An investigation into the evolution of communicative

Abstract

Communication is a phenomenon with many different aspects, and it has at-

their definitions, creating an interesting ory. For the same reasons of continuity, I start with a classical game-theoretic approach to the problem, which I extend in order to account for the evolutionary dynamics, because these constitute the real object of investigation. This extension shows that the traditional approach is limited, because it is based on finding what conditions lead to an equilibrium situation (an Evolutionarily Stable Strategy), and, in this particular problem, such an equilibrium may be unreachable or many viable equilibria may co-exist. The possibility of a further study into the dynamics of the problem suggests that the most practical way is the computational approach, so general issues about using this technique as a proper scientific tool are also discussed.

The mathematical model that results from extending the game-theoretic approach is presented in Section 5. Here I try to address the question about how important the dynamics of an evolutionary process are and when and how they can complement a stationary study of the problem. The results provide an answer to this question, but unfortunately not much insight into the original problem of the origins and evolution of communication. I claim that this is because many interesting mechanisms are still left out or simplified in this model, so that we are left with two choices, either to extend the model in order to account for such mechanisms, incrementing its complexity and also extending the number of assumptions, or to build a bottom-up computational model of the same problem in which all the features of interest are included from the start[1]. A simple potentiality vs. cost analysis suggests the second alternative as the best one.

The computational model itself is discussed in Section 6. The obtained results are very interesting. They show that communication evolves even in cases that go against our immediate intuitions, and, most importantly, they provide us with a way of explaining why this evolution occurs. Coordinated activity is explained by the interplay of the spatial organization of the population and selection mechanisms. I present a first order analysis of the complex network of mutual influence between these and other mechanisms to explain some features of self-regulation and change in spatial structures and their influence on the degree of communicative behavior.

Also in this section I present a modified version of the communication game, in which the subject of the misuse of the concept of information is addressed again. Contrary to traditional views on the subject, we see in this game communication evolving in a non-trivial manner even when all agents have the same access to environmental information. While performing their coordinated activity, agents are able to achieve tasks that are impossible for them at the individual level, suggesting an interesting metaphor with some affinity to theories that view the evolution of cognition as rooted in the evolution of social activity.

Finally, in Section 7 I discuss the relevance of these results both in terms of the contribution to the way that scientific research can face the study of complex processes, and in terms of their relevance to the problem itself. Some parallels between emerging features of our model and some existing hypotheses about communication in primates are also mentioned along with some limitations of the model and some interesting avenues for further exploration.

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[1] Note that this is different from still another possibility: to build a computational simulation that *extends* the mathematical model.

1993). Burghardt defines it as a behavior that is "likely to influence the receiver in a way that benefits, in a probabilistic[3] manner, the signaller or some group of which it is a member" (Burghardt, 1970; MacLennan & Burghardt, 1994). 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" (Maynard-Smith & Harper, 1995).

All these definitions (and many more coming from the biological literature) are questionable on simple methodological grounds: *they mix a characterization of the phenomenon with a possible (and, admittedly, plausible) explanation of it.* In other words, these definitions resolve *a priori* the problem of why communication has been established in animal societies, leaving no room for alternative/complementary explanations or their rebuttal, while at the same time providing a poor characterization of the phenomenon. We may think of a similar situation in which a physicist defines a "phase transition" as a "change in structure observable in certain systems or aggregations of matter that occurs when energy is continuously added to or taken away from that system". There are two things that are patently wrong with this definition. First, if we have never seen a phase transition before this definition doesn't help us much. What kind of change in structure? How is energy supplied? Secondly, it is known that phase transitions can occur in energetically isolated (adiabatic) systems when pressure changes. So, the explanation that has been built into the inme.j16.80Td(simple80Td(simple80Tdfould)-16000.4(aggrega1400 advantages, even if we explain their presence in those terms. Moreover, if there is no present it, is a probabilistic concept that has little to do with the kind of information that is often invoked when explaining communicative behavior[4] (Oyama, 1985, pages 64 - 71).

All an observer can say when witnessing an act of communication depends only on the activity of the participants and on the observer herself (particularly, on her ability to draw inferences from her observations). A given behavior identified as a signal can trigger different responses in the participant identified as the receiver and can be interpreted differently by the observer in different circumstances. There is no actual, observer-independent, ground for identifying any informational content in a signal. Information does not exists before the activity and it cannot be separated from it. It cannot be searched for before the signal is emitted, so it cannot be an objective, independent quantity that exists "out there":

> "... We believe that information can even be stored and then, later on, retrieved: witness the library, which is commonly regarded as an information storage and retrieval system. In this, however, we are mistaken. A library may store books, microfiches, documents, films, slides and catalogues, but it cannot store information. One can turn the library upside down: no information will come out. The only way to obtain information from a library is to *look* at those books, microfiches, documents, slides, etc. One might as well speak of a garage as a storage of and retrieval system for transportation. In both instances a potential vehicle (for transportation of for information) is confused with the thing it does only when someone makes it do it. *Someone* has to do it. *It* does not do anything." (von Foerster, 1980)

The idea of something being transmitted in communicative interactions is probably an extension of our idealizations of human language, in which we think that every utterance carries some informational content from emitter to receiver about a given state of affairs. And this is possible because we suppose that both participants share the same cognitive properties and therefore can interpret the message in the same way as it happens with man-made communication devices. However it is known that this is a questionable idea when applied to the way language is *actually* performed in everyday activity (see Section 3.3). So, without any objective way to grasp *the* interpretation of the message, on what grounds can we speak of the information contained in it? If anything at all, what we call information "in the colloquial sense" is not only dependent on, but is in fact a *posterior* interpretation of, the activity that generates it and, therefore, it cannot be used to explain how that activity originated.

Another criticism to the idea of communication as an exchange of information is that it implies the view signals must denote something. They must refer to some feature of the world, or stand for some state of affairs.

is more a feature of the description rather than a feature of the behavior itself and, therefore, it "belongs" to the observer.

Let us examine some of the consequences of the metaphor of the exchange of information in the way that the problem of the origin of communication has been addressed. This view has led many researchers to assume that a necessary condition for communication to arise is that not all relevant

1972; Watzlawick, Beavin, & Jackson, 1968; Watzlawick & Beavin, 1977). From a philosophical perspective many traditions converge to similar views (Austin, 1962, 1971; Dewey, 1958; Habermas, 1979; Wittgenstein, 1963; Heidegger, 1962).

3.1 Ontogeny and Phylogeny in autopoietic systems

It is far beyond the scope of this section to give an introduction to autopoietic theory and the reader is referred to (Maturana & Varela, 1980, 1988) for a complete account of this important field[7]. Certain concepts will be needed for the definition of communication that I wish to present and they will be briefly explained. This is not an easy task because concepts in this theory are linked by a very compelling logic and it is difficult to present isolated ideas without doing some injustice to the theory as a whole. I hope that readers knowledgeable in this area will understand this point, while others will recur to the mentioned sources if they are looking for a deeper account.

Autopoiesis is a theory of the organization of living organisms as composite, autonomous unities. An autopoietic system is a 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 interactions between these components, the organization that maintains them (both the components and their relations) is specified. 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 behavior of an organism that we can witness as observers is a direct result of the organism's own structure and of its history. Thus, autopoietic systems are a subset of the larger set of operationally closed systems[8].

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. Put crudely, we can think of this as a system whose states are determined by a set of differential equations and as a result of interactions (coupling) with another system (the medium) some parameters in this set of equations are perturbed. The state of the system will still be determined by the equations but the trajectories will generally differ if the perturbations are different. The structure of the system, then, 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 disintegration or loss of its autopoiesis, then the system is said to undergo a process of *structural coupling* with the medium.

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[7] A good introduction can be found in chapter 4 of (Winograd & Flores, 1986)

[8] "Closed" is used here in the mathematical sense. Organizational closure can be defined when the organization is characterized by processes such that: "the processes are related as a network, so that they recursively depend on each other in their generation and realization of the processes themselves, and 2. they constitute the system as a unity recognizable in the space (domain) in which the processes exist" (Varela, 1979, page 55). It is important not to confuse this notion with that of a system being "closed" to interactions with its medium.

In the analogy with the set of differential equations not only would some parameters be perturbed but the form of the equations themselves would suffer a change.

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:

> " Adaptation, then, is always the trivial expression of the structural coupling of a structurally plastic system to a medium. ... It follows that, in the operation of living systems as autopoietic unities in a medium, the coincidence between a given structure of the medium (place in the medium) and a given structure in the living system is always the result of the history of their mutual interactions, while both operate as independent, structurally determined systems. Furthermore, as a result of the structural coupling that takes place during such a history, history becomes embodied both in the structure of the living system and in the structure of the medium, even though both systems necessarily, as structure-determined systems, always operate in the present through locally determined processes." (Maturana, 1978, page 39)

In slightly different terms Ashby arrives at the same definition of adaptation in terms of stability and homeostasis: "... a form of behaviour is adaptive if it maintains the essential variables ... within physiological limits" (Ashby, 1960, page 58).

This view 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. It is important to remark that this concept of adaptation implies that all living systems are and have been equally adapted to their environments. They have succeeded in conserving their adaptation without disintegrating or going extinct, therefore, there are no grounds to compare the adaptation of two different organisms either living at the same time or at different points in evolutionary history. This marks a difference with the traditional neo-Darwinian view of evolution in which the existence of multiple mechanisms is not denied but their relevance is downplayed against the role of natural selection and, therefore, the structure of organisms is accounted for as a result of a process that optimizes fitness. Researchers within this tradition do not hold the naïve view that organisms optimize as the "rational man" of classic economic models does, but they use optimization as an explanatory tool (see Maynard-Smith, 1978). However, "no global optimal fitness scheme apparently suffices to explain evolutionary processes. There are, to be sure, local genetic agents for, say, oxygen consumption or feather growth, which can be measured on some comparative scale where optimality may be sought, but no single scale will do the job for all processes", (Varela, Thompson, & Rosch, 1991, page 194). In the words of the same authors, the autopoietic view of adaptation requires a switch from a "prescriptive logic to a proscriptive one, that is, from the idea that what is not allowed is forbidden to the idea that what is not forbidden is allowed" (Varela et al., 1991, page 195), and, furthermore, it requires the departure from the idea that adaptation can be measured by observer-dependent scales and that evolution proceeds in accordance with those measures.

Another important issue that is explicitly accounted for in this view of evolution is the mutual specification of changes of structure both in the organism and in its environment, particularly when this environment is partly constituted by other organisms, as in the case of communication that concerns us here. This has been recognised, at least implicitly, by researches from the neo-Darwinian tradition in their use of game-theoretic approaches to account for frequency-dependent effects on fitness. However the previous criticism still applies[9]. These issues has also been addressed independently (see Lewontin, 1982, 1983, 1984).

3.2 Communication in structure determined, closed systems.

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 this deformations will provoke future perturbations in the organism. In the particular case in which the medium includes another autopoietic system their individual ontogenies become coupled. Maturana and Varela speak of a *network of co-ontogenies* (Maturana & Varela, 1988). A domain of interlocked triggering of states between the organisms participating in the 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. They are both arbitrary and contextual:

> "The behaviors are arbitrary because they can have any form as long as they operate as triggering perturbations in the interactions; they are contextual because their participation in the interlocked interactions of the domain is defined only with respect to the interactions that constitute the domain." (Maturana, 1978, page 47)

An observer can describe behaviors in a consensual domain 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* (Maturana & Varela, 1988). Behaviors within a consensual domain have also been referred to as *linguistic behaviors*[10] (Maturana, 1978; Maturana & Varela, 1980).

It is important to notice that all behaviors that arise from coordination of actions in a consensual domain are included in this definition of communication and not only those that can be described in semantic terms by an observer. Therefore, behaviors such as grooming, playing, the building of social relationships and the formation of hunting patterns *are* communicative behaviors.

Through the history of structural coupling with the medium, a correspondence can be identified by an observer between features, or 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 denote or describe a certain state of affairs. However it is a mistake to consider communication to be just a set of descriptive interactions used by the organisms to pass on information

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[9] As a symptom of this, we may consider the complications with these models that arise if the effects of phenotypic fitness, besides those of frequency-dependent fitness are included, (see Repka & Gross, 1995)

[10] Later on, the "linguistic" adjective has been reserved for those higher order recursive communicative behaviors in which the actions being coordinated are in themselves communicative actions.

in order to handle a particular situation. This is to ignore the fact that all interactions arise as a consequence of structural coupling between unities and that the relevant behaviors arise in each unity as a result of its own structure and are not prescribed by the perturbations that the unity suffers. Besides, denotations and descriptions cannot be primitive operations in the consensual domain. They require the existence of previous agreement. Therefore they cannot, by themselves, give rise to what we have called communication:

> "Language must arise as a result of something else that does not require denotation for its establishment, but that gives rise to language with all its implications as a trivial necessary result. This fundamental process is ontogenic structural coupling, which results in the establishment of a consensual domain.
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> Within a consensual domain the various components of a consensual interaction do not operate as denotants; at most, an observer could say that they connote the states of the participants as they trigger each other in interlocked sequences of changes of state. Denotation arises only in a metadomain as an a posteriori commentary made by the observer about the consequences of operation of the interacting systems" (Maturana, 1978, page 50)

From this point on this view can be extended in order to address many features of natural language including the behaviors of humans as observers, which, naturally, occur *in* language, but I will stop here, as the concepts of main relevance to the present work have already been presented.

3.3 Consequences and similar views

The most obvious consequence of adopting this point of view about communication is a broadening of the scope of phenomena that can be considered communicative. As the idea of a composite autopoietic unity that interacts with its environment through a process of structural coupling does not allow an account of its behavior in terms of inputs and outputs, at first sight, this account of communication will tend to be more complex than accounts that reduce the phenomenon to an informational exchange. What is gained, then, by adopting the former instead of the latter?

Independently of what one may think about theories of biological organization (of which the number is very small, partly because of the difficulty of the subject and not because of its importance), there are some characteristics of the autopoietic view of communication that, in my view, can only improve the current state of research. First of all, the scheme is unifying both "horizontally" and "vertically". I have mentioned that behaviors that cannot be accounted for in terms of information, such as group-behavior, playing, and many other social behaviors are included within this view along with more "traditional" communicative behaviors. Also, the same view can characterize communication at different levels of complexity. I will argue in the rest of this section how similar views have been used for studying the psychology of human interactions as well as to support certain philosophical views about human language.

Secondly, the focus on behavior, history the reality is that, while these mechanisms still need to be considered, their functioning is embedded in a set of constraints that most of the time is ignored. In the autopoietic view, ignoring these relationships is much more difficult, as they play a fundamental role in the definition of the phenomenon, so that one is compelled to address them.

The other advantage of the autopoietic point of view is that it explicitly addresses the relevance of the observer, by pointing at things that arise only in the domain of descriptions in contrast to features that are inherent to the process. This introduces the need to be careful and self-aware about the use of certain terms we take for granted.

Although the language of autopoietic theory was needed to make a concise presentation of this idea of communication as a process of interactions and recursive orientations of behaviors, this same view has also been expressed in a variety of forms in different fields. For instance, viewing the issue from a cybernetic perspective, it is possible to identify the most relevant exponents of this position: Pask's Conversation Theory (Pask, 1980) and von Foerster's eigen-behaviors (von Foerster, 1977, 1980) applied to communication.

Von Foerster builds his concept of eigen-behaviors based on the simple idea that perceptions and actions in an organism in possession of a nervous systems are circularly defined: actions determine future perceptions and vice versa[11]. This fact was already mentioned as one possible consequence of structural coupling in which an organism becomes recursively coupled with its own states. Put very simply in von Foerster's notation, if s_i stands for the activity in the sensorium and m_i for the motor activity at time i, this idea can be illustrated in the following way:

$$s_0 = M(m_0)$$

$$m_1 = S(s_0)$$

$$m_1 = S(M(m_0)) \doteq Op(m_0)$$

where S and M can be thought of as mappings from sensory to motor activity and vice versa. This implies the recursive application of the operator Op indefinitely until we arrive at:

$$m_\infty = Op(m_\infty)$$

where m_∞ is called an eigen-behavior of the organism which is the stable result of the infinite mapping of Op onto itself.

In communication we have two organisms mutually triggering each other's behaviors so that:

$$m_{\infty 1} = Op_2(m_{\infty 2})$$

$$m_{\infty 2} = Op_1(m_{\infty 1})$$

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[11] This is also an extension of the Piagetian concept of equilibration (see also von Foerster, 1977; Varela, 1979).

an activity in which there are partners, and in which the activity of each is modified and regulated by partnership. To fail to understand is to fail to come into agreement in action; to misunderstand is to set differences to be, in fact, their main concern. Therefore, it is possible to claim that the working out answers to many aspects of that problem, and producing a coherent account of those answers and their implications to be shared with the rest of the scientific community only to start the cycle the findings of this modification in the mathematical tools of game theory do not differ much from the original approach, then the latter should be used because the dynamics do not add much to the understanding of the problem. If, however, there are significant differences, then dynamical approach will be justified.

The computational approach, however, is still unjustified so far. This will be done at the end of Section 5 where the results of the mathematical modelling will be available. For now it will be broadly justified by stating that the mathematical modelling is itself very limited particularly in those aspects that may prove more relevant.

As a consequence of the definition of communication presented in Section 3, the computational model will be used in order to look at the mechanisms that affect the emergence of coordinated activity in a society of agents that evolves from an initial state of uncorrelated interactions. This will be done by simulating evolution under a scheme very similar to the one used in the mathematical model minus some simplifying assumptions. Computational simulations will be used to study spatio-temporal patterns and structures emerging in the geographical distribution of individuals, as well as correlations between signalling behavior and other activity.

Explanations provided by this approach will not have the character of general laws. They will rather address the importance of effects usually unaccounted for, such as structure, contingency and stabilizing mechanisms, all within the constraints provided by the satisfying scheme. Also, correlated activity will be shown to emerge even between agents sharing all the relevant information, proving that the metaphor of information exchange is inaccurate, and suggesting an interesting avenue of further research.

In other aspects the model will remain as simple as possible. A feature that will not be considered in the present work is the adequate modelling of the agent's structure. The focus will be primarily in global structuring patterns that emerge from, and constrain, the evolutionary process. No ontogenic model will be included, so no claim will be made about the very important effects of ontogenic structural change during the coordination of actions with the medium. Agents will be seen as simple unities for 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 very useful for the design and understanding of the present study.

Explanations will be built upon emerging properties of the model and, hopefully, we will be able to point to analogous properties in real ecological systems, so enabling us to formulate clear hypothesis about the role of those properties in such systems.

Other methodological considerations will be presented when the models (mathematical and computational) are described in detail.

5 A game of action coordination: mathematical model

In order to study the origins of communication as orienting activity I propose the following "game" to be played by pairs of agents living in a shared environment[15]. We will consider an *agent* as an unity that is able to act in the environment and, as a consequence of its actions, it can receive certain payoff in a given currency that we may call *energy* and also spends a certain amount of its own accumulated currency. For

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computational model with important differences in the results.

[15] This game is similar to the Basic Action-Response Game discussed in (Hurd, 1995).

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, for to act correctly over the piece of food that they are not able to see. However this may be against the immediate interests of the first agent who may receive a lesser payoff. The possibility of signals evolving out of non-signalling behaviors has been postulated by approaches from theoretical biology (see for instance Krebs & Dawkins, 1984) and can also be accommodated as an observer's description of a historical process of structural coupling. So, 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.

An interesting feature of this game is the temporality that is introduced in the with the computational implementation).

I will consider an environment in which there are only two relevant actions ("A" and "B") that the agents can perform in order to extract energy from a piece of food. Agents playing the first role in the game will emit one of two signals given unbiased choice of possible behaviors. With this information we may calculate the c^k_{ij} for this game, (Table 3):

$i \to j$	c^1	c^2	c^3	c^4
$1 \to 1$	1	-	-	-
$1 \to 2$	1/2	1/2	-	-
$1 \to 3$	c	-	0	-
$1 \to 4$	c	-	-	0
$2 \to 1$	0	c	-	-
$2 \to 2$	-	c	-	-
$2 \to 3$	-	1/2	1/2	-
$2 \to 4$	-	1/2	-	1/2
$3 \to 1$	0	-	c	-
$3 \to 2$	-	0	c	-
$3 \to 3$	-	-	1	-
$3 \to 4$	-	-	1/2	1/2
$4 \to 1$	1/2	-	-	1/2
$4 \to 2$	-	1/2	-	1/2
$4 \to 3$	-	-	0	c
$4 \to 4$	-	-	-	c

Table 3: Payoff matrix (c^k_{ij}) for the agent types 1, 2, 3 and 4. All numbers indicate the proportion of the average energy per food piece, c is the payoff for not communicating ($0.5 \leq c \leq 1$).

We must include one further constraint in this model: in order to model the μ_{ij}'s correctly it is necessary to characterize the species with a simple genetic model. The simplest is a 2-gene haploid model in which the first position indicates the signals that the agent emits and the second how signals are interpreted, with only two possible alleles. It is easy to see that, under these circumstances, μ_{ij} will be significantly greater between "neighboring" types than between "non-neighboring" types, (type 1 and type 3 are non-neighboring types, both alleles would have to be changed to go from one to the other). Otherwise, the μ_{ij}'s will be the same for each gene and for analogous mutations.

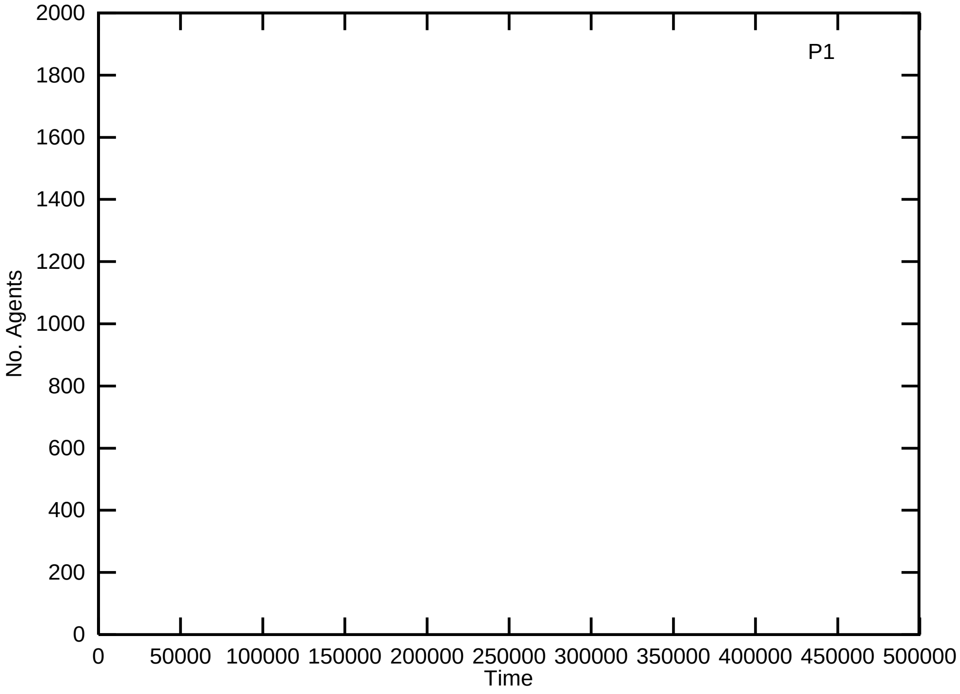
It is possible to prove that the system has a stable fixed point attractor in:

$$P_{1a} = P_{3a} = c,$$

$$P_{2a} = P_{4a} = N_a/2 - c,$$

$$F_a = \frac{2RF_Q(N_a - 1)}{N_a(N_a(1-c) + 2c)},$$

where $N_a = R/D$. In this scenario, the whole population is divided between agents of type 2 and 4 ($c = 0$). This is equivalent to say that a mixed strategy in which


P1
No. Agents
0
200
400
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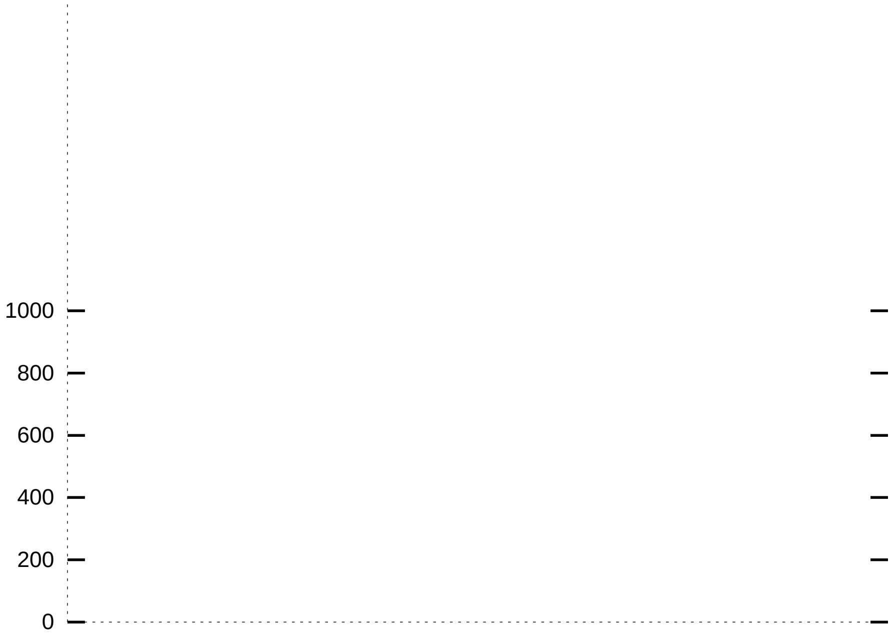
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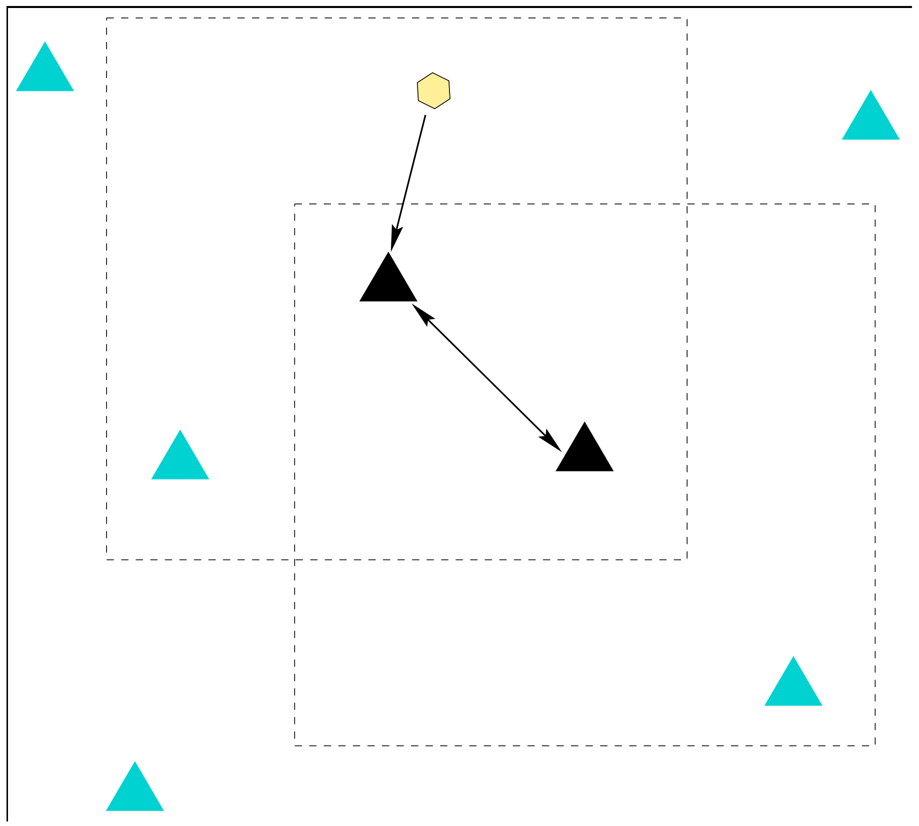
possibilities for studying the problem are greater due to the inherent flexibility of this approach.

6 A game of action



in the present work these features have been reduced to a minimum.

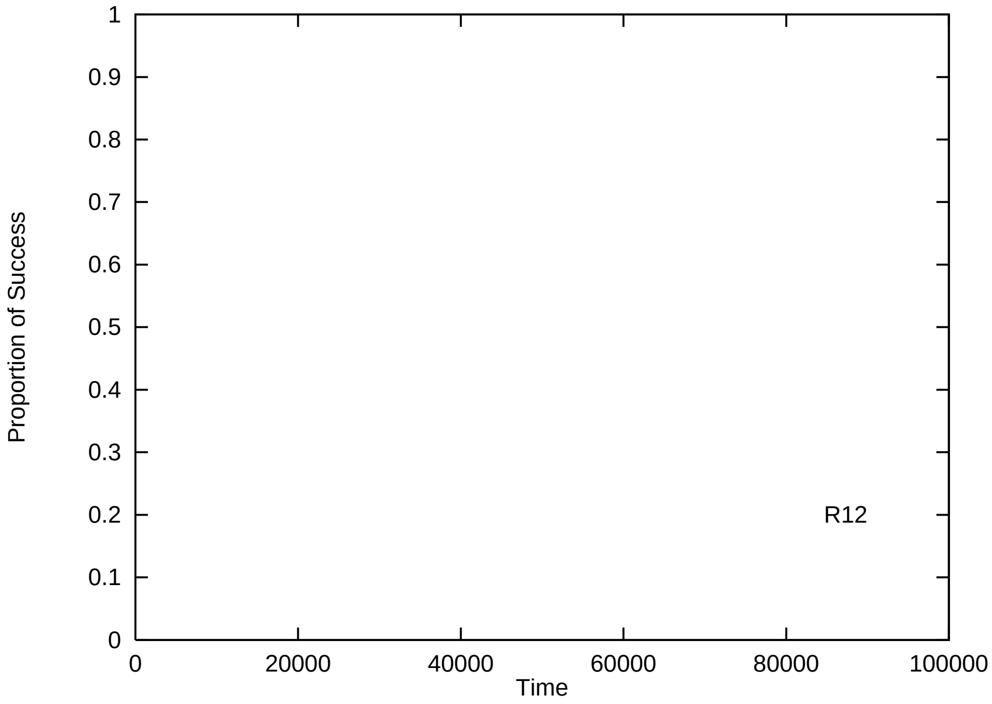
Actions depend on the perceived food type and on the perceived external manifestation of the partner in the game, when these are visible (an example of a behavioral matrix is shown in Table 4). The results presented later, with the exception of those in Section 6.4, correspond to simulations in which the game is played as described in Section 5, that is, with non-sharing of information about the environment. Agents playing the second role will only act according to the perceived external manifestation of the actions of the first agent, and on the base hypothesis that the food is type “A”. Correspondingly, the actions of the first player will depend on the perceived food type and on the base hypothesis that they perceive an external manifestation α. This means that, for this particular game in which there is only one interactive step, only one column and one row of the behavioral matrix will be used. Nevertheless, the whole matrix representation is kept as it will be used completely in the

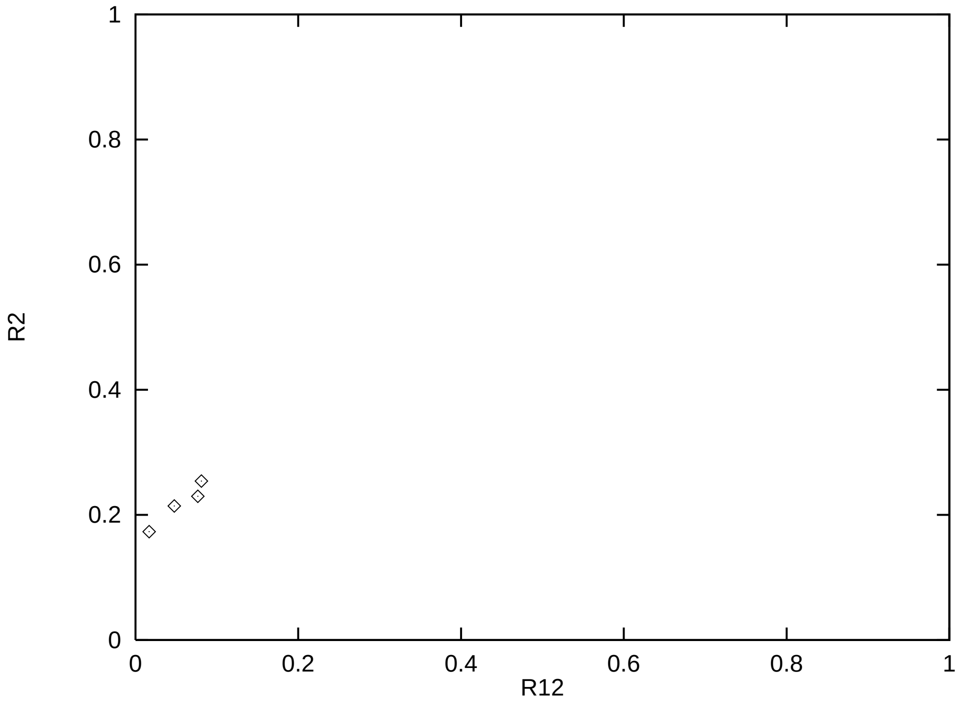
6.2 Success in coordination and correlations.

Results discussed in this section were obtained from two sets of simulations in which only four different types of food were included in the environment, in one of them each food type had a different associated action, and in the other a given action was correct for two food types and, therefore, only two actions were relevant (even when agents were able to perform more). Simulations with more food types and actions were also carried out, and the results were similar, though much more expensive to obtain and analyse.

In contrast with the mathematical model of Section 5, agents are initialized totally at random. This means that they will also have to evolve an association between food types and the effective components of actions when they play the first role, (in Section 5 we supposed that the first agent always acted correctly). This is a task that is consistently and very rapidly achieved in all the simulations, and its explanation in selective terms does not present any problem, given that each new correct association that is incorporated into the agents provides a net benefit for them and does not interfere with previous associations. In other words, the specific genes that code for these associations have no epistatic links with other genes in the genotype.

Both in simulations with four food types and four actions, and simulations with four food types and two actions (henceforth: “4-4” and that


Proportion of Success
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
20000
40000
60000
80000
100000
Time
R12


R2
R12
0
0.2
0.4
0.6
0.8
1
0
0.2
0.4
0.6
0.8
1

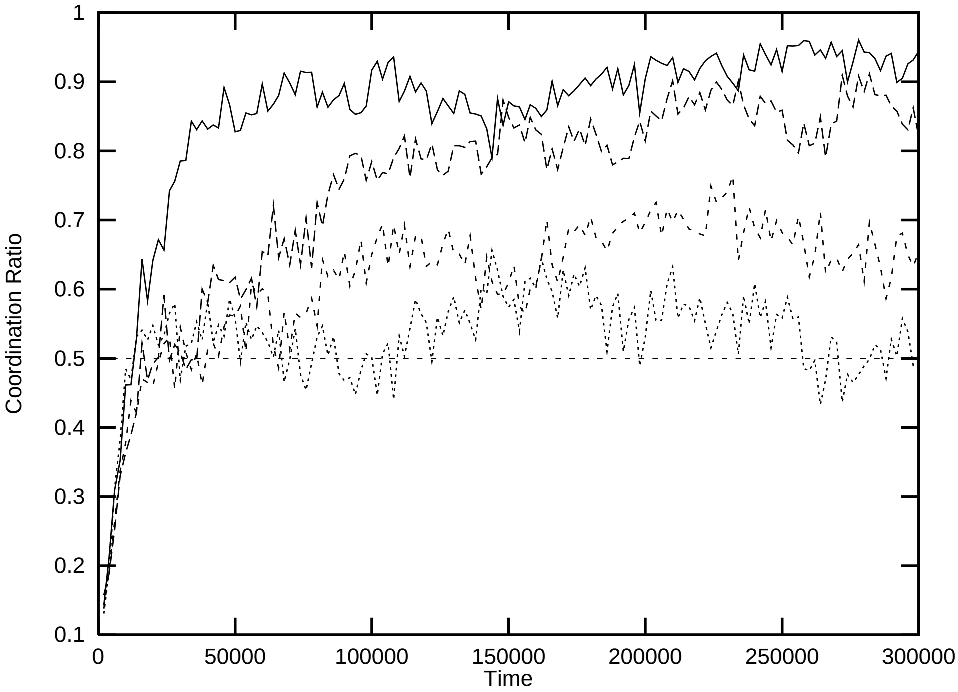
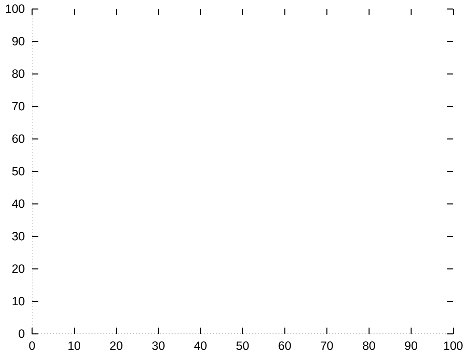
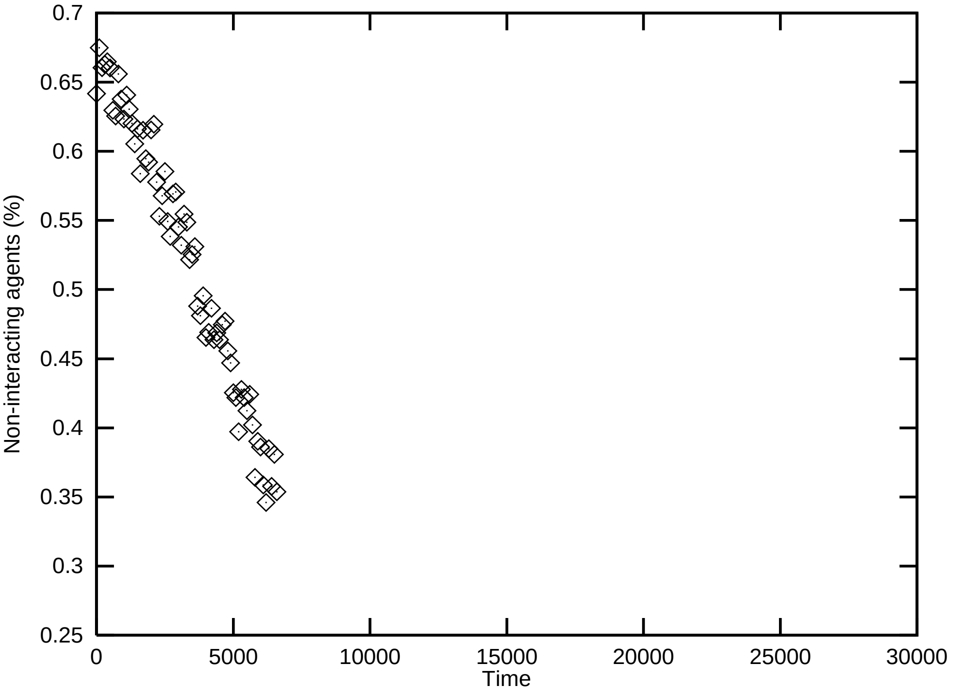

Coordination Ratio
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
50000
100000
150000
200000
250000
300000
Time

Figure 8:


100
90
80
70
60
50
40
30
20
10
0
0
10
20
30
40
50
60
70
80
90
100

agents will find a partner in another time step, and therefore they will still have a chance to survive. As far as the previous explanation goes this process ends once clusters are formed, and there are no agents that do not "belong" to a cluster.



involved are and how they reach an equilibrium and what happens when they don't. This task implies looking more sparse, and therefore, they will, on average, play the first role more times than the second role. The ratio between the frequency of being the second player with respect to the frequency in which agents act as first players have 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 play the game more frequently and, besides, they will perform the second role more frequently than agents living in sparse areas so they will stand a better chance of receiving (by communication, or just by guessing) more energy per unit of time. This provides the cluster with a tendency to *collapse*.

The equilibrium of both these tendencies determines, in principle, the size of the quasi-stable cluster. At a certain size the extra energy gained by the peripheral subpopulation will match the energy lost by their being more sparsely distributed than the center subpopulation (regions *C2* and *C1* in Figure 11). Resulting clusters have been observed to have a typical radius of 1 or 2 neighborhood sizes.

Energy transport. There is also a dynamical effect that reinforces the achievement important point to bear in mind in the argument that will follow.

6.3.2 Why does communication 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 *satisfy the conditions of both micro-environments and, consequently, they will necessarily possess the ability to communicate up to a certain level.*

This is consistent with the observed variation of the coordination ratio for the whole population with c (Figure 8). The level of successful coordination is above the baseline case for $c > 0.5$ and decreases until it reaches this level for $c = 0.7$. According to the above description at this value of c the advantages of being good interpreters for the center population are overcome by the advantages of not communicating even within their poorer-resource micro-environment.

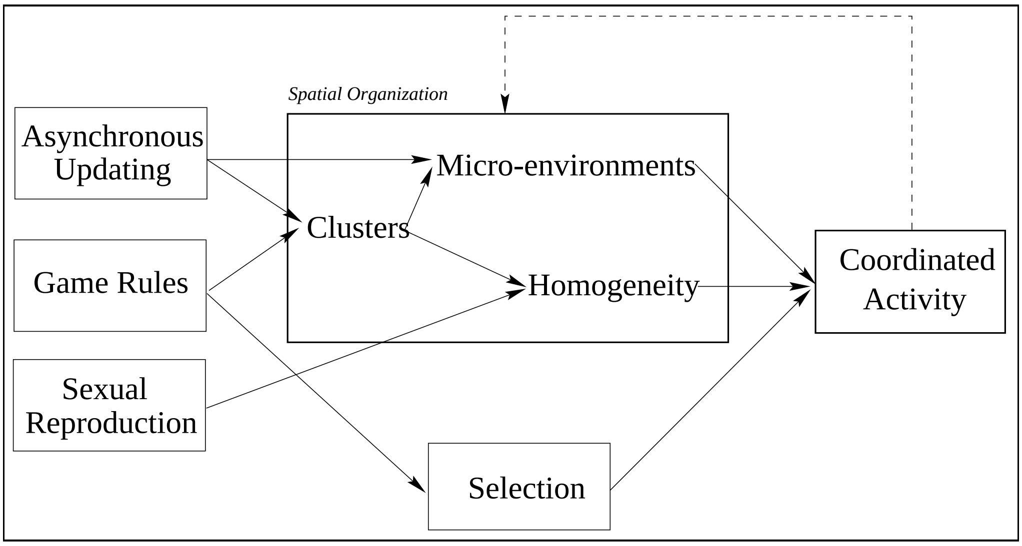


Figure 12: Explanatory mechanisms involved in the evolution of coordinated activity in the computational model.

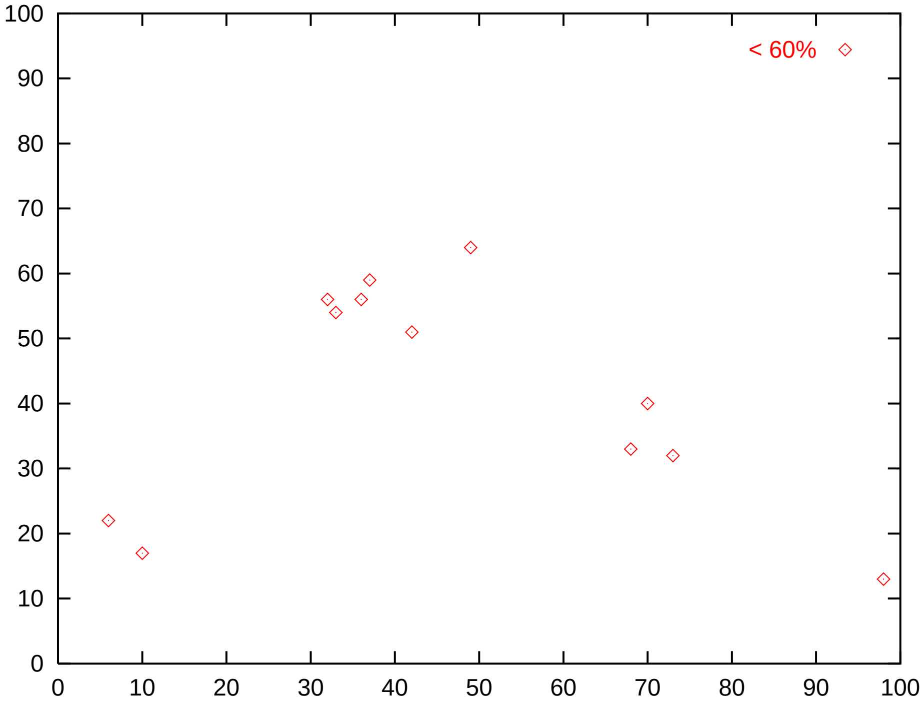
Thus, the evolution of communication in this model can be explained by the interplay of self-organizing and selective mechanisms. A diagram showing the relation between the components of this explanation can be seen in Figure 12, (the dashed line will be explained below). An alternative explanation could be attempted in terms of the mechanism of *kin selection*. Given the relatedness of agents inhabiting the same cluster, and given that coordinated activity results in greater payoffs at the population (if not at the immediate individual) level, then it would make sense for an individual to communicate with related individuals thus spreading the benefits over a number of other agents carrying the same genes. This is one of the possible mechanisms in which cooperative action can evolve within the neo-Darwinian framework. While kin selection may be playing an important factor in this case, this explanation cannot account for the stability of communicative behaviors in our model just by itself. If we ignore spatial factors, kin selection can explain good interpreter and a bad signaller, and therefore collecting the benefits of the existing communicating behaviors of others without contributing to those behaviors. Kin selection would work as an explanation only in the case of deceivers being sufficiently far in genotype space, so that the only way they could be reached is by the Dobzhansky-Muller (see Orr, 1995) mechanism of speciation, that is, by reproductive isolation.

In contrast, the explanation in terms of spatial organization can account for the stability of partial coordinated behaviors because it cannot be subject to the same criticism that the kin selection explanation. A lineage of deceivers *can* be born into a cluster with good communication level, and indeed these deceivers may do better than their communicating neighbors. But eventually, if not right at the beginning of the lineage, deceivers will have to inhabit a micro-environment in which communicators do better. As a consequence, the deceiver lineage cannot grow beyond a certain limit.

However, this explanation is itself, a first order approach. It has been found that, in general, coordination levels differ importantly among clusters. We still haven't explained the first question we set about to answer: why are there differences in the communicative behaviors of agents.

6.3.3 Many satisfying possibilities.

I have called the state achieved by the clusters quasi-stable. The fact is that clusters do change over time, but not very rapidly; the velocity of change is related to the speed of reproduction and the longevity of the agents. The more obvious


< 60%
0
10
20
30
40
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70
80
90
100
0
10
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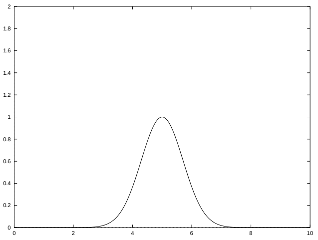
70
80
90
100



(a)

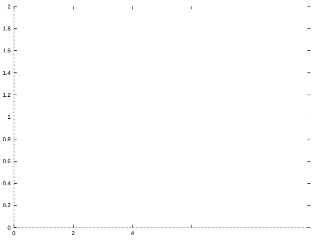


Figure 15 shows the evolution of the average instantaneous success in dialog over time for two typical runs with different values of c (variations a rather

sometimes conflicting, sometimes cooperating, processes underlying the phenomenon and, after that, proceed with the addition of hypotheses and simplifying assumptions.

Traditional approaches to the evolution of communication have shown a tendency to apply the simplifying step right at the beginning, proposing a single explanatory principle, natural selection, even a the definition level, and consequently, trying to understand the actions of this principle almost in a decontextualized manner.

This has been the reason for criticizing the "beneficial-information-exchange" approach to communication; because it is necessary, in order to view the phenomenon in its whole complexity, to deconstruct the simplifying steps of traditional approaches and rebuild our understanding of what constitutes communication and what does not on a more solid basis. Fortunately, autopoietic theory provided both a good candidate and a concise language for this task. Thus, communication was defined as the coordination of the actions of more than one organisms that arise during their structural coupling in a consensual domain, a description that parallels many other approaches to communication and language in cybernetics, psychology and philosophy. Also, a definition one can work with.

However, my critical stance does not compel me to blindly ignore the technical and methodological aspects of previous work in the area. This is why my first step was the choice of a game similar to those proposed in the theoretical biology literature on the evolution of communication, in which a common language in terms of costs, payoffs, etc., provided a continuity with these and the present works. Also, I did not ignore the tools, such as game-theory, used in these traditional approaches to understand conditions that allow equilibrium situations, but rather showed that the benefit of their use was limited even when modifications were introduced in order to account for dynamical effects as well. In this way the need for a computational approach was justified.

The computational model 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 can provide to study the actions of natural selection in the context of other concurrent processes such as spatial organization. Of course, nothing can stop us from changing the roles as to which mechanism should be viewed as the explanatory principle and which others as the context, except for questions of clarity. All we can really say is that evolution of communication in this model, can only be accounted for as the result of more than one interacting factor, and that such interaction can be explored and grasped, at least partially, thanks to the flexibility of the computational approach. The fact that these many concurrent processes influence each other is not enough to say that one is the cause of the other, thus it can be claimed that spatial organization is influenced by selection, processer and factors could have had an important influence in the real process. One such factor is, undoubtedly, *spatiality*.

An interesting case, in which the researchers arrive at very similar conclusions in another context, can be found in (Boerlijst & Hogeweg, 1991). This

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