Social aggregations in evolving neural networks

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Abstract. Sociality is related to space because it can only develop inside spatial aggregations of individuals that can physically interact with each other. We present simulations of populations of simple organisms living together in the same environment. The simulations use genetic algorithms to model the evolution of neural networks behaving in the environment. Spatial aggregations emerge evolutionarily (a) as an indirect by-product of the spatial distribution of resources in the environment and of the actions of the organisms on these resources, (b) as an advantageous adaptation of living inside social groups that function as "information centers", (c) as a pre-condition for learning from others.

Space and sociality

How is sociality related to space? Since social interactions ultimately are physical interactions, sociality can only develop within the boundaries of possible physical cause-effect relations. An individual can only interact socially with another individual if the first individual can physically affect and be affected by (e.g. perceive and be perceived by) the second individual. This imposes a requirement on a group of individuals if these individuals must interact socially and develop some form of sociality among them: the individuals must live sufficiently close together in space. Therefore, the spatial distribution of a set of individuals is a crucial factor for the development of sociality. Being near one another in space is necessary for interacting socially and is a favourable pre-condition for developing various forms of sociality.

In human beings this spatial requirement for sociality is attenuated for two reasons. First, human beings have developed technical means for interacting at a distance. Social interaction still requires physical interaction but communication technologies have greatly overcome the spatial and temporal limitations of face-to-face interaction. Second, human beings live a mental life in addition to a physical life. They think, remember, imagine, desire, love, hate, etc., in addition to interacting physically with the external environment. Hence, their sociality can be incorporated and expressed in their mental life (e.g. in thinking of another person) and not only in their social/physical interactions.

And, of course, space is less critical for conducting a mental life, including a social mental life, than for direct physical interaction with others.

These qualifications notwithstanding, it would appear that even in the case of human sociality physical proximity remains an important factor. This applies to all kinds of humans societies although it is especially true for "primitive" societies [8]. But an understanding of more technically advanced societies requires a reconstruction of their development from earlier societies where space was a crucial determinant of sociality.

Since physical proximity is a pre-condition for the development of sociality it is interesting to investigate what factors can cause a tendency for a certain number of individuals to live together or to occasionally gather together in the same place at the same time. There appear to be a large variety of factors that can cause organisms to aggregate. In some cases organisms can develop a tendency to stay together because social aggregation can procure some benefits to the individuals who aggregate with respect to individuals which live in isolation. In other cases, social aggregation is a by-product of other factors but it may have no utility by itself or it can even have costs associated with it. In all cases, provided that a number of different individuals have a tendency to remain in proximity to one another, spatial proximity can be a favourable condition for the development of social behaviors and of social structure.

In another paper [9] we have discussed how genetically related individuals can evolutionarily develop a tendency to live together and to form a social group. In the research discussed in that paper the social group was a family and the ultimate factor that causes its existence was biological reproduction. More specifically, we examined the role of altruism directed toward kin and attachment behavior in the emergence of the social groups that are called 'families'.

In the present paper we examine three factors that can cause the emergence of spatial aggregations of individuals: the physical distribution of inanimate resources in the environment, the role of social aggregations as "information centers", and the utility of learning from others. Unlike the preceding paper, this paper is not concerned with genetically related individuals and with families but, with a single exception (cf. the next Section), discusses causes of spatial aggregation which are independent from biological reproduction.

As in the preceding work, we will examine the role of these three factors by simulating the evolution of populations of very simple organisms that live in an environment [10]. Each organism is modeled by a neural network that receives some encoding of environmental information as (sensory) input and generates an encoding of some movement of the organism in the environment as (motor) output. An algorithm controls the propagation of activation through the network from input to output, executes the motor action, and computes the next sensory input for the network.

The population evolves using a genetic algorithm [5]. Individuals reproduce on the basis of some criterion of fitness, i.e. they generate copies of their matrices of connection weights with the addition of some random mutations. This causes the occurrence of evolutionary change from one generation to the next. What emerges evolutionarily is a genetically inherited tendency to move in the environment in such a way that different individuals tend to aggregate, i.e. to form spatially defined social groups. The paper examines the role of various factors that can determine the emergence of these group-forming behaviors.

2. Social aggregations as a by-product of the distribution of inanimate resources in the environment

The physical distribution of resources in the environment can be a factor that causes the emergence of social aggregations. If the resources are clustered, i.e. are more dense in some local environments than in others (or even absent in others), the behavior of going to where the resources are located will inevitably have as its unintended consequence the formation of spatial aggregations of individuals [2,16].

Imagine a population of simple organisms that live in an environment where food elements are initially evenly (randomly) distributed but are periodically (say, seasonally) reintroduced in such a way that food elements tend to form food clusters separated by more or less 'desert' zones. Each organism perceives only the single nearest food element provided the food element is within a given distance from the organism (conspecifics are not perceived) and it reacts by generating a motor action that allows the individual to turn or to move forward in its facing direction. The organisms reproduce on the basis of a criterion of fitness which privileges individuals that eat more food than other individuals. Hence, successive generations of these organisms gradually evolve an ability to approach the food elements and to eat them. (For a more detailed description of these simulations, cf. [11]).

Since food elements tend to disappear from the environment because they are eaten, they are periodically replaced by new food elements. The new food elements are not randomly distributed but they tend to "grow" in clusters. Hence, there will be a tendency for the organisms to move in the environment in such a way that they converge to locations where food is more dense. The emergence of these social aggregations and the history of colonization of the various food clusters present in the environment are graphically shown in Figure 1.

Notice that although genetic relatedness is not the primary focus in these simulations it still may play some role because we are working with biological propulations, that is, with sets of individuals that are related because of genetic descent. The link between genetic relatedness and the social aggregations observed in our simulations (cf. Figure 1) is constituted by the fact that when offspring are born they are initially placed in the environment near their parent. (Reproduction is agamic, i.e. with a single parent, in all our simulations.) Since both parent and offspring can independently displace themselves in the environment spatial dispersal may occur subsequently. But there is an initial bias toward the formation of spatial aggregations of genetically related individuals ('families') - and the clustering of food will have a tendency to maintain these social aggregations of genetically related individuals.

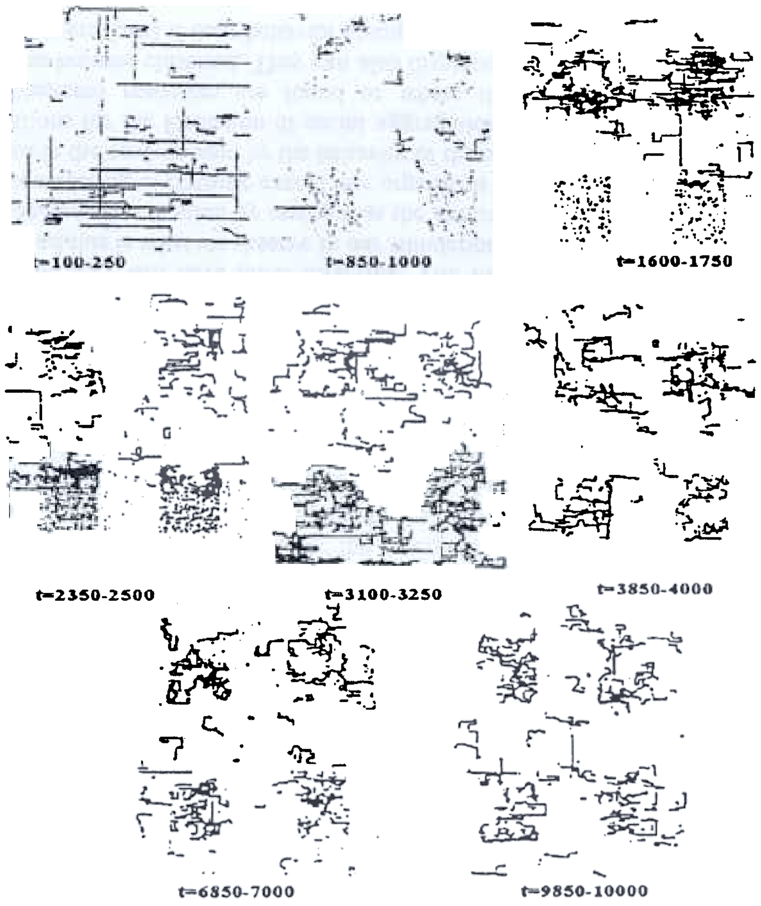

Figure 1. Seven successive snapshots of the spatial distribution of a population of organisms in an environment in which food tends to be clustered in four areas. Little dots represent individual food elements. Lines represent the trajectories of individual organisms during 150 time units. The organisms are initially evenly spread in the entire environment because food clusters have not formed yet. Then, they colonize first the two nothern areas and, later on, the two southern areas. Food clusters create social aggregations of organisms.

This has a number of consequences. Since genetically related individuals tend to behave in similar ways (because due to genetic inheritance they have similar connection weights), we observe in our simulations the emergence of spatially aggregated groups of individuals that tend to behave in similar ways. This similarity of behavior can be a significant pre-condition for the emergence of some particular

forms of sociality. Furthermore, geographical isolation (due to the fact that food clusters may be separated by 'desert' zones that are hard to traverse without risking extinction) can cause behavioral divergence. Distinct food clusters tend to host social aggregations of genetically related individuals which exhibit behaviors that are similar locally but different from the behavior of individuals in other social aggregations. In other words, we see the emergence of distinct ethologies. (We cannot speak of 'cultures' here because behaviors are genetically inherited. For culturally transmitted behaviors, cf. Section 4.)

These simulations show that social aggregations can be a result of the geographical distribution of resources. Individuals aggregate because they are attracted by clustered food. But nonhomogeneous distributions of organisms in the environment and the formation of social aggregations can also occur in environments where food is evenly distributed. This results from the actions of the organisms themselves on the environment.

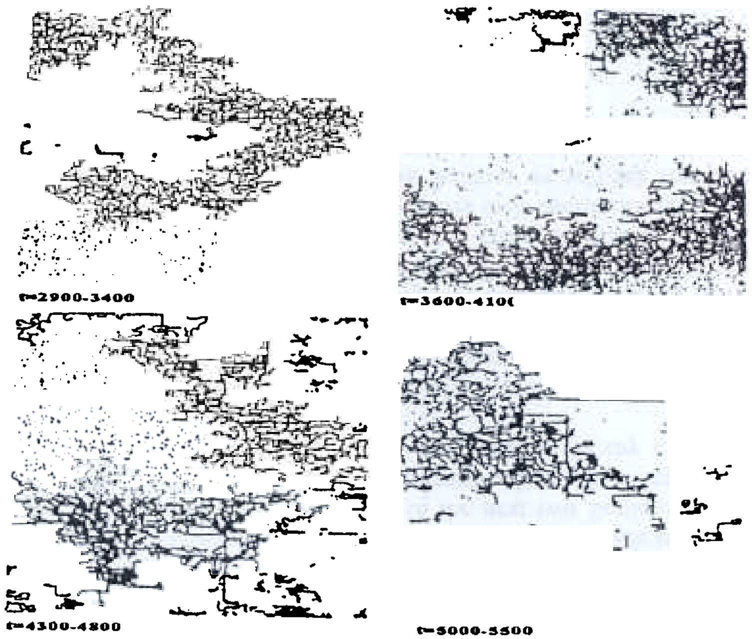

Figure 2. Spatial distribution of a population of organisms in an environment with evenly distributed food elements. Four successive temporal snapshots are shown which demonstrate cyclic migratory waves from center to periphery and then back from periphery to center.

Imagine another environment where food is always evenly distributed. There are no food clusters. However, since the food is eaten by the organisms, the action of the organisms (eating) can create zones where there is less food than in other zones. Therefore, food can become clustered because of the action of the organisms.

The results depend of the food reintroduction rate. If food is periodically and evenly reintroduced at short time intervals, the population of organisms keeps on being spread evenly in the environment and there are no social aggregations. However, if food reintroduction is at longer time intervals, then the action of the organisms on the environment changes the environment in ways that lead to particular patterns of occupancy of the territory on the part of the organisms.

What is typically observed are oscillatory migratory waves that cause the population of organisms to collectively move away from a particular centrally located zone in all directions, reach the periphery of the environment (the organisms can go outside the environment but there is no food outside), and then return to the centrally located zone. (Cf. Figure 2.) This migratory cycle can be repeated a certain number of times. This happens because the particular food reintroduction rate and the effects of the eating behavior of the organisms (disappearence of food in densely inhabitated areas) create the conditions for collective displacements of the entire population. Some densely inhabitated areas are depleted of food and the population is collectively attracted by neighbouring areas where there is plenty of food.

If food is reintroduced at even longer time intervals, the population may become extinct because food is not reintroduced soon enough to reintegrate the food eaten. The population may be unable to traverse 'desert' areas to reach more food-rich areas - and it becomes extinct.

These simulations show that not only the independent structure of the environment (clustered resources) but also the action of the organisms on the environment can create conditions for the emergence of social aggregations and of collective displacements in the environment. In these conditions too, genetic factors can interact with social and environmental factors. An individual can eat many food elements because it has genetically inherited a high level of food finding ability. Therefore, it generates many offspring. Since the offspring are initially placed near its parent the local environment becomes densely inhabitated by individuals (the individual's offspring) which are very good at finding food (the offspring resemble their parent). This introduces a stabilizing mechanism. These individuals (both parent and offspring) will eat less food because less food is locally available (since it is eaten) and they will have fewer offspring. The way out from this dilemma is to migrate - and this is what we observe in our simulations.

We conclude this Section by saying that the nature of the inanimate environment (we are considering everything except our organisms as inanimate) and the changes introduced in the environment by the behavior of the organisms themselves can create the conditions for the formation of social aggregations. Organisms aggregate where needed clustered resources are found or where their own behavior causes the resources to become clustered. They can also displace themselves in the environment in groups (migrations) if their behavior changes the environment in ways that require

such collective migrations. Genetic factors interact with these social and environmental factors in determining the spatial distribution of organisms in the environment.

In the simulations described in this Section there is no direct social interaction among organisms. An individual perceives the location of the nearest food element (provided the food is not too far away) but is does not perceive its conspecifics. The interaction among organisms is indirect, through the inanimate environment. An organism can change the environment of another individual by eating the food present in the shared local environment and this can have an effect on (the behavior of) the other organism (for example, the other organism can migrate). (On the emergence of complex behaviors in populations of individuals which influence each other through the environment, cf. [1,4,15].) In the next two Sections we will see simulations in which organisms perceive their conspecifics and therefore they can actively tend to remain in proximity to their conspecifics, thereby creating social aggregations.

Another property of the social aggregations of the present Section is that these aggregations are an indirect by-product of the environment but they do not emerge because they have any specific usefulness. On the contrary, in these simulations living too close to other individuals can be disadvantageous because these other individuals by eating the local food can decrease the food available to the individual. Hence, in these conditions, one would expect social dispersal rather than social aggregation. The problem is that these individuals cannot perceive their conspecifics and therefore cannot move away from them. In the next two Sections we will see simulations in which there are benefits (and no costs) for living in social aggregations. Hence, what emerges is an active aggregative behavior.

3. Social groups as "information centers"

The perceptual capacities of an individual organism are limited. For example, in the simulations of the preceding Section an organism could perceive a food element if the food element was located within a given radius from the organism. Otherwise, the organisms did not perceive anything. On the other hand, it would generally be useful for an organism to know about its environment at greater distances than those covered by its senses. The individual could move toward a food zone even if the food zone is not directly perceived at the moment or the individual could go away from a danger even if the danger is not currently perceived.

Ethologists talk about social groups as "information centers" [12]. If individuals live in social groups they can collect more information about the environment than the information they have direct access to through their senses. The social group functions as a center for collecting and distributing information. This is true even if there is no particular organization to serve this information gathering and distributing function but all there is are the normal interindividual interactions. Some interesting environmental feature can be perceived by one individual but not by another individual. If the second individual can perceive the first individual (although it does not perceive the environmental feature), then the second individual can be informed about the environmental feature by observing how the first individual reacts to the feature.

If social groups can function as information centers there may be an evolutionary pressure to evolve a tendency to remain in the vicinity of other individuals in order to obtain this type of benefit of living in a social group. In this case the emergence of social aggregations would be not a by-product of other mechanisms but an actively pursued goal of individual behavior.

Consider the following situation. A population of organisms lives in an environment where a predator can suddenly and unpredictably make its appearence. If an individual finds itself within a given distance from the predator its fitness is decreased. Therefore, when an individual perceives the predator it automatically flies away and it lands on a randomly chosen new location in the environment. However, the predator can be perceived by the individual only at a distance which is smaller than the dangerous distance. Hence, in some circumstances the reproductive chances of an individual may be decreased although the individual is unaware of the predator.

These organisms can perceive their conspecifics. More specifically, when an individual sees another individual that flies away, it reacts by also flying away. This is advantageous from the point of view of avoiding being at a dangerous distance from the predator. The predator can be perceived by individual A but not by individual B, although both A and B are at a dangerous distance from the predator. A flies away. B sees A flying away and it reacts by also flying away. In this manner both A and B can escape from the predator.

The problem is that an individual can perceive another individual only if the other individual is not too far away. In particular, an individual can see a conspecific fly away only if the conspecific is within the same distance from which the individual could see the predator. As a consequence, it is advantageous for an individual to remain in the vicinity of other individuals. If an individual lives inside an aggregation of other individuals it can avoid the predator even in cases where the predator is not directly perceived by the individual. Furthermore, it is advantageous for the individual to live not simply near another single individual but inside a group of conspecifics which should be as large as possible. In this way, the individual would increase its chances of being informed of the presence of the predator from whatever direction the predator could make its appearence.

We have run a set of simulations with a population of organisms that automatically fly away when they perceive a predator and when they perceive a conspecific fly away - both perceptions at the required distance only. These capacities are already wired in in the organisms and not evolved. What is evolved is a tendency to move in the environment in such a way that individual organisms tend to remain in proximity to other organisms. More specifically, what evolves is a tendency to remain at the center of groups of conspecifics which are as large as possible.

The organisms are modeled by neural networks. A network's input units encode a measure of the density of conspecifics in the immediate surroundings of an

individual. More precisely, the local environment around each individual is divided up into four quadrants and the four input units of the network encode the number of conspecifics currently present in each of the four quadrants. The network's output units encode motor actions with which at any given time the individual can displace itself one cell in one of the four directions (N, S, E, and W).

A genetic algorithm is applied to this population of networks. The behavior that evolves is the expected aggregatory behavior. At the end of evolution individuals use the sensory information about the location of conspecifics in the local environment - more precisely, about the direction in which a majority of conspecifics are located - to move in the environment in such a way that they tend to always find themselves at the center of a group of conspecifics. (Cf. Figure 3.)

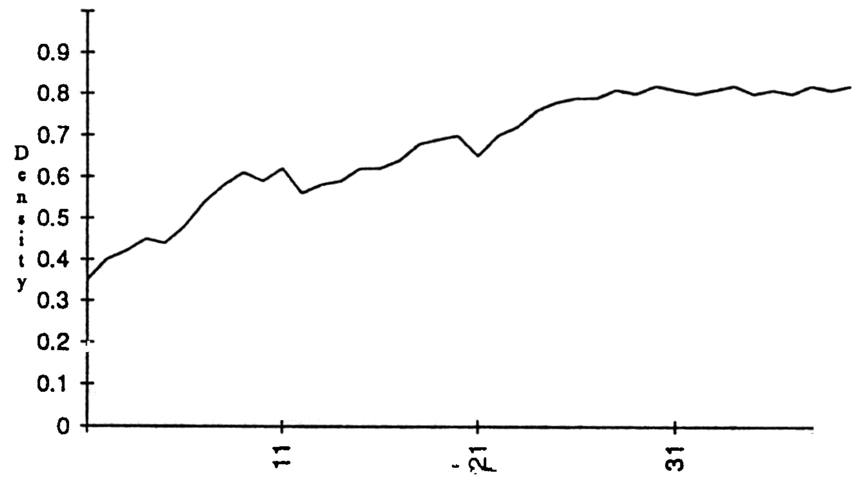

Figure 3. Increasing density of conspecifics around an average individual across evolutionary time

Notice that there are two mechanisms that have the opposite effect of causing a dispersal of these organisms. First, the appearence of a predator causes the dispersal of a social aggregation because individuals fly away in any possible direction (randomly chosen). Second, when an offspring is born it is not located near its parent, as in the simulations of the preceding Section, but is placed in a randomly selected location in the environment. Hence, the genetically inherited tendency to aggregate is always competing with these two dispersal mechanisms to maintain social groups together.

Notice also that the evolved behavior that tends to keep the individual inside a social group is not directly rewarded. There is no direct advantage in being inside a group instead than in isolation. The selective advantage is indirect. By living inside a group of conspecifics an individual can be informed of crucial features of the environment (the presence of a predator) that it would ignore if the individual would live alone, The social group functions as an information center. This is a property of social groups that can explain their emergence and the emergence of behaviors that can guarantee their continued existence.

4. Staying near other individuals in order to learn from them

Conspecifics can not only function as amplifiers of the senses of the individual organism so that the individual can access parts of the environment that would be precluded given the limitations of its senses. Conspecifics can also be sources of learning. An individual can learn to behave in particular ways by imitating how other individuals behave. This, of course, is the mechanism of cultural transmission. Particular behaviors are transmitted from one generation to the next, and also within one and the same generation, because individuals learn from others, i.e. learn to behave as others behave.

A simple neural network model of learning from others (imitation) is the following. In backpropagation learning [13] a neural network learns by being told for each given input what is the correct (expected or desired) output. The network compares this externally provided correct output (called teaching input) with the actual output the network itself has generated in response to the input, and it uses the discrepancy between the two (error) to modify its connection weights in ways that guarantee a better approximation to the correct output in future occasions.

A neural network can be said to imitate another network if the first network (the imitator) learns by using as its teaching input (correct output) the output generated by the other network (the model) in response to the same input [3,7,17]. After a certain number of learning trials the behavior (output) of the imitator will tend to be similar to the behavior (output) of the model. Whatever skill or capacity was incorporated in the behavior of the model, that skill or capacity has been transferred to the imitator.

Now, assume that an imitator can only imitate a model if the imitator is at a distance from the model such as that imitator can perceive the model. This is quite plausible since to use the behavior of the model as its teaching input the imitator must perceive the model's behavior and, therefore, the model itself. From this simple condition it follows that learning from others can be a powerful force for the establishment and maintenance of social groups. Individuals may develop a tendency to live together (permanently or occasionally) because this allows them to learn from others.

Imagine a population of organisms that live in an environment and perceive each other. Individual organisms reproduce as a function of how much they possess a particular ability. (In our case it is the ability to do the Exclusive OR task. Cf. [14].) This ability is not genetically inherited but it is learned during life. Each individual is modeled by a neural network with randomly assigned initial weights and the ability which determines the individual's reproductive chances is learned by using the backpropagation procedure. At any given cycle all networks receive the same input and each network generates its own output. However, the correct teaching input is

provided to a small proportion of randomly selected networks only. The other networks can only learn in that cycle if they can imitate a conspecific. In other words, the output generated by a conspecific (the model) can be used by a network as its teaching input. However, a conspecific can be imitated (used as a model for learning) only if the distance between the imitator and the model is less than a certain maximum distance. Otherwise, a network won't learn anything (no changes in the network's connection wieghts) because no external teaching input is provided to the network.

This implies that the networks which are more likely to reproduce are those that tend to be near other networks that can function as models for imitation. These networks will learn more of the critical ability because in addition to the correct teaching input they happen to receive in some occasions they can still learn from their conspecifics when the correct teaching input is lacking. (Notice that an ability can spread in an entire population even if the correct teaching input is provided only in some cases and in the other cases the networks imitate each other. Cf [3].) Isolated networks can only learn from the unfrequently provided teaching input but in the other occasions they do not learn anything because they don't perceive any conspecific they can imitate.

In addition to the network that learns in the manner described, the "brain" of these organisms includes a second network that allows the organism to displace themselves in the environment. This sensory/motor network encodes the position of the nearest conspcific in its input units and generates in response to this sensory information a decision on how to move in the environment. Unlike the connection weights of the first network which are learned, the connection weights of this network are genetically inherited and are subject to evolution. The reproductive chances of a particular individual are determined not by how the individual moves in the environment, however, but by how much the individual learns during life to do the Exclusive Or task. But, as we have seen, this learning depends on the availability of models to imitate when the correct teaching input is lacking. In turn, the availability of models to imitate depends on an individual's ability to remain in proximity to conspecifics. We conclude that there is a selective pressure to evolve a tendency to move in the environment in a way that leads to the formation of social aggregations.

As a matter of fact, this is what emerges in our simulations. In the early evolutionary stages individual networks displace themselves in the environment more or less haphazardly. But later in evolution we observe the emergence of social aggregations. (Cf. Figure 4.) Individuals are born with a genetically inherited tendency to move toward conspecifics and to remain in proximity to them thereby forming social groups. In this way they can imitate them and learn more of the crucial ability that decides of their reproductive chances. (For a more detailed description of these simulations, cf. [3].)

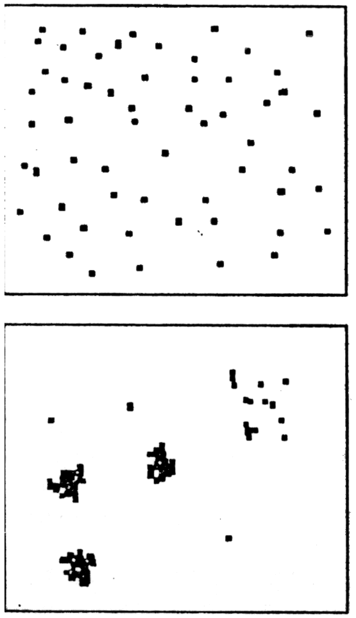

Figure 4. Spatial distribution of a population of organisms that can learn some useful behavior from others only if they are in proximity to others. Individuals are randomly distributed at the beginning of evolution but they aggregate in social groups in later evolutionary stages

5. Summary and conclusions

We have described three sets of simulations that demonstrate how populations of artificial organisms (neural networks) can evolve a tendency to form social aggregations. The factors explaining the emergence of social aggregations can be various. In the first set of simulations social aggregations are the indirect and unintended result of how inanimate resources are geographically distributed in the environment. Spatially clustered resources lead inevitably to social aggregations because many individuals tend to converge to the same locations where the resources can be found. But even in environments with evenly distributed (nonclustered) resources the dynamics of interaction between the organisms and the environment can create nonhomogeneities in resource distribution that can cause social aggregations and collective displacements of the population in the environment (migrations).

In the second and third sets of simulations the organisms can perceive each other and they evolve a tendency to move in the environment in such a way that they reduce their distance from conspecifics and remain in proximity to them. In one case the selective pressure is represented by the utility to be in social groups that function as

"information centers". The sensory abilities of a single individual are limited but by living inside a social group the individual can amplify the range of available environmental information by observing its conspecifics and how they react to environmental information accessible to them but not to itself. In another case the selective pressure is learning from others. If what is learned from others is useful from the point of view of one's reproductive chances but learning from others is only possible if the learner is near its "teacher", then individuals will evolve a tendency to remain in proximity to conspecifics in order to learn from them. In both cases, we observe the evolutionary emergence of social aggregations.

Social aggregations are a form of sociality by themselves but, what is more important, they can represent favourable pre-conditions for the development of various types of social interactions and for the emergence of social structures. A tendency to aggregate socially, whatever the factors that have caused its emergence, functions as a pre-adaptation for the development of more or less complex forms of sociality. However, it is possible that the kind of sociality which emerges inside a particular social aggregation is dependent on the particular factors that have caused that social aggregation to emerge. For this reason it may be important to examine the various types of factors that can originate social aggregations. In the present chapter we have examined three such factors: the distribution of resources in the environment, the advantages of living in social groups that function as "information centers", and the advantages of learning from others. In other work we have already cited [9], we have described simulations that study the emergence of social aggregations in genetically related individuals. Future work will be dedicated to an exploration, via computer simulation, of the social phenomena (communication, social exchange, cooperation, social roles, etc.) that can emerge in individuals that live inside social aggregations rather than in isolation.

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