of group members in the reaching of consensus and in the maintenance of social coherence. This often implies that group members have to choose between exclusive opportunities and decide to either join the group or not.

Swarm-robotic systems, in contrast with other multi-robot systems, explicitly exploit self-organization as a main coordination mechanism, although often the ingredients used by the individuals to achieve such organization are fairly different from those found in biological systems¹⁰⁻¹². Individual robots are behaviour-based designed²⁴: (i) they are situated in their environment and do not deal with abstract representations; (ii) their bodies act and interact with their close environment that sends immediate feedback to their receptors in response to their own actions and the actions of others.

This experimental study demonstrates that autonomous robots can be mixed with cockroaches and that this integrated society is able to perform self-organized collective decisions, as groups comprising exclusively cockroaches do. Our experimental set-up consists of a circular arena endowed with two shelters (Fig. 1). In the presence of two identical shelters, large enough to host the entire group, all the cockroaches choose collectively to rest under one of the shelters²⁵⁻²⁷. When one shelter is darker than the other, cockroaches select the darker shelter by amplifying their individual preference

through inter-individual interactions. This self-organized choice does not require leadership, reference to the final pattern, or explicit comparison between the shelters. This mechanism leads to shelter selection and optimal group formation²⁷.

A mathematical model in quantitative agreement with the experiments was developed²⁷ considering the following experimental facts: (i) individuals explore their environment randomly and thus encounter sites randomly; (ii) they rest in sites according to their quality i.e. mainly darkness; (iii) they are influenced by the presence of conspecifics through social amplification of resting time, all individuals being considered equal. Here, this model forms the core behavioural module of the robot program and is also used to forecast the outcome of shelter selection by mixed groups (supplementary). Therefore, the robots are designed to discriminate: (i) cockroaches from other robots, these two types of agents being considered as conspecifics; (ii) shelters from the rest of the arena and shelter darkness; (iii) the wall around the circular arena and other obstacles (supplementary).

The main prerequisite for self-organization based on social amplification is that each individual is able to recognise its conspecifics. In insect societies, recognition signals are transmitted by semiochemicals²⁸. Cockroaches carry on their cuticle a blend of molecules that represents their identity²⁹. Acceptance of robots within a cockroach group is related to the ability of robots to bear the correct chemical signal. Therefore robots were conditioned with the cockroach recognition pheromone that is mainly a blend of cuticular hydrocarbons. Chemical analyses and behavioural tests were performed to identify all the molecules composing the odour that carries cockroach identity. This odour was then collected from male cockroaches and calibrated to a known concentration used to condition filter papers dressing the robots. The concentration per cm² of filter paper corresponded to that found on one cockroach (supplementary). Therefore natural and artificial agents were equally attractive to one

another. Tests with encounters between robots and cockroaches demonstrated that cockroaches were lured and interacted with chemically dressed robots. Comparisons with unmarked robots stressed the importance of this chemical message (see supplementary).

We extend the classical semiochemical luring method by using autonomous robots. Not only do these robots move autonomously but they are also able to tune their resting time in relation to the presence of cockroaches, as cockroaches do²⁵⁻²⁷. In turn, the insects are influenced by the presence of robots closing the loop of interactions between animals and machines.

The first set of experiments demonstrated the sharing of the collective decision making for shelter selection in mixed cockroach-robot groups. The robots were programmed to select dark shelters as cockroaches do. We demonstrate that interactions between robots and cockroaches lead to selection of a common shelter (Fig. 2). Given the choice between two identical dark shelters, both types of groups chose to rest under one of the shelters and behaved as a whole irrespective of their natural or man-made origin. In most trials, both cockroach groups and mixed groups selected one of the shelters. In 93% of the trials (28 of 30 trials), mixed groups presented a clear choice for one of the shelters and 75% of cockroaches and 85 % of robots aggregated under the same selected shelter. Comparisons of these results with computer simulations of the model confirmed that the choice corresponds to the coexisting states of a non-linear system (supplementary).

The second set of experiments was designed to demonstrate the control of the collective choice by mixed groups when shelters differ in attractiveness; in this case darkness (Fig. 3). Cockroaches prefer to aggregate under the darker shelter (brown bars in Fig.3a). This selection process is explained by the same model as above with a bias

induced by the darkness level of the shelters. When cockroach groups selected one of the shelters (73% of 30 trials), the darker shelter was selected in 73% of the cases and the lighter one in only 27% of the cases (Fig. 3a). As in the first set of experiments with two identical dark shelters, these proportions correspond to the coexistence of multiple states in a non-linear system.

In the case of mixed groups (yellow bars in Fig.3a), the robots were programmed to prefer the lighter shelter, contrary to the cockroaches. This effect was obtained by keeping the same behavioural model and swapping the parameters controlling the robot response to darkness with respect to those measured for cockroaches. Given the choice between a dark and a light shelter, robots were able to induce a change of the global pattern by inverting the collective shelter preference. Under these conditions, the shelter less preferred by the cockroaches (i.e. the lighter one) was selected by mixed groups in 61% of the trials compared to only 27% of the trials done without robots. Despite the individual preference of robots for lighter shelters, they were socially driven by the cockroaches into the darker shelter in 39% of the trials (Fig. 3a). These results are explained by the non-linear mechanism governing the self-organised choice as shown by stochastic simulation of the model. In some trials, the choice was induced by the robots and in others by the cockroaches. The robots did not act as a mere attractant but were involved in the decision-making mechanism as if they were cockroaches.

These experimental results demonstrate the existence of shared and controlled collective actions between machines and animals. This systems biology-based approach involves two novelties. First, technically, we introduce lures able to perceive animal response and able to respond to it. The robots were designed to interact and to collaborate autonomously both with the animals and with one another. Second, conceptually, we exploit the non-linear dynamical properties of regulatory feedbacks to introduce a form of control that can require only a small number of social lures. Possible

ways to identify individual behavioural algorithms could consist in replacing some animals within a group by robots or other artificial devices and in comparing collective responses in “mixed” and “natural” groups. In a synthetic manner, artificial agents such as robots or networks of sensors and actuators could also be used to introduce new regulatory feedback loops at the social level inducing new patterns of collective behaviour. They could also be used to test hypotheses about the origin of cooperation among group members. This work could be extended to vertebrates taking into account specific forms of communication and interaction. Animal societies could be one of the first biological systems where autonomous artefacts cooperate with living individuals to solve problems.

Methods

Prototyping the robot and experiments with cockroaches and mixed groups required about 600 3-hour trials. Experiments were performed with *Periplaneta americana* cockroaches. Cockroaches were bred in large cages with water and dog food pellets provided *ad libitum*. The temperature in the breeding room was 298 ± 1 K with a 12h:12h light-dark cycle. Adult males were taken randomly from the breeding cages 48 hours before each trial. Individuals with any external damage were discarded. Each individual was tested only once.

Groups of 16 individuals, including 16 cockroaches or 4 robots plus 12 cockroaches, were given a choice between two shelters in a large circular arena. For each trial, a group was placed in a circular arena delimited by a black polyethylene ring (diameter: 1 m, height: 0.2 m) (Fig. 1). Cockroach escape was prevented by an electric fence placed on the inner lower-side surface of the arena.

The experimental setup was maintained at 293 ± 1 K. The white paper sheet covering the floor of the arena was replaced before each trial to avoid chemical

marking. Lights placed over the centre of the arena produced 355 ± 5 lux at the ground level. The centre of each shelter was 230 mm from the edge of the arena and 30 mm above the ground. A shelter is made of Plexiglas disc (diameter: 150 mm) suspended by nylon threads and covered with red filter (Rosco color filter, E-Colour #019: Fire). One layer of red filter was used to obtain a light shelter (100 ± 5 lux), and two layers for a dark shelter (75 ± 5 lux). Discs were cleaned with denatured alcohol (97.1% of ethanol + 2.9% of ether) between each trial. To avoid bias, the setup was surrounded by an opaque white enclosure to prevent perception of potential external visual landmarks. The angular position of each shelter pair was randomized between replicates.

Before each trial, robots were wrapped with filter paper (Whatman, grade 1) that covered their entire surface except for the sensors. This paper was conditioned with the recognition odour. It was collected by extracting cuticular hydrocarbons²⁹ of adult males in dichloromethane. Each robot was conditioned with 60 μ l of the blend concentrated so that the robot carried the same concentration per cm^2 as live cockroach cuticle (see supplementary). A trial began when cockroaches and robots were placed in the arena. All individual movements were recorded for 3 hours by a video camera (Fire-I Digital camera, Unibrain). The recordings were analysed with a tracking software³⁰ giving the position of each individual every 1/25 s.

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Figure 1. Experimental set-up. (a) Two shelters made of plastic disks covered by red film filter are suspended above the floor of a circular arena. The darkness under the shelter is controlled by the number of layers of red film. Cockroaches aggregate under the shelters. The self-organised collective shelter selection is based on social amplification of resting time²²⁻²⁴. (b) Close-up of one of the shelters chosen as resting site by a mixed group of cockroaches and robots.

Figure 2. Shared collective choice between two identical shelters (30 trials). (a) Shelter selection. Groups of 16 cockroaches (brown bars) selected one of the two shelters. Mixed groups of 12 cockroaches plus 4 robots (yellow bars) presented the same distribution, demonstrating that the mixed groups made the same collective decision as cockroaches alone. The probability of selecting one of the shelters is about 0.5 in accordance with a multi-state dynamics^{22,24}. (b) Fraction of the group present under the shelters (mean +/- s.d.) in relation to time showing that selection has similar dynamics in both types of groups.

Figure 3. Controlled collective choice between dark and light shelters. (a) Groups of cockroaches without robots (brown bars) select the dark shelter in 73% of the trials and the light shelter in 27% of the trials. Mixed groups with robots programmed to prefer the light shelter (yellow bars) select it in 61% of the trials. The robots induce a change of the collective choice by modulating the non-linear collective mechanism. Nevertheless, the dark shelter is still selected in 39% of the trials because the robots also socially respond to the cockroaches. In all selections, robots and cockroaches shared the same shelter. (b) Fraction of the group present under the shelters (mean +/- s.d.) as a function of time showing that the selection has similar dynamics in both types of

groups (dark blue: dark shelter; light blue: light shelter). In red, number of selections out of 30 trials.