

Supplemental Data

Evolutionary Conditions for the Emergence of Communication in Robots

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Supplemental Experimental Procedures

Data Analysis

To compare colony performance between treatments in the simulations, we calculated the average performance of the 100 colonies over the last 50 generations for each of the 20 replicates per treatment. The resulting 20 values per treatment were compared with nonparametric (Kruskal-Wallis and Mann-Whitney) tests because some of the data did not follow a normal distribution (Kolmogorov-Smirnov test).

The signaling strategy s was quantified by estimation of the average frequency of signaling near food F and poison P of the ten robots present in a colony. This was quantified by:

$$s = \frac{1}{10} \sum_{r=1}^{10} \left(\frac{1}{N^F} \sum_{n=1}^{N^F} b_{r,n}^F - \frac{1}{N^P} \sum_{n=1}^{N^P} b_{r,n}^P \right) \quad (1)$$

where N^F represents the total number of cycles spent near the food (i.e., over the paper circle), and N^P represents the total number of cycles spent near the poison, and $b_{r,n}^F$ and $b_{r,n}^P$ represent whether robot r was emitting blue light (a value of 1 if it was and 0 if it was not) at cycle n near the food or poison, respectively. The signaling strategy value s can therefore vary from -1 to 1 , with a value of -1 indicating that robots signaled only when near the poison and a value of 1 indicating that signaling occurred only when near the food. A value of 0 would indicate that robots were not more likely to signal near food or poison.

The tendency b of robots to be attracted by blue light was quantified by the placement of robots at 50 cm from a stationary robot emitting blue light. After ten time steps, we checked the location of the moving robot r relative to its original position, where a decrease in the distance from the signaling robot was counted as

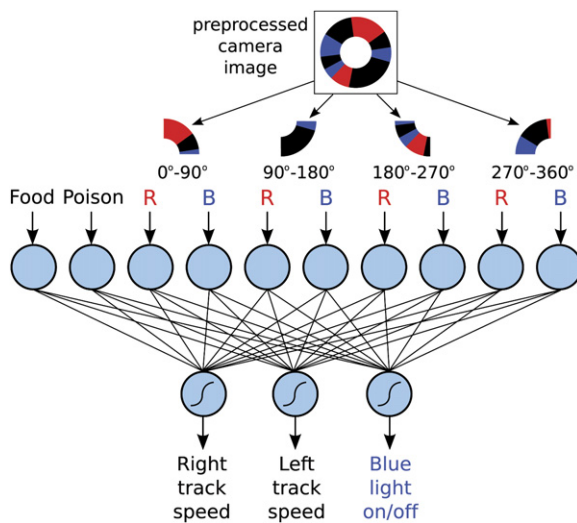


Figure S1. Neural-Network Architecture

The first two input neurons are activated when robots fed on either food or poison. The omnidirectional camera image is preprocessed for filtering out red and blue channels, divided into sections, and input to the neural network as fractions of red or blue in each section (between 0 and 1). Three output neurons with sigmoid, asymptotic activation receive weighted input from the ten input units, which encode the speed of the tracks and whether to emit blue light.

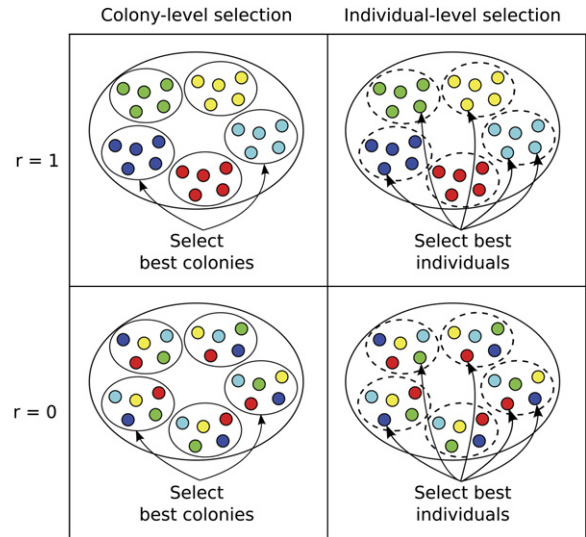


Figure S2. Four Treatments

An illustration of the colony composition and selection regime in the four treatments.

attraction (increment a_r by 1) and an increase in distance was counted as avoidance (increment v_r by 1). The test was run four times for each of the ten robots of a colony, and b was calculated as follows:

$$b = \frac{1}{4 \times 10} \sum_{r=1}^{10} (a_r - v_r), \quad (2)$$

representing an average over the four tests for the ten robots. Therefore, if all robots were repelled by blue light in all tests, the score was -1 ; if they were all attracted, the score was 1 . A score of 0 would indicate that there is no general tendency for the robots to be attracted or repelled by blue light. Both s and b were calculated for the 100 colonies in the population and averaged to produce one value for each of the 20 replicates of the experiment.

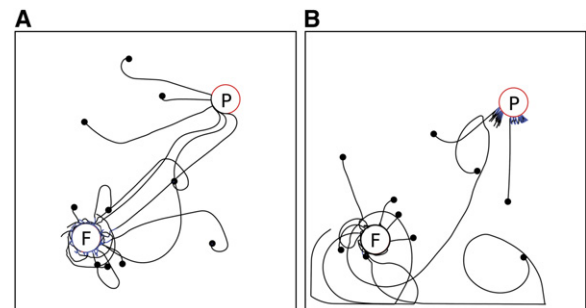


Figure S3. Trajectories and Signaling Strategies

The trajectory of each of the ten robots is shown; the dots represent the starting point of each robot and the blue sections of the lines show when the robots were signaling. (A) shows food-signaling strategy, and (B) shows poison-signaling strategy.