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Patterns of Interactions in Shared Environments

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Abstract

Biological organisms very often share the same environment and also compete for the same resources. There are two main sources of interactions among the organisms. The first comes from the fact that they modify the physical characteristics of the environment and thus affect the behaviour of the other individuals. The second comes from the sensory perception of the other individuals that may be responded in various manners. This research has attempted to study both these aspects in populations of evolved artificial organisms whose nervous system is represented by neural networks. For each environmental condition, two different sets of simulations have been compared, one in which the organisms receive local sensory information only about the food, and one in which they can also perceive the presence of other individuals in their own surroundings. The criterion for survival and reproduction has been always the number of food tokens eaten during the life span. An important result of this set of simulations is that shared environments introduce new complexities that require a new level of analysis. The population emerges as an entity with its own behaviour and dynamics. Furthermore, it has been seen that in certain environmental conditions the organisms make use of the additional information about the presence of other organisms and display a "hostile" behaviour by avoiding the other individuals.

Introduction

The research being reported in this paper focuses on the emergent patterns of interactions among artificial organisms that share the same environment. Specifically, I have addressed collective foraging dynamics and the question whether the sensory information about the other organisms can be exploited even though it is not directly connected with the fitness of the individuals. This laboratory study has been carried out in various environmental conditions.

Ecosystems are the fundamental units of evolution and provide the only viable mean of studying the emergent behavioural capabilities of all living organisms. An ecosystem consists of a physical environment and of a population of organisms living in it. This has many implications. Behaviour is more than the expression of a number of neurons wired up in some way and embedded in a body; it is rather the set of interactions between an organism and its environment. The organisms become part of the physical characteristics of the environment and must be taken into proper consideration. The organisms act on the environment in order to survive, they change its physical appearance both at a local and at the global level, and they are affected by this modifications. A very common feature of all ecosytems is that many organisms (belonging to the same or to a different population) share the same ecological resources. Very often it is the case that much of the behaviour is dedicated to the interactions among the organisms. Only recently experimental studies have paid attention to this important aspect (see, e.g., Piazzalunga & Parisi, 1992). The degree of interaction among organisms can vary from purely passive indirect reactions (when they exploit the same food sources) to more active attempts to regulate their own behaviour as a consequence of the presence of other individuals. The goal of this research is to reproduce, describe, and understand some of the complex dynamics of a shared environment in relation to the physical characteristics of the environment and to the sensory system of the organisms.

The Ecosystem

The nervous system of the organisms studied is represented by artificial neural networks. The emergent phenomena have been obtained by evolving populations of organisms in various environments characterised by a different distribution of food tokens. For each environmental condition, two different sets of simulations have been compared, one in which the organisms receive local sensory information only about the food, and one in which they can also perceive the presence of other individuals in their own surroundings. The criterion for survival and reproduction has been always the number of food tokens eaten during the life span. Traditional Genetic Algorithms (Holland, 1975; Goldberg, 1989) have been applied on the genetic strings of the organisms which code the weight values of each synaptic connection with floating point precision. Biased mutation, two-cuts node-crossover (Montana & Davis, 1989), and a sort of dominance mask controlling the expression of the synapses in the phenotype have been repetitively applied on the nervous systems of selected organisms starting from an initial population of neural networks with random synaptic weight values (more details are given in a companion paper, Floreano, 1993). The nervous system of each organism is simulated by a three-layer neural network. The input layer receives sensory information from the receptors attached to the body of the organisms. There are two types of receptor. One type is activated by the presence of food, the other one from the presence of other individuals. Each set of receptors is organised as a matrix centred at the organism location. The activation of the receptors is filtered by a log transform

$$\frac{\mathrm{Log}\,(x + 1)}{\mathrm{Log}\,(\max x)}$$

that normalises the activation in continuous values between 0 and 1 and compresses the high values of the physical stimulation. In those simulations where the organisms cannot perceive the other individuals, the activation of the organisms receptors is set to 0. The hidden and output layers are composed of sigmoidal units. The output units code four possible motor actions: go forward, turn left, turn right, and stay still. When the organism turns on itself also the receptors attached to its body receive new sensory information (except for the receptor centred at the body location). A set of context units (Elman, 1990) has been added to allow the network to extract the temporal structure needed to co-ordinate the actions[1].

The environment is a thoroidal grid of 128*128 cells. Each cell can contain one or more food tokens and/or one or more organisms. In each simulation there are 128 organisms living in the same environment. When an organism reaches a location with food, a food token is automatically eaten at each time step. The number of food tokens at a given location decreases more rapidly if there is more than one organism feeding at once. Also, if there are more organisms than food tokens at a certain location, the total amount of food is divided in equal parts among them. In all the simulations reported below all the organisms always start their life in the same cell and facing north.

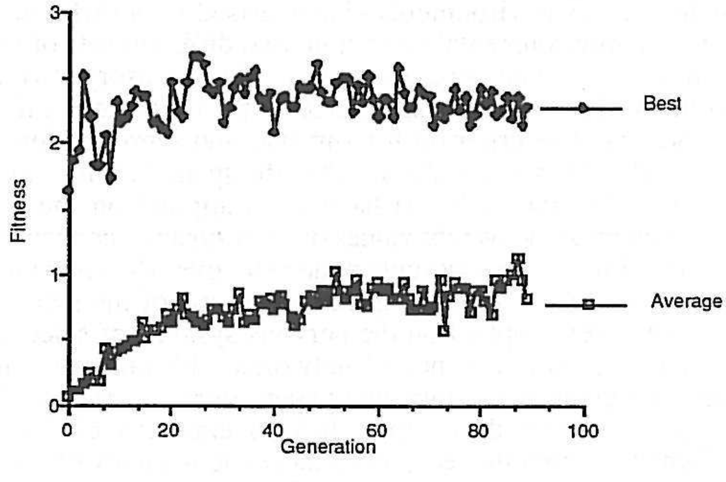
The program has been developed in C* (the parallel version of C created by Thinking Machines Corporation) and all the simulations have been run on a 16,384 processors Connection Machine (CM-200).

The Simulations

Given the stochastic nature of Genetic Algorithms, all the data reported below are the average over three different runs (unless otherwise stated) with different initial random synaptic weights and new random food distribution at each generation.

Dynamics of a shared environment

A first set of simulations has been performed in an environment where the food tokens are distributed in food sources. A food source occupies a single cell and it contains 100 food tokens. The food sources are randomly scattered around the environment with a certain density. In order to discover the aspects related to the shared environment itself, the receptors for the organisms are turned off.



Graph 1. Comparison between the fitness of the best individual and the average fitness of the whole population along the evolutionary process. 1 point of fitness here means 100 food tokens eaten.

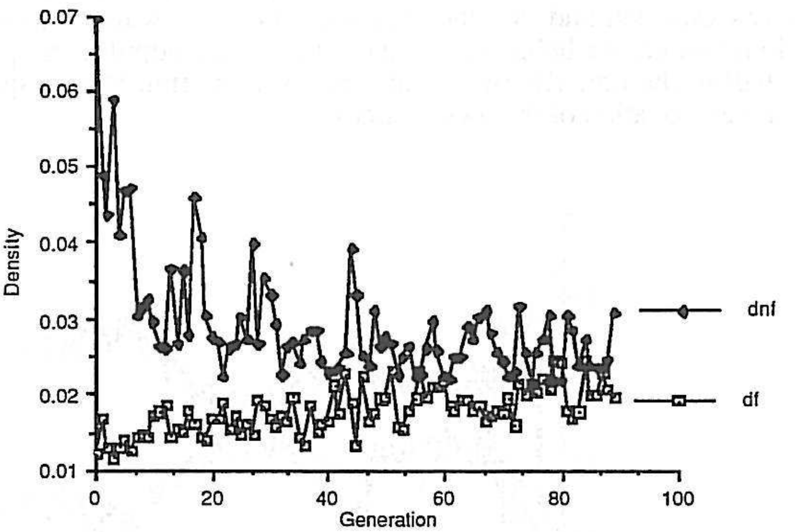
The first important result, that differentiates the "shared environment" from the "single-organism environment" simulations, is that the performance of the best

[1] Some preliminary simulations have shown a decrement in performance when the context units are not used (Floreano, 1992).

individual is not any longer an informative index of evolutionary progress[2]. The performance of the best individuals may not increase, or it may even decrease, along generations while the average fitness of the population increases (Graph 1). In fact, a higher number of organisms developing better food-approaching strategies may reduce the quantity of food that is available for the best organism. Furthermore, in this environment the high performances reported by the best organisms of the first generations do not imply that they have developed efficient behavioural strategies. They may simply happen to be close to a food source. The global dynamics of the population can be described at a first approximation by measuring the density of individuals on the occupied cells; this measure can be further detailed by separating the locations with food from the locations without food. The density df_g of organisms on food locations at generation g is given by

$$df_g = \frac{\sum_{i}^{s} \sum_{j}^{cf} \left(\frac{n_j}{cf} \right)}{s}$$

where cf is the number of cells occupied by food and organisms, and n_j is the corresponding number of organisms on the jth cell with food. The density of organisms on cells without food (dnf_g) can be computed in the same fashion by considering the cells with organisms, but without food (cnf). These measures give information about the food-reaching abilities of the population. While the number of organisms on empty locations decreases along generations, the number of organisms on the food sources slowly increases (Graph 2). This means that the organisms increase their ability to approach a food source in their visual field.



Graph 2. The average density of organisms on food locations (df) and on empty locations (dnf) at each generation.

As it can be expected from the initial conditions (all the organisms are born in the same cell, facing the same direction), dispersion seems to be the global strategy used by the population to achieve higher fitness. The dispersion is given by an initial change in orientation at the beginning of the life (which is known to the neural networks because it is the only case when the context unit activations are null) and by the presence of food sources encountered during life.

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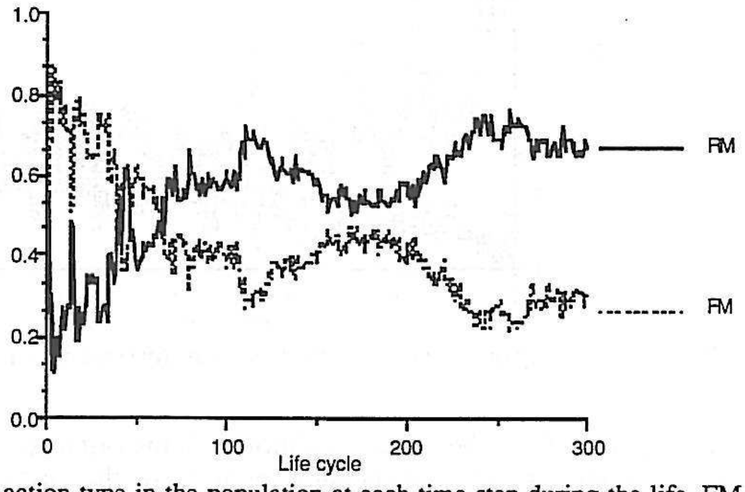
2 See also [Piazzalunga & Parisi, 1992] for analogous conclusions.

Once that a population of such organisms has been evolved, it can be tested in a new environment and the same measures described above can be taken during the life of the organisms. When one compares the global fitness of the population (Graph 3) with other behavioural measures (Graph 4), a rhythmic global foraging pattern is observed.

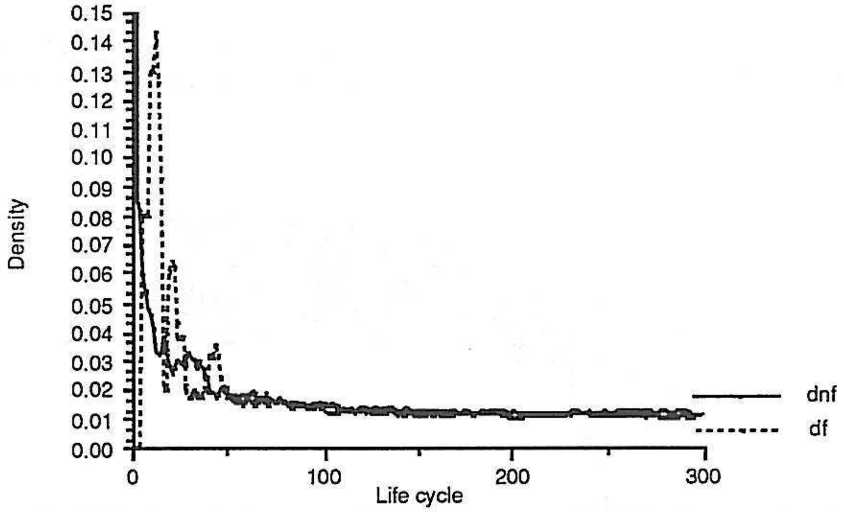
Graph 3. Average fitness of the population (90th generation) at each time step during the life. The data refer to a single simulation.

The rhythmic patterns in the two measures are in perfect synchrony. The average fitness increases when the percentage of turns increases and the percentage of forward moves decreases. The hypothesis that the organisms feed by continuously turning on a food source is confirmed. The decrement of the fitness and of the turns is accompanied by an increment of forward moves. This means that the food sources found are gradually exhausted and that the organisms move forward to look for new sources. This global emergent behaviour at the level of the population appears again in the second half of the life. The two highest peaks in the fitness correspond to the point of maximum exploitation of the food sources.



Graph 4. Percentage of action type in the population at each time step during the life. FM=Forward Move. RM=Right Move. Data for Left Move and Stay Still are not plotted because constantly close to 0. The data refer to a single simulation.

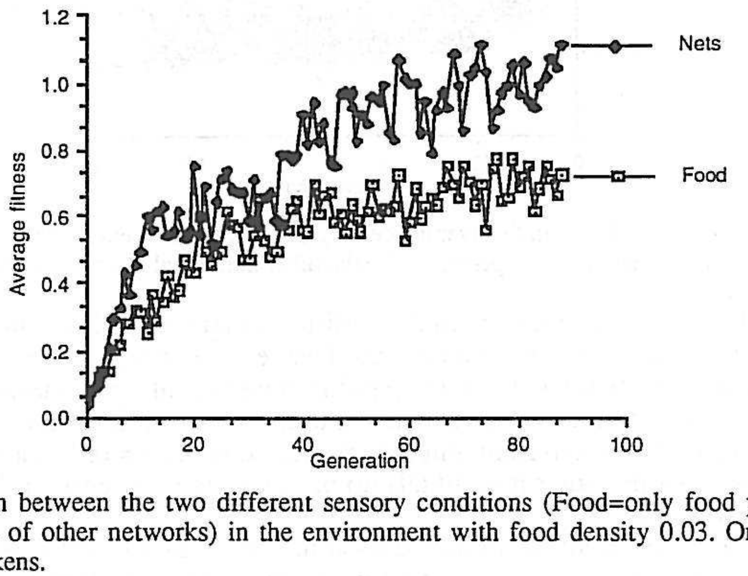
The initial 70 (or so) steps correspond to the outward spreading from the centre of the environment before the ecosystem settles down in its oscillatory behaviour, as it can be seen by the distribution during life of organisms in the empty cells and in cells with a food source (Graph 5).



Graph 5. Density of individuals on food sources (df) and on empty cells (dnf). One organism is 0.01 on the y axis. The data refer to a single simulation.

Perceiving the others

In a second set of simulations two sensory conditions are compared: in one (as in the simulations described above) the organisms can perceive only the food, in the other they can perceive also the other organisms. The two sensory conditions have been tested in 4 environments with different density of food sources, namely 0.01, 0.03, 0.05, and 0.07. In both the sensory conditions the average fitness of the population is a linear function of the food density: as more food sources are distributed in the environment, the higher is the average fitness of the organisms during the evolutionary process. However, when the food sources occupy 3% of the cells in the environment, the organisms take advantage of the additional sensory information about the other individuals (Graph 6). Only in this case, their average performance differs (it is higher) from the other sensory condition.

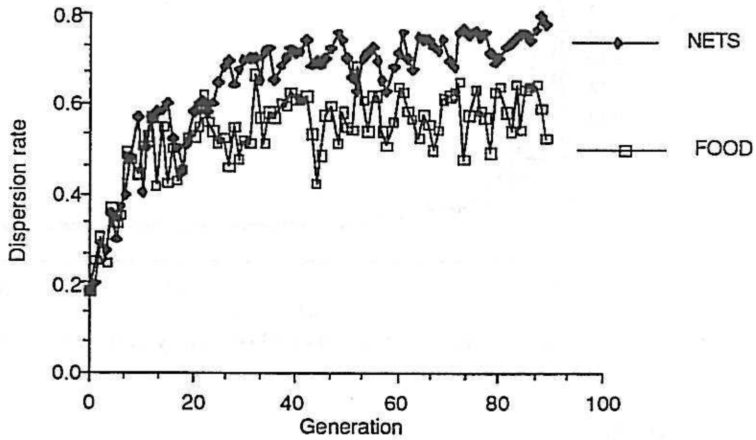


Graph 6. Comparison between the two different sensory conditions (Food=only food perception; Nets=also perception of other networks) in the environment with food density 0.03. One point of fitness is 100 food tokens.

This improvement is achieved by a higher dispersion rate D_g, measured as

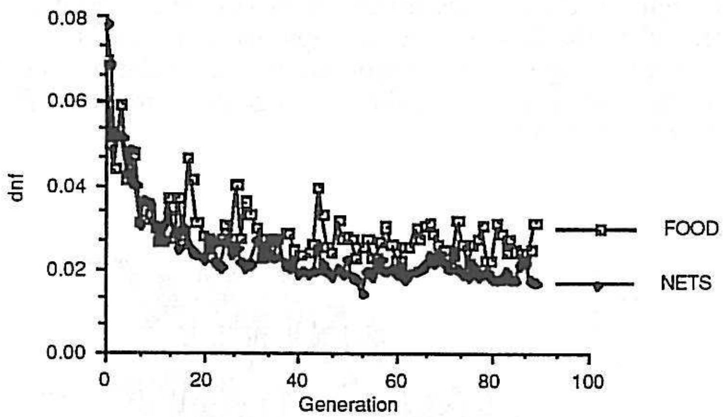
$$D_g = \frac{\sum_{i=0}^{s}\left(\frac{c_i}{p}\right)}{s}$$

where c_i is the number of cells occupied by one or more organisms at time step i; s is the length of the life time, and p is the number of individuals in the population (Graph 7).



Graph 7. Comparison between dispersion rate in the case when the organisms can perceive only the food (FOOD) and when they can perceive also the other individuals (NETS) (food density = 0.03).

Higher dispersion is accompanied by a lower density on the empty cells when the organisms can perceive the other individuals in their surroundings (Graph 8).



Graph 8. Comparison between the average density of organisms on empty cells when they can perceive only the food and when they can perceive also the other individuals (food density = 0.03).

In all the other environmental conditions there have been no differences in the performance and behavioural measures. Hence, it seems that when the environment is very sparse (density 0.01) there is no point in taking into considerations what the other organisms do; in that case, the best thing to do is to search for any food source. On the other hand, when the environment is very rich (density >= 0.05), again there is no need to observe what the other individuals do because there are enough food sources to feed all the organisms.

In another set of simulations the food has been distributed in gaussian clusters. At each generation the environment contains three new randomly-positioned gaussian clusters of food. Each cluster is formed of 256 food tokens (Figure 1).

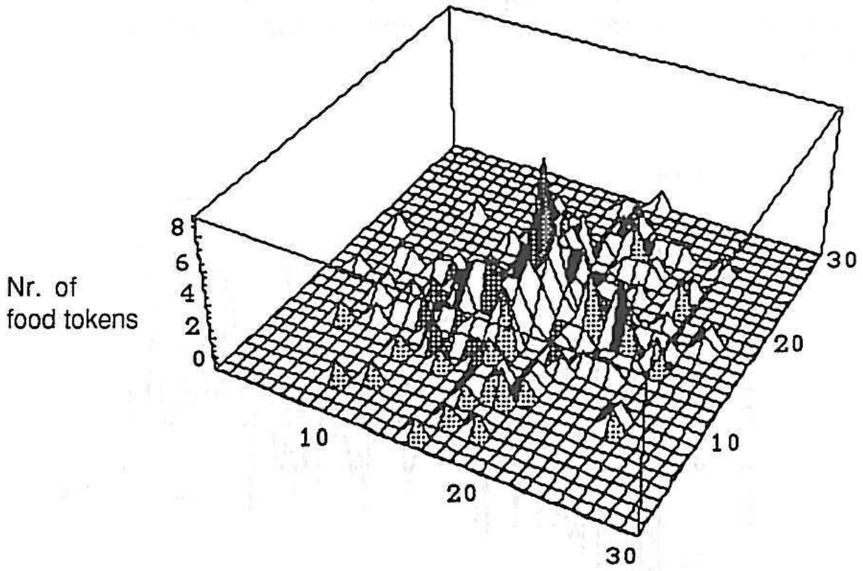
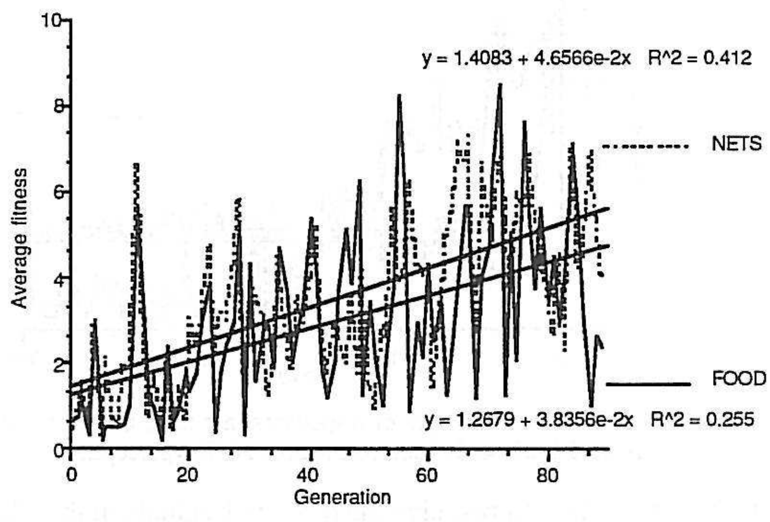


Figure 1. Zoom on a gaussian cluster of food tokens. The z axis shows the number of food tokens in a single cell.

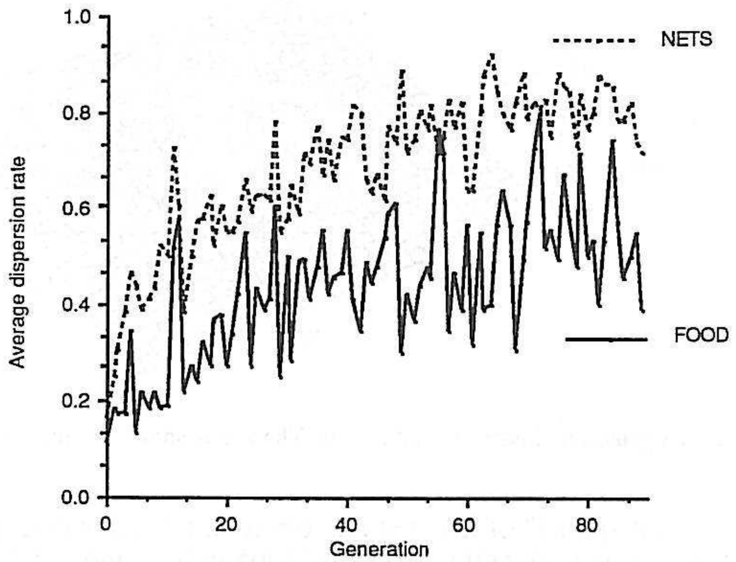
In addition, a "light spread" of isolated random food tokens is distributed all over the environment by giving each cell probability 0.005 to host another food token. Hence, there are approximately 850 food tokens in the environment (much less than 49,152 as in the case when 3% of the cells where occupied by food sources of 100 tokens each). If, during the life of the organisms, the total amount of food tokens becomes less than 0.3% of the number of cells (i.e., less than 50), a new gaussian cluster is randomly placed in the environment. The population size has been reduced to 64 organisms, but the number of selected individuals that are allowed to have offspring has been kept constant in order to keep a high exploration rate for the Genetic Algorithm.

Once again, the organisms that can perceive also the other individuals report a higher average fitness as compared to the simulations where the organisms can perceive only the food (Graph 9). However, the advantage is very small and the average performance of the population is very oscillatory in both the sensory conditions.



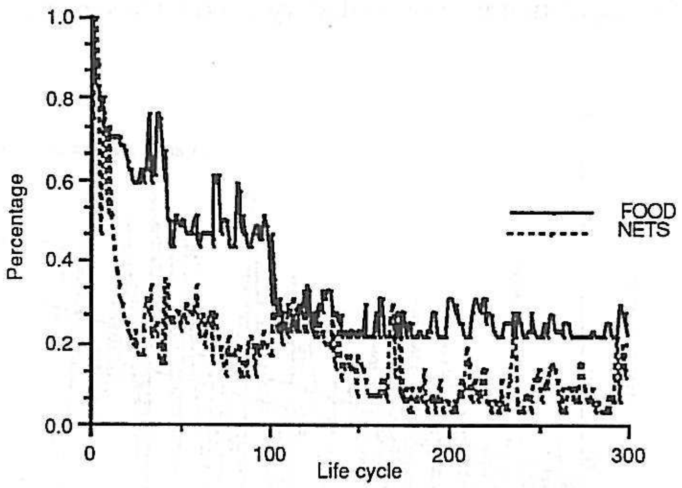
Graph 9. Comparison between the average fitness of organisms evolved in the two sensory conditions. FOOD=only food perception. NETS=also perception of the other individuals.

By looking at the data on the dispersion rate, it seems that the organisms make use of the additional sensory information to keep further apart from each other in this environment too (Graph 10).



Graph 10. Comparison between the average dispersion rate of organisms evolved in the two sensory conditions. FOOD=only food perception. NETS=also perception of the other individuals.

In order to understand the dynamics of the ecosystems, for each sensory condition the organisms of the last generation have been put in a new environment and let free to move as during the evolutionary process. A new statistic concerning the percentage of individuals with one or more organisms in their local area (the area covered by the receptors) has been collected at each time step (Graph 11).



Graph 11. Comparison of the percentages of organisms that have one or more individuals in the are covered by their receptors. FOOD=only food perception. NETS=perception also of the other organisms.

When the organisms can perceive the other individuals in their local area they move away. Instead, as already mentioned above, the dispersion of the individuals that can perceive only the food is given only by the interaction with the food tokens encountered and the initial dispersal in the four cardinal directions. A more qualitative impression of what happens is gained by looking at a snap-shot of the environment from the top

(Figure 2) at the 20th cycle of life in both the sensory conditions. The organisms that perceive only the food move in groups (the central group spreads outwards later and some few organisms will never move) that break apart when they come in contact with the food tokens. On the other hand, the organisms with both the receptors functioning spread apart also when there are not food tokens, but only other organisms in their local area.

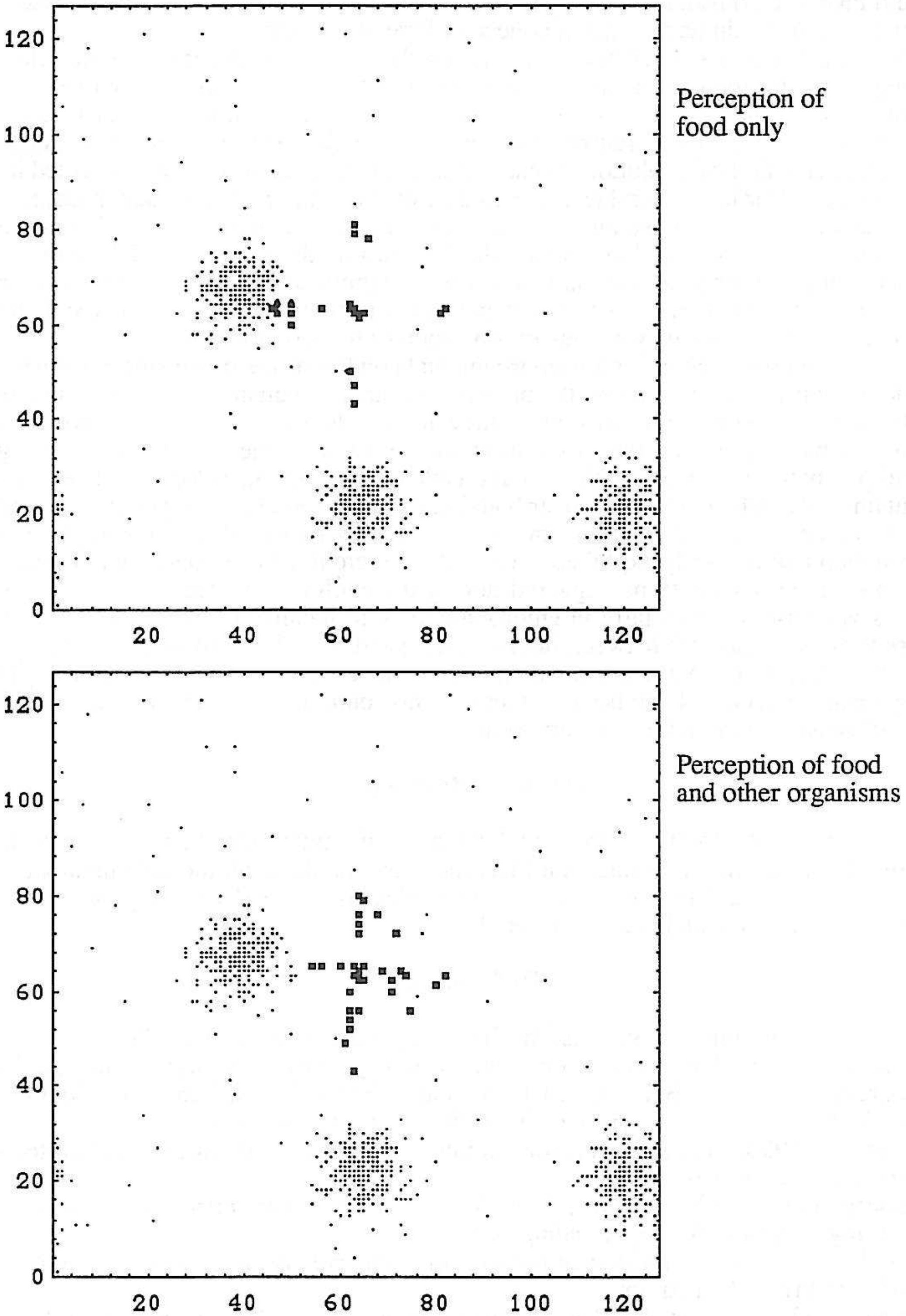


Figure 2. Snap-shot of the environment taken at the 20th life cycle in the two sensory conditions. The thick dots are the organisms; each dot represents one or more organisms. The thin dots are the food tokens; each dot represents one or more food tokens. The population is composed of 64 individuals.

Discussion

The first result of this set of simulations is that shared environments introduce new complexities that require a new level of analysis. The population emerges as an entity with its own behaviour and dynamics. The observation of a single individual does not carry information about the evolution and the dynamics of the system. The measures should take into consideration the whole population. When the analysis is focused on the population, rhythmic patterns of collective foraging emerge.

In the simulations described in this research, maximum dispersion is the global strategy used by the organisms to maximise their fitness. This is mainly due to the competition for the same food resources and to the very local information provided by their receptors. When the organisms can perceive only the food, the need for dispersion is partially satisfied by evolution. In each generation the organisms can be divided in 5 lineages after their behavioural response to the initial conditions of life (that is identified as the only moment when the memory units are not active). Despite the fact that they all start from the same cell and all face north, they turn on themselves until 4 groups are formed that face each a cardinal direction. The fifth group stays idle for some steps, and then it also spreads apart. This initial dispersion is further enhanced by the local turns of the individuals when they encounter food sources (or food tokens).

It has been seen that in certain environmental conditions the organisms make use of the additional information about the presence of other organisms. They use it to keep further apart from each other also when they are not close to the food: this gives them higher probability to find their own food source. Despite the fact that this strategy would pay better in a world with scattered isolated food tokens (Floreano, 1993), it is maintained also when the food is distributed in compact sources or in gaussian clusters. The receptors of the other organisms provide a very powerful -even though local-information that is readily exploited to control the searching behaviour. This avoidance behaviour is very easy to be triggered during the evolutionary process, but it is not always very useful, especially in environments with localized few clusters of food. There must be a trade-off between flock-foraging and individual-foraging; however, it is very unlikely to obtain the development of true co-operative behaviour in the ecosystems described above because there are no communication means and both the types of sensory information are very local.

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