Social coordination and spatial organization: Steps towards the evolution of communication.

Ezequiel A. Di Paolo
School of Cognitive and Computing Sciences
University of Sussex, BRIGHTON BN1 9QH, U.K.
Fax: 44-1273-671320
`ezequiel@cogs.susx.ac.uk`

Abstract

Traditional characterizations of communication as a biological phenomenon are theoretically criticized, and an alternative understanding is presented in terms of recursive action coordination following works on cybernetics and autopoiesis. As first steps towards a study on the evolution of communication, two sets of computational experiments are presented, one dealing with non-recursive coordination and the other with coordination of recursive actions. In the first one coordinated activity evolves even in cases in which a game-theoretic analysis predicts the contrary. This is explained by studying the spatial organization in the distribution of agents. The second one shows the inappropriateness of the metaphor of communication as an exchange of information.

1 Introduction

The study of communication from an evolutionary perspective has received much attention lately. However, the view of communication traditionally advanced is far from theoretically unified and it is subject to much discussion and potential confusion, (see [17]).

I claim that this confusion is rooted in the way communication has been defined, partially as a consequence of using as primitives the same phenomena to be explained, (for instance, terms like "signal", "information", "reference", etc.). Two preconceptions in particular are disclosed and criticised here, together with their implications for the way the problem has been approached.

An alternative description of the phenomenon that avoids these criticisms is presented in terms of behavioral coordination as described by an observer. In order to support this view two sets of computational experiments were carried out, one dealing with simple (non-recursive) action coordination (presented and analysed in detail in sections 3 and 4) and the other with coordination of recursive (dialogic) action in the absence of hidden relevant information (section 5). The results obtained from these models show how coordinated activity can evolve in circumstances beyond the explanatory scope of the traditional theoretical framework.

The reader will notice that the limitations of game-theory and mathematical modelling appear as an underlying theme in section 3. Although, some conclusions are derived for the present piece of work, a full exploration of the methodological implications would deserve a separate treatment.

2 Theoretical considerations

Traditional studies on the evolution of communication in animal societies have, in general, approached the subject with too narrow a focus, characterizing the phenomenon with intuitive terms and *ad hoc* redefinitions. Evidence of this can be found in the presence of two important preconceptions in the theoretical understanding of communication. By preconceptions I do not necessarily mean *mis*conceptions. I am referring to those unspoken assumptions that are accepted as such and deserve no further discussion.

2.1 The role of selection

The first of these preconceptions has to do with the use of selective advantages as a necessary ingredient in *defining* communication. For instance, Wilson defines communication as the altering by one organism of the probability pattern of behavior in another organism in a manner adaptive to either one of them or to both [26]. Lewis and Gower define communication as "the transmission of signals between two or more organisms where selection has favoured both the production and reception of the signal(s)" [11]. Burghardt defines it as a behavior that is "likely to influence the receiver in a way that benefits, in a probabilistic manner, the signaller or some group of which it is a member" [6, 12]. Maynard-Smith and Harper define a signal "as an action or structure that increases the fitness of an individual by altering the behaviours of other organisms detecting it, and that has characteristics that have evolved because they have that effect" [17].

In these definitions communication is *characterized* in the same terms which are used to *explain* it, which is not only confusing, but methodologically very questionable as descriptions of phenomena and descriptions of the generative mechanism that give rise to such phenomena (explanations) belong necessarily to different domains. In other words, the question of how communication has come to exist is resolved *a priori* at the definition level, leaving no room for alternative/complementary mechanisms or their rebuttal, while at the same time providing a poor characterizations of the phenomenon. We do not *define* "wings" in terms of their selective advantages even if we may *explain* their presence in those terms.

Many biologists have appealed to these characterizations in order to rule out behaviors that intuitively do not constitute acts of communication but that would have to be included with the adoption of loose definitions such "an exchange of signals." However, the problem of poor characterization remains. Is an organism that has developed a mimetic character emitting a signal in order to confuse predator, as defended in [17]? Can we say that the predator acknowledges the signal by not receiving it? Such problems arise from deriving the logical conclusions of the idea of self-benefit in a description of the phenomenon that can be characterized independently of it. If we saw a group of animals committing collective suicide after a call given by one of them, we still would like to describe this as a case of communication. The fact that we rarely see such behaviors should perhaps be used to support selective *explanations.*

As I mentioned, one of the consequences of this mixing of descriptive and explanatory discourse is that complementary mechanisms that may play a role in explaining the evolution of communication, not necessarily in contradiction with natural selection, are out of the question. Even if such mechanisms played little or no role, the methodological problem would remain. By adopting the above definitions one is forced to ignore the *possibility* of such mechanisms as a genuine empirical question. If such mechanisms were found, one would be forced to adopt a theoretical framework that allows them.

2.2 Communication as information exchange

Another preconception about communication often found in the biology literature, is that it involves operationally the transmission of information from a sender to a receiver. This view implies that there is "something" that is being transmitted through some channel, although few researchers specify what it is. Hardly ever used in its technical sense [17], information is seen as a "thing" the pre-exists the activity we want to explain while, in fact, it is a consequence of that activity as seen by an observer, therefore it cannot play any operational role in its generation. Only after observing the activity are we able to speak about informational exchanges, and only in certain circumstances, (see [8, 19, 20, 24] for complete discussions on this point).

This metaphor has led many researchers to assume that a necessary condition for communication to arise is that not all relevant aspects of the environment are equally known to all the participants. It is interesting to see how this idea has influenced the computational approach to the problem, (see [12]). If all the relevant "information" is readily available to everyone, why "should" communication arise? In this view, communication can be understood only if there is some relevant feature of the environment whose conspicuousness has to be enhanced by a signal (such as a predator, or food), or if some internal state needs to be publicized.

2.3 Communication as coordinated activity in a consensual domain

Is it possible to *define* communication without appealing to concepts such as selective advantages or information? More importantly, can we work with such a definition? The understanding of communication that I will offer here is not new and it has been concurrently developed in different, though related, contexts including cybernetics [20, 24], autopoietic theory [13] and some branches of psychology and psychotherapy [4, 25]. Many philosophical perspectives also converge into similar, though not identical, views [3, 7, 10, 27]. Perhaps the most concise way of presenting this view is by using the language of autopoietic theory. It is, however, far beyond the scope of this section to give a thorough introduction to these concepts and the reader is referred to [14, 15] for a complete account of this important field.

Autopoiesis is a theory of the organization of living organisms as composite, autonomous unities. An autopoietic system is a dynamical system whose organization is maintained as a consequence of its own operation. Autopoietic systems in a given space produce their own components and boundaries and, as a result of the network of processes (of production, transformation and destruction) realized by the relations between these components, their organization is maintained dynamically. All living organisms are autopoietic systems that inhabit physical space. Autopoiesis is a property of the organization of the system; a given autopoietic organization is embodied in a particular *structure* or physical realization, and each state of such a system is determined *only* by that structure and a previous state. This seems almost trivial, but it is a fundamentally important point. It implies that any state of the system that we, as observers, can relate to a particular behavior when it is situated in an environment, is a direct result of the system's own structure and of its history. Thus, autopoietic systems are a subset of the larger set of operationally closed systems[1].

Any autopoietic system exists in a medium with which it interacts and, as a result of that interaction, its trajectory in state-space (its history) changes, although its operation as a dynamic system remains closed. As a structure-determined system, its structure determines its *domain of perturbations*, that is, what are the possible trajectories that can be triggered by interactions with the medium given a certain initial state without destroying the system. If the system undergoes changes of state that result in plastic changes of structure, and therefore changes in its domain of future perturbations, and all this happens without loss of its autopoiesis, then the system is said to undergo a process of *structural coupling* with the medium. If the medium is also a structurally plastic system then both systems may become structurally interlocked, mutually selecting their plastic changes, and thus defining a history of plastic interactions that for the organism is its *ontogeny*. As long as autopoiesis is maintained during this history, the organism is said to be adapted to the medium[2].

The process of structural coupling can not only account for changes in the individual during its lifetime, but also for phylogenic changes during evolution. *Phylogeny* is the result of the history of structural coupling of a series of autopoietic unities connected sequentially by reproduction during which adaptation is conserved. Selection acts negatively when, as a result of interactions with the medium, autopoiesis is lost, but it also acts through the process of structural coupling between medium and the organisms.

An organism undergoing a process of structural coupling with the medium may act recursively over its own states if the plastic deformations of the medium have been triggered by the organism's previous actions and at the same time these deformations will provoke future perturbations in the organism. In the particular case in which the medium includes another autopoietic system their individual ontogenies may become coupled. A domain of interlocked triggering of changes of state between the organisms participating in this network of co-ontogenies is established as long as the coupling subsists. This is called a *consensual domain.*

Behaviors in a consensual domain are mutually orienting behaviors. An observer can describe these behaviors as a case of coordinated activity. *Communication* is then defined as *the behavioral coordination that we can observe as a result of the interactions that occur in a consensual domain* [13, 15]. It is important to notice that by definition activity in a consensual domain is recursive, and we can distinguish it as coordinated activity, however, this is not to be confused with the idea of recursion upon already existing coordinations. The latter enters as a further recursion which is identified as a defining characteristic of the phenomenon of "languaging" [13] which will not be addressed in this paper.

It is important to notice that all behaviors that arise from recursive actions in a consensual domain are included in this understanding of communication and not only those that can be described in semantic terms by an observer. Therefore, behaviors such as grooming, playing and the formation of hunting patterns *are* communicative behaviors. It is only through the history of structural coupling with the medium that a correspondence can be identified by an observer between situations in the medium and the behaviors which are coordinated and oriented in their presence as a result of communication. In these cases the observer may speak of certain actions as being signals that stand for a certain state of affairs or serve a certain function. However, a failure to find a semantic interpretation does not imply that the observed phenomenon is necessarily different in its essence. Even though more behaviors are embraced by it, our definition of communication is not a loose one. On the contrary, it is far more precise than traditional definitions, because it is based on operational considerations. While it is true that functional descriptions are very useful when we want to bracket complex operational details and view the phenomenon at different time scales, an operational description, if possible, is much preferred in the present context of model building.

3 Evolving non-recursive coordination

Let us consider the following game to be played by pairs of agents living in a shared environment. We will see an *agent* as an unity that is able to act in the environment. As a consequence of its actions, the agent receives certain payoff in a given currency that we may call *energy* and also spends a certain amount of its own accumulated currency. For most parts of this work agents will be seen as simple rather than composite unities, so that the focus will be more on global patterns of behavior rather than on the structural features of individual unities. When a certain level of energy is reached the agent is able to reproduce, and when this level falls below a certain minimum the agent dies. Energy can be accessed by the agents if they perform a correct action on an energy container or *food source*, of which there can be various types, each one of them requiring different actions in order to extract part or all of its energy. The total environmental energy contained in these sources is constantly renewed at a fixed rate.

There are two "components" to each agent's actions: the *effective component*, upon which the allocation of payoff is decided, and the *external manifestation* of the action, which is not directly relevant to the allocation of

---

[1] "Closed" is used here in the mathematical sense, see [1, 23].

[2] In slightly different terms Ashby arrives at a similar definition of adaptation in terms of stability and homeostasis: "... a form of behaviour is adaptive if it maintains the essential variables ... within physiological limits" [2, page 58].

payoffs. This means that for an agent to get a certain payoff the effective component of its action must match the action required by the particular food source it is dealing with. Behaviors that are required to get a certain amount of food in natural organisms, such as shaking the branch of a tree or digging the ground, can be thought of as the effective component, and the appearance of the movements implied in those behaviors to another organism as an example of one possible external manifestation of that behavior. Others may be sounds, gestures, etc. While in real cases it may be hard to decouple these two components in a single action, for simplicity's sake, we will suppose that, in this model, any effective component can be found with any external manifestation[3].

At each time step agents are selected to play the following game:

1. Each selected agent, who will play the *first role* (A_1), selects at random another different agent in its vicinity, who will play the *second role* (A_2).
2. A food source is randomly selected from A_1's vicinity.
3. A_1 perceives the type of the food source.
4. A_1 acts.
5. A_2 perceives the external manifestation of A_1's action, but not the type of food.
6. A_2 acts.
7. The payoff is distributed. If both agents perform the correct effective component the total amount of energy is equally distributed in halves. If only one of them performs the right action, that agent receives a proportion c of the total energy ($0.5 \leq c \leq 1$), the other receives no payoff and the rest of the energy remains in the food source.

The game is played indefinitely or until the population becomes extinct. All agents have the same chance of being picked as A_1. The possibility exists that effective components and external manifestations of actions may become correlated in such a way that agents playing the second role may "use" them as a prompt to act correctly over the food source even though they cannot perceive its type. However this may be against the immediate interest of the first player who may receive a smaller payoff. For convenience, I will speak of "signals" and "signalling" whenever I refer to the external manifestation of actions in the following paragraphs without attempting to make this a strict definition.

We can see that this game includes the feature of hidden information, as the agent playing the second role is not able to see the food type that it is dealing with. In section 5 I show that the assumption that this is a necessity is invalid.

A game-theoretical dynamical analysis of a population of players of this game has been carried out for simplified conditions [8]. In order to make the model tractable geographical considerations were ignored so that agents can have access to any food source and play the game with any other agent in the population. Behavioral strategies were reduced to four possibilities without bias towards coordination. The results of this analysis show that an Evolutionarily Stable Strategy (ESS) exists in the total absence of coordinated activity. This means that a population consisting almost entirely of agents that behave selfishly and do not coordinate their activity cannot be invaded by any mutant population.

However, only a subset of initial conditions leads to this situation. For initial conditions outside this set the system does not evolve towards an equilibrium at all. The long term behavior is characterized by the presence of a periodic attractor in which the whole population oscillates indefinitely between periods of coordination and non-coordination, (Figure 1). Once within the regime, the system will remain in it permanently; therefore, the ESS state will never be reached. This sort of situation has been recognised as "an obvious weakness of the game-theoretic approach to evolution", [16, page 8]. Natural occurring examples of these cycles have been recently found in the mating strategies of the male side-blotched lizards [22]. In more general terms Zeeman showed that global convergence to an ESS is assured only in the absence of other attractors, which may exist and not be ESS's themselves [28].

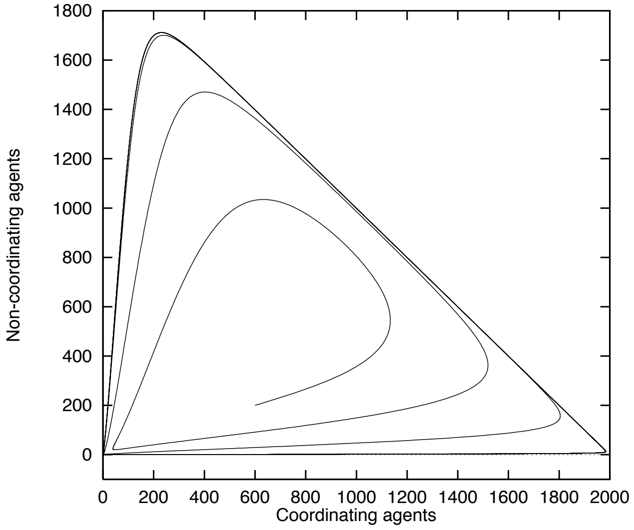

Figure 1: Periodic attractor (for 2 of the 4 species).

The game-theoretic dynamical analysis is important from a methodological viewpoint but not very conclu-

---

[3] This move leaves on one side an important area of research, namely the study of how signals or displays evolve out of preexisting body structures and dispositions. Thanks to Jason Noble for pointing this out.

sive in terms of the processes leading to the evolution of coordinated activity. One immediate hypothesis is that spatiality may play an important role. Global accessibility does not represent interactions among real organisms fairly. In real life, neighbors tend to remain neighbors and the habitat of the offsprings tends to be the same habitat of the parents.

In order to account for these factors a computational model was developed in which the agents play the same game. Agents are situated in a toroidal grid (100 x 100) initially with a random distribution. In the same way a large number of food sources of different kinds is uniformly distributed in this grid. Neither the agents nor the food sources change positions with time. A neighborhood is defined as a square (10 x 10) centered around an agent, which represents the area the agent occupies during its lifetime. Agents play the game as described above, which means that they must perform a correct action depending on the type of food source they are dealing with in order to increase their energy level. There are around 100 food sources in an agent's neighborhood and only four different types of them. Each food source contains a certain amount of energy which is constantly being renewed at a fixed rate using a stochastic update rule. Agents will die if their energy level reaches zero. On the other hand, if the energy level increases, the agent will accumulate enough energy to reproduce. In this case a mate is selected from the neighborhood, and the offspring will occupy a randomly chosen position within the first parent's neighborhood, deriving its initial energy level from this parent. As the energy extracted from the agents in the form of costs does not return to the environment in reusable form, this scheme guarantees that the equivalent first and second law of thermodynamics are observed.

At each time step a number of agents equal to the size of the current population is randomly selected to perform the first role in the interactional game. The updating is performed asynchronously. A second player and a food source within the neighborhood of the first player are randomly selected. If no agent is found after a finite number of trials (about 10), the first player looses its chance to play the game, and the energy cost is discounted anyway.

The structure of agents is that of a state-less machine. The focus of this work will be on the global mechanisms that allow or constraint the evolution of coordinated activity as a first step towards an understanding of the evolution of communication. No claim will be made about the very important effects of ontogenic structural changes during the coordination of actions with other agents. Agents will be seen as simple unities most of the time. This is a strong simplification for a model which is partly based on concepts derived from autopoietic theory, however, I maintain that the framework provided by this theory is still applicable for the design and understanding of the present and future studies.

The behavioral matrix is encoded in a haploid genome, represented by a bit-string. Offsprings receive their genome from the result of a uniform crossover operation on their parents genotypes, plus certain probability of mutation μ per place.

In this model there is no fitness function, neither are there any special rewards nor punishments for behaving in an specific way apart from the rules of the game. A problem derived from the use of this scheme is the lack of obvious measures of evolution. For our purposes, the simplest way to monitor the evolution of action coordination, is to look at changes in the average simultaneous success of the first and second players for the whole population.

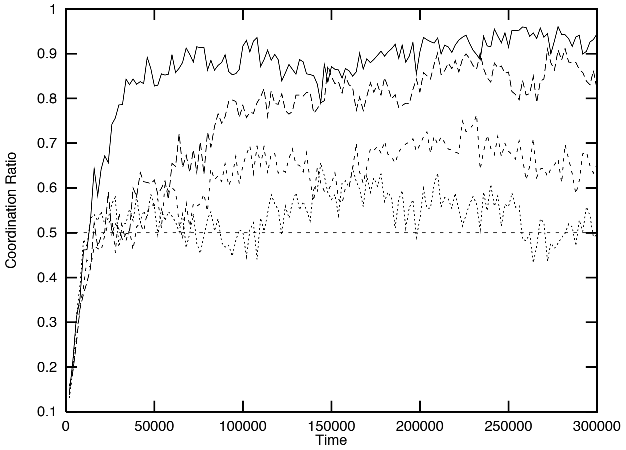

Figure 2: Coordination ratio for different values of c. The top (full) line between 90% and 100% corresponds to $c = 0.5$, the line between 80% and 90% to $c = 0.55$, the one between 60% and 70% to $c = 0.6$ and the one between 50% and 60% to $c = 0.65$. Values of c equal or greater than 0.7 reproduce the baseline case for this game.

In the simulation runs described here agents were able to perform 16 actions (4 effective components and 4 external manifestations). Only two of the effective components were actually relevant for the four food source types. A baseline case was run in order to understand what kind of activity evolved when agents weren't able to perceive each other reliably. In these runs, the external manifestation of the first player's action was replaced with a random signal when perceived by the second player. We may call the proportion of cases in which both players acted correctly simultaneously, the *coordination ratio*. This ratio stabilized at 50 % for random signals. Since no food type is predominant, the best "guess" a second agent can make given that there is no correlation between the "signal" it perceives and the particular type of food it is dealing with, is to perform any of the two relevant out of the four possible actions. For non-random signals any success in coordination of behaviors will be manifested as a greater coordination ratio than the one observed in the baseline case.

A study of the effect of parameter c on the coordination ratio was performed to see how the extra payoff against coordination affected the level of simultaneous success. Figure 2 shows the resulting evolution for different values of c in typical runs. We see that the proportion of coordinated activity for the whole population decreases as c is incremented from 0.5 to 0.7, and for greater values the baseline case is reproduced. This means that the level of coordination goes from almost perfect for $c = 0.5$ (neutral cost) to coordination by guessing when $c \cong 0.7$. No cycles are observed as in the mathematical model. The fact that for a certain range of costs *against* it, coordinated activity evolves anyway is in contradiction with the intuitions that can be gained from the mathematical model or from simplified selective arguments. Explanations for this phenomenon are found in the spatial organization of the system.

4 Spatial structures.

A simple inspection of the resulting data in all simulations shows that the individual history of coordination success can differ significantly from agent to agent and from the value of the coordination ratio at that time. For instance, groups of agents achieving 90 % of coordination success can coexist with other groups that achieve 60 % both in a stable state during the same simulation run. Even though an individual historical average is qualitatively different to an instantaneous population average, one would expect the resulting numbers not to differ much, especially if the coordination ratio has been stable for some time. This suggests that there may be some structure in the population that prevents the homogenizing effects of sexual reproduction.

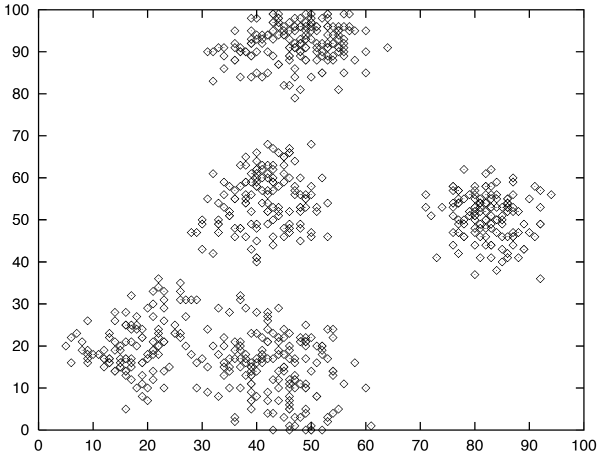

Figure 3: Distribution of the population in clusters.

4.1 *Cluster formation and stability.*

Figure 3 shows the spatial distribution after a short transient. Initially agents are distributed randomly across the whole environment. We can observe that the initial symmetry is broken and that agents show a tendency to aggregate into clusters. Symmetry breaking is caused by minor differences in the initial distribution of positions and is also due to the updating rules; so that some agents will be more successful than others just because they have a few more agents to interact with or have been called to act a few more times and, therefore, they have a slightly greater chance of accumulating enough energy for reproduction. As reproduction is also a local process and the position of the offspring does not differ much from the position of the the parents, there is a positive contribution to the same effect, namely the accumulation of agents in these particular areas.

Unfortunately, cluster formation mechanisms do not provide a satisfactory explanation of why clusters remain more or less stable structures as it is generally observed.

Tendency to expand. Figure 4 shows a qualitative model of a typical observed distribution of environmental energy and density of agents inside and in the vicinity of a cluster. It is easy to see that resources will be more frequently used in more populated areas towards the center of the cluster than on peripheral areas in which the population is more sparse, so that the amount of available energy will, on average, decrease towards the center as shown in the figure. Agents living in the periphery will have access to resources of greater quality, and the average energy gained per game played will be greater than that of agents in the center region. So, at first glance, peripheral agents would seem to be better off and have a better chance of having more offsprings, therefore the cluster would seem to experience a tendency towards *expansion.*

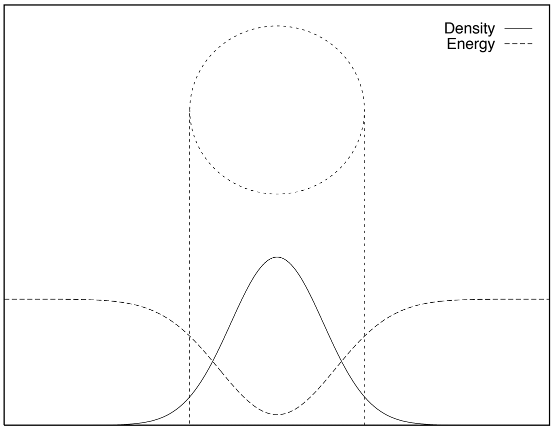

Figure 4: Energy and population distribution inside and around a cluster (circle).

Tendency to collapse. While all agents have the same probability of being *chosen* to play the first role in the game, the frequency with which an agent *actually* plays the game depends on the surrounding population density. The more densely populated the area, the higher the chance of finding a partner to play with. For this reason, agents living near the center of a cluster will play the game more frequently. Moreover, the probability of an agent playing the second role also depends on its position within the cluster. Given that the density distribution is not uniform, second players will be chosen more frequently from more populated regions. Agents in the center of a cluster will benefit from this effect in a cumulative way, and will, on average, play the second role more times than they play the first role. Conversely, agents living near the periphery will be chosen less frequently for playing the second role because their distribution is more sparse, and therefore, they will, on average, play the first role more times than the second role. The ratio (Second-role-frequency)/(First-role-frequency) for each agent has been observed to range from a minimum of 0.9 at the periphery to a maximum of 1.25 at the center of the cluster. In short, agents living in the populated areas near the center will 1) play the game more frequently than agents living in sparse areas and 2) they will perform the second role more frequently than the first one. So, in principle, they will stand a better chance of receiving more energy per unit of time. This provides the cluster with a tendency to *collapse.*

The equilibrium of both these tendencies determines the size of the quasi-stable cluster. Resulting clusters have been observed to have a typical radius of 1 up to 3 neighborhood sizes.

4.2 Why does action coordination evolve?

I said that clusters as quasi-stable structures result from an interplay of two opposing tendencies in the spatial organization that arise from the fact that conditions differ at the center and at the periphery of the cluster. The next obvious question that must be examined is if this difference of conditions has any effect on the evolution of coordinated activity.

Genetic homogeneity. Due to the nature of the cluster formation process and the homogenizing effect of sexual reproduction, clusters tend be inhabited by agents who are very similar genetically. Spatial homogeneity within a cluster will still be the case even when a new mutation appears. After a sufficiently long time (in practice not very long) there will be agents bearing the new mutation distributed across the whole cluster.

Conditions at the periphery of a cluster. Agents are subject to two qualitatively different "micro-environments" which emerge as a result of the spatial organization[4]. We saw how agents living in the periphery have access to resources of better quality (Figure 4) and how these agents tend to play the second role less than they play the first one. Besides, they also tend to interact fewer times in absolute terms because of their sparse distribution. This means that, for these agents, to engage in coordinated activity is particularly costly because every time they do so they lose one of their fewer opportunities to obtain a greater absolute payoff.

Conditions at the center of a cluster. Agents inhabiting the center of a cluster have access to poorer, much more frequently used, resources, therefore the individual gain for not coordinating is not too high in absolute terms, though still positive. On the other hand, these agents tend to play the second role more times than they play the first one, which means that there may be cases (depending on the value of c) in which they will have a positive *individual* gain if they *do* coordinate their actions, simply because they will be acting as second players more frequently, provided that c is not too high. From a cost-benefit viewpoint, while it may pay a little extra to be a "deceiver", the situation may be that once a "deceiver" lineage starts to grow, it will pay more to reestablish coordination.

Selection. Ideally this situation would result in the existence of two distinct subpopulations, one of coordinating agents at the center of the cluster and one of non-coordinating agents at the periphery, but this is not possible due to the genetic homogeneity within a cluster. Given that the sizes of each subpopulation are comparable, and a newborn agent has comparable probabilities of being placed in any of the "two" regions, then there is no ground for selection to be very specific about which of the extreme behaviors to choose. Therefore, surviving agents will tend to be able to partially satisfy the conditions of both extreme micro-environments and, consequently, they will necessarily possess the ability to coordinate their actions up to a certain level.

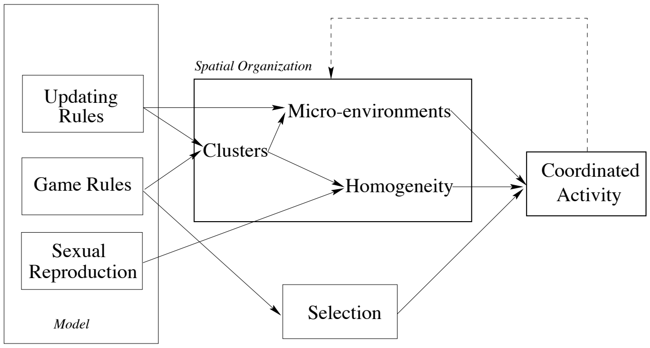

Figure 5: Explanatory mechanisms involved in the evolution of coordinated activity in the computational model.

---

[4] Or an environment presenting a continuum of variation to be more precise.

Thus, the evolution of coordinated activity in this model can be explained by the interplay of spatial organization and selective mechanisms. A diagram showing the relation between the components of this explanation can be seen in Figure 5.

It has been observed that the level of coordinated activity may have considerable variations from cluster to cluster in the same simulation run. Clusters can grow and, more rarely, shrink. These are interesting phenomena because they are related to the level of coordinated activity within the clusters. The following correlation has been consistently observed: *clusters with high level of success in coordination are larger in size and more populated than clusters with a lower level.* In general, the former can have a radius of up to 3 neighborhood sizes, while the latter have a radius of 1 neighborhood size or even less.

Why a particular cluster is small with a low level of coordinated activity while another is large with a high level of coordination must mainly be attributed to contingencies in their respective histories. We cannot look for general reasons because all agents evolve under the same general rules. All we can do is to describe, in terms of feedback mechanisms (see the dashed line in Figure 5), certain tendencies that appear once a cluster is already embarked in a particular historical path. What it is interesting is that this correlation can be deduced from the same explanatory mechanisms derived from the model in Figure 4, this is shown with some detail in [8].

Alternative explanations for the evolution of coordination could be attempted in terms of *kin selection*, but this would still require (at least some of) the mechanisms of spatial structuring to work, all of which should be "brought back" again in order to explain the cluster size/coordination correlation.

It must be remarked that these explanations are in fact simplifications of complex dynamical processes in which more ingredients than those mentioned may play an important part. For instance, I have followed a quasi-static approach, in which inertia has been unaccounted for. The complex effects arising from cluster interaction have also been ignored. The reason for this is that, interesting as these phenomena may be, they do not much further our understanding of how action coordination evolves due to the interplay of spatial organization and selection in this model.

5 Coordination of recursive actions

Coordination, as presented in the previous model, does not reflect the idea of ongoing mutual orientation of behaviors that is implied by the view of communication as arising from activity in a consensual domain. This sort of coordination is similar to that that can be observed between traffic lights and motorists, a simple traffic light system would operate independently of the actions of the motorists, but not the other way around. Genuine consensual interactions could be expected, for instance, among drivers participating in a race. As the next logical step in the project, the previous model could be extended in order to approach a situation in which we may speak of a consensual domain. Strictly speaking, this will not be possible as long as the structure of the agents remains non-plastic, so this will not be yet a model of communication. However, the following modifications to the game can take us near this situation.

Instead of requiring an unique action, access to energy in the food sources requires the performance of a specific sequence of actions by both agents. Energy is released partially depending on an action being correct at the required step of the sequence. In this case the actions of *both* players depend on the perceived food type and the perceived external manifestation of the other agent in the previous step. This means that the second player has access to information about the food type. In spite of this, it is clear that the task the agents have to perform in not trivial. This game has a dialogic structure, the actions of an agent depend not only on the perceived food type but also on the previous actions of its partner, which recursively depend on the agent's previous actions. This provides a more realistic analogy with natural cases of coordinated behavior.

A simulation was run with four different types of food, two of them requiring a sequence of actions such as "A, B, C, D" where the first player must perform "A, C" alternating with the second player who must perform "B, D" and the two others requiring the sequence "C, D, A, B" which means that each agent must revert the order of its own actions. Payoffs are allocated after the first two actions, and then again after the last two actions in the same manner as in the previous game.

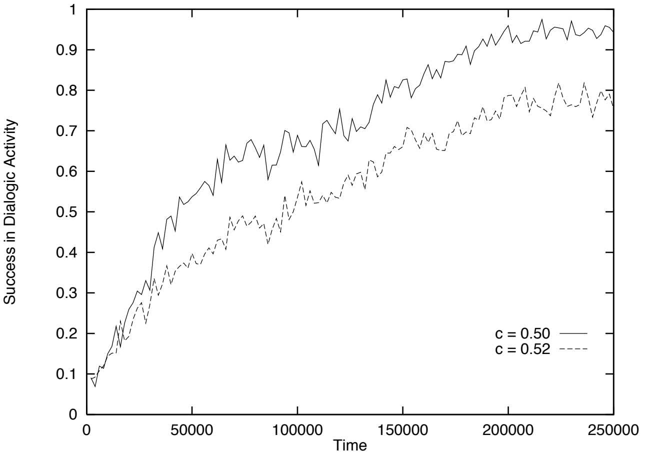

Figure 6: Evolution of dialogic coordinated activity for two values of c in two typical runs.

Figure 6 shows the evolution of dialogic activity (defined as the ratio of successfully produced sequences over the total number of games at each time step). We see that coordination of recursive actions evolves towards a high level. The same considerations about the spatial organization of the agents made for the first set of experiments still apply, and the level of dialogic activity has a dependency on c similar to that of the level of coordinated activity for those experiments.

These results show how agents coordinating their activity are able to perform tasks beyond their individual abilities. This particular game requires that both agents perform a sequence of actions (which depend on their role) in the presence of an external environmental feature that remains unchanged with time. Given that agents are state-less machines, this is something impossible for them to do individually. However, a couple of interacting agents can achieve an important level of success in this task, each one taking advantage of the presence of the other and "using" their interactions as the internal states they lack.

We see that a description of their behavior in terms of traditional notions of information is useless. If by information we mean information about features of the environment, we find that these are equally accessible to both participants, if we mean information about the state/intention of the agents, they haven't got any.

6 Conclusions

The first part of this paper was aimed at a methodological and conceptual criticism of the current approach to the question of the origin and evolution of communication. An analysis of the way the phenomenon is characterized in theoretical biology provided the necessary guidelines for identifying two important preconceptions prevalent in those studies, namely the use of selective advantages, elsewhere used only in explanatory discourse, at the definition level, and the loose use of the idea of communication as an informational exchange. A different understanding of communication was considered as a way of characterizing the phenomenon while avoiding the consequences identified with the inclusion of the previous preconceptions.

The computational model used for investigating the evolution of non-recursive coordination has demonstrated that coordinated activity can evolve even in those cases in which the static and dynamic mathematical models showed it would not. And the reason for this difference has been mainly the possibility that the computational model provides for studying the actions of selective mechanisms in the context of other concurrent processes such as spatial organization.

We observe clusters emerging as self-regulating spatial structures but to say that some complex structure "emerges" out of something simple is to locate the problem, not to solve it. That is why an explanation was advanced in terms of a qualitative model of the observed distribution of population and energy in the region occupied by a cluster. In exploring certain issues arising from this model we were able to explain many of the observed phenomena like cluster quasi-stability, genetic homogeneity, etc., including the evolution of action coordination even in the presence of individual costs against it. It is apparent that spatial structures can provide a very strong influence on the outcome of an evolutionary process, resulting sometimes in far from intuitive characteristics (see also [5, 18]).

A broad analogy can be drawn between the position of an agent in a cluster in our model, and the degree of participation in a social organization for a natural organism. For instance, animals spending more time in social activities as a consequence of their developmental stage, or their social status, will be analogous to agents living in the center of a cluster. Such an analogy would suggest that many answers to the question of natural communication could be sought in the nature of group structure, and social hierarchies.

Interestingly, one of the correlations found in this study, the correspondence of cluster size and degree of coordinated activity, has a very suggestive parallel in primate societies: that of typical group size and relative neocortical size [21]. It has been suggested that language evolution has been deeply influenced by the growth in group size in humans as compared with other primates, and a functionalist explanation was advanced in terms of the role of language as a bonding mechanism in the maintenance of stability in large groups [9]. The way that the analogous correlation was explained within the present model has been rather different, more in terms of structural dynamics rather than functional adaptations, but the parallel is worth noting.

The following step towards an understanding of the evolution communication corresponds to a game in which agents act recursively, still without constituting a consensual domain in the strict sense. In this game, action coordination evolves non-trivially even when information is previously shared. This result also points to the relevance of social interactions in the evolution of cognitive capabilities, as agents in this simple model are able to perform actions not allowed by their structures at the individual level. It can be expected that the addition of plasticity to the structure of the agents will constitute an important further step.

The computational approach is particularly appropriate for the study of structures and concurrent processes in which the limitations of pure mathematical modelling are tested. In this case the addition of spatial considerations dramatically changed the results obtained by a simple cost-benefit selective analysis. This can be considered as a methodological warning sign, not only for the present project, but for many other projects in the study of biological phenomena.

Acknowledgements

Thanks to Phil Husbands, Inman Harvey and an anonymous reviewer for their helpful comments on previous versions of this work. The author is grateful to the *Consejo de Investigaciones Científicas y Técnicas de la República Argentina* and the Argentine Ministry of Education for their support.

References

[1] W. R. Ashby. *Introduction to Cybernetics.* Chapman and Hall, London, 2nd edition, 1956.

[2] W. R. Ashby. *Design for a Brain: The origin of adaptive behaviour.* Chapman and Hall, London, 2nd edition, 1960.

[3] J. L. Austin. *How to Do Things With Words. The William James Lectures delivered at Harvard University in 1955.* Oxford at the Claredon Press, 1962.

[4] G. Bateson. *Steps towards an Ecology of Mind: collected essays in anthropology, psychiatry, evolution and epistemology.* Intertext Aylesbure, 1972.

[5] M. C. Boerlijst and P. Hogeweg. Spiral wave structure in pre-biotic evolution: hypercycles stable against parasites. *Physica D*, 48:17 – 28, 1991.

[6] G. M. Burghardt. Defining 'communication'. In J. W. Johnson, Jr, D. G. Moulton, and A. Turk, editors, *Communication and Chemical Signals.* Appleton-Century-Crofts, New York, 1970.

[7] J. Dewey. *Experience and Nature.* Dover, 1958.

[8] E. A. Di Paolo. An investigation into the evolution of communicative behaviors. Cognitive Science Research Paper 445, School of Cognitive and Computing Sciences, University of Sussex, 1996.

[9] R. I. M. Dunbar. Co-evolution of neocortex size, group size and language in humans. *Brain and Behavioral Sciences*, 16:681 – 735, 1993.

[10] M. Heidegger. *Being and Time.* Harper and Row, New York, 1962. Trans. J. Macquarrie and E. Robinson.

[11] D. B. Lewis and M. D. Gower. *Biology of Communication.* Blackie, Glasgow, 1980.

[12] B. J. MacLennan and G. M. Burghardt. Synthetic ecology and the evolution of cooperative communication. *Adaptive Behavior*, 2(2):151–188, 1994.

[13] H. Maturana. Biology of language: The epistemology of reality. In G. A. Miller and E. Lennenberg, editors, *Psychology and Biology of Language and Thought. Essays in Honor of Eric Lennenberg*, pages 27–63. Academic Press Inc. New York, 1978.

[14] H. Maturana and F. J. Varela. *Autopoiesis and Cognition: The Realization of the Living.* D. Reidel Publishing, Dordrecht, Holland, 1980.

[15] H. Maturana and F. J. Varela. *The tree of knowledge: the biological roots of human understanding.* Shambhala, Boston, Mass, 1988.

[16] J. Maynard-Smith. *Evolution and the Theory of Games.* Cambridge University Press, 1982.

[17] J. Maynard-Smith and D. G. C. Harper. Animal signals: models and terminology. *Journal of Theoretical Biology*, 177:305–311, 1995.

[18] M. Oliphant. Evolving cooperation in the non-iterated Prisoner's Dilemma: the importance of spatial organization. In R. Brooks and P. Maes, editors, *Proceedings of Artificial Life IV.* MIT Press., 1994.

[19] S. Oyama. *The Ontogeny of Information.* Cambridge University Press, 1985.

[20] G. Pask. Developments in conversation theory - part 1. *International Journal of Man-Machine Studies*, 13:357 – 411, 1980.

[21] T. Sawaguchi and H. Kudo. Neocortical development and social structure in primates. *Primates*, 31:283 – 290, 1990.

[22] B. Sinervo and C. M. Lively. The rock-paper-scissors game and the evolution of alternative male strategies. *Nature*, 380:240, 1996.

[23] F. J. Varela. *Principles of Biological Autonomy.* Elsevier, North Holland, NY, 1979.

[24] H. von Foerster. The epistemology of communication. In K. Woodward, editor, *The Myths of Information: Technology and Post-industrial Culture.* Routledge, 1980.

[25] P. Watzlawick, J. H. Beavin, and D. D. Jackson. *Pragmatics of Human Communication: a Study of Interactional Patterns, Pathologies and Paradoxes.* Faber, 1968.

[26] E. O. Wilson. *Sociobiology: The new synthesis.* Belknap Press of Harvard University Press, Cambridge, Mass., 1975.

[27] L. Wittgenstein. *Philosophical Investigations.* Oxford: Basil Blackwell and Mott, 2nd edition, 1963.

[28] E. C. Zeeman. Population dynamics for game theory. In Z. Nitecki and E. Robinson, editors, *Global Theory of Dynamical Systems.* Springer Verlag, Berlin, 1980.