# Emergence of Communication in Embodied Agents:
## Co-Adapting Communicative and Non-Communicative Behaviours

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## Abstract

*In this paper I discuss in which conditions a population of embodied and situated agents that have to solve problems that requires cooperation might develop forms of ritualized interaction and communication. After reviewing the most relevant literature I will try to identify the the main open research problems and the most promising research directions. More specifically I will discuss: (a) the type of problems, the agents' characteristics, and the environmental/social conditions that might facilitate the emergence of an ability to interact and communicate, and (b) the behavioral and cognitive capabilities that are crucial for the development of forms of communication of different complexity.*

## 1. Introduction

Existing models of emergence of communication often focus on specific aspects, such us (a) how a shared communication system can emerge in a population of interacting agents (e.g. Steels, 1999; Cangelosi & Parisi, 1998), (b) how a structured form of communication can emerge from a simpler unstructured communication system (e.g. Kirby, 2001; Cangelosi and Parisi, 2001), (c) language acquisition and transmission (e.g. Billard & Dautenhahn, 1999; Steels & Kaplan, 2001; Sugita & Tani, 2004). In this paper, instead, I will focus on the more general question of how a population of embodied and situated agents that have to solve a given adaptive problem might develop forms of interaction and communication that enhance their adaptive capability.

The motivation of this choice is twofold. The theoretical motivation is that communication and communication systems are adaptive capabilities shaped by their function. What, when and how agents communicate (and whether agents do or do not communicate) depends on the adaptive function of communication. Similarly the type of communication system that might self-organize in a population of interacting agents will strongly depends on the type of behaviour that individuals display in isolation and on the complementary functions that interactions and communications might have. The underlying assumption is that communication and language can be properly understood by taking into account their relation with other important behavioural, social, and cognitive processes. The practical motivation is that, from an application point of view, the possibility to develop embodied agents able to solve real life problems by exploiting complex forms of interaction and communication might have huge application potentials.

In this perspective, three additional aspects play a crucial role.

We are interested in models that not only lead to the development of a communication ability but that also allow the *discovery of categories (or coupled internal/external dynamical processes) that are useful from the communication and cognitive point of view* and that are not already explicitly or implicitly identified in the experimental set. Indeed, the need to communicate might lead to the development of an ability to categorize different environmental situations that in turn might constitute important pre-requisite for the development of individual cognitive abilities.

We are interested in models in which individuals, beside from reach signalling and interaction capabilities, also have a *reach sensory and motor non-communicative repertoire* that might allow them to improve their ability to solve their cognitive/adaptive problems by improving both their individual and their social/communication capabilities. This claim is based on the assumption that only by co-adapting their behavioural non-communicative and communicative abilities, individuals might develop a really useful communication system grounded in the physical and behavioural characteristics of communicating individuals and able to exploit active perceptual capabilities. Moreover, this claim is based on the assumption that one of the key aspects of communication is the possibility to rely on implicit information that does not need to be communicated.

Finally we are interested in models in which *forms of communication of different complexity might be used***.** By forms of communication we refer to the protocol with which individuals interact during communication and to the way with which communication signals are structured. Forms of communication might range from simple continuous broadcasted signalling to complex regulated communication protocols in which, for instance, communication acts are episodic and asynchronous, communication protocols are negotiated on the fly between the two communicating agents, and communication acts consists of sequences of signals organized according to a grammar. This claim is based on the assumption that more complex forms of communication are not effective in general terms. Therefore agents should be left free as much as possible to select the communication form that is most useful, given their current behavioural/cognitive capabilities.

The goal of this paper is that to identify the main open research problems and the most promising research directions. In the next section, I will briefly review the most relevant experimental work. In section 3, I will describe the crucial cognitive and behavioural capabilities that agents should have or should be able to develop in order to develop complex forms of communications. In section 4, I will try to identify the conditions that might lead to the emergence of effective embodied and communicating agents. Finally, in section 5, I will present my conclusions.

## 2. State of the art

In this section I will review the research works that are more relevant to the perspective outlined in the previous section. In section 2.1, I will review experiments in which agents, that are asked to solve simple tasks that require cooperation and coordination, develop simple forms of ritualised social interactions and/or signalling capabilities. In section 2.2, I will review experiments in which agents interacting according to predetermined ritualised interaction schemes and able to modify their internal states on the basis of the result of such interactions, develop an ability to successfully categorize external objects according to a self-organized shared vocabulary and ontology. The aim of this section is not that to provide an exhaustive review of the area (for broader reviews see Cangelosi and Parisi, 2002; Wagner et al., 2003, Steels, 2003a) but rather to identify theoretical and experimental contributions that might lead to the development of more powerful models and/or to models in which aspects previously studied in isolation can be integrated.

### 2.1 How simple forms of communication might emerge in teams of adaptive interacting agents

One interesting demonstration of how behaviours with communicative functions might emerge from the attempt to solve a task that requires cooperation and coordination has been provided by Quinn et al. (Quinn 2001; Quinn et al, 2003). The author evolved a team of mobile robots for the ability to move by remaining close to one another. Robots are only provided with proximity sensors (that also allowed robots to avoid colliding with one another) and therefore do not have dedicated communication channels. Evolved individuals are able to solve the coordination problem by communicating through a sequence of sensory-motor interactions. For instance, in a simple case described in Quinn (2001), two evolved agents coordinate according to the following sequence of behaviours: (1) both agents rotate clockwise, (2) the agent that first faces the other agent with its front (agent B) moves toward the other agent (agent A), (3) agent B remains close to A by moving backward and forward in order to compensate A's movements, (4) once agent A faces agent B with its front, it reverses his direction and then it starts to move forward by being followed by agent B. Agents A and B thus assume the roles of leader and follower respectively.

The motor action of the first aligned agent (i.e. the back and forth behaviour that allows agent B to stay close to agent A and that, consequently, produces a high activation of A's infrared sensors) serves as a signal for the other agent (as reported by Kirby [2002] we might gloss it in English as "after you"). In fact, "if the agent perceives the signal while it is still rotating, it will adopt the leader role. However, if it becomes aligned without having perceived the signal, it will perform the signalling action and subsequently take the follower role" (Quinn, 2001).

By analysing how the evolved behaviour originated evolutionarily, the authors observed how the behaviour of one agent that produces sustained proximity and that triggers the reverse behaviour in the other agent (i.e. the behaviour that has a communication value) resulted from the adaptation of other elementary behaviours (the obstacle avoidance behaviour and the back away behaviour) that did not have communicative functions. Indeed, by analysing the evolutionary process, the authors observed four phases:

(1) Initially (20-50 generations) agents just turn both motors on thus moving in straight lines
(2) Later on (50-100 generations) agents develop an ability to avoid each other. During this phase, the turning and halting responses displayed by the agents to avoid each other often result in 'deadlock' situations in which the two agents remains close one another.
(3) Later on (110-370 generations) deadlock situations are broken as a result of the fact that one of the two agents backs away from its partner after some time allowing the partner to move towards it for a while. The continuation of this process leads to a slow and jerkily movement of the couple.
(4) Finally (from generation 370 on) agents display an ability to reverse in response to sustained proximity. This new reversing behaviour that allow agents to start moving in a coordinated manner capitalises on the straight movement and avoiding behaviour that previously served other functions.

It might be questionable whether this form of interaction is a form of communication or not. Indeed, this is a paradigmatic case in which actions in general and communication actions can hardly be differentiated. This difficulty can be explained by considering that the term communication does not have a clear and uncontroversial definition (Di Paolo, 1997; Castelfranchi, in preparation) and that distinguishing between communicative and non-communicative actions is especially difficult in the cases of simple forms of communication. For the purpose of this paper it is sufficient to say that I will attribute a communication value to all actions or sequences of actions that, by influencing the sensory-motor flow of other agents, enhance the adaptive ability of the group as a whole. The reason why I do not simply call these actions communication acts is that, in addition to a communication value, they might have other functions (e.g. they might allow agents to avoid obstacles, an ability that does not necessarily influence the behaviour of other agents).

In another recent work, teams of 4 mobile robots have been evolved for the ability to aggregate and to move together towards a light target (Baldassarre et al. 2002, 2003). Robots are provided with two motors controlling the two wheels, a speaker continuously emitting a sound, infrared sensors, and directional microphones. As in the case of the Quinn's experiments described above, evolved individuals display an ability to coordinate by interacting/communicating so as to assume and maintain different roles. In particular, robots are able to form a square-like formation in which each individual robot maintains its relative position with respect to the light and to the other robots, while the whole group moves straight toward the light. Interestingly evolved robots are able to assume different roles despite teams are constituted by identical reactive individuals (i.e. agents that always react in the same way to the same sensory state).

By evolving teams of robots for the ability to solve a collective navigation problem, Marocco and Nolfi (submitted) showed how robots develop communication abilities and a vocabulary including 4 signals that influence both the motor and signalling behaviour of other robots. Robots are asked to find and remain on two feeding areas by equally subdividing themselves between the two areas. The team consists in wheeled robots provided with infrared and sound sensors and actuators controlling the two wheels and a sound speaker.

In this experiment: (1) the number, the form and the meaning of signals (i.e. the effects of signals on other agents) are not implicitly determined in the experimental setting but rather emerge during the evolutionary process, (2) non-communicative and communicative actions are tightly co-adapted so as to maximize useful properties emerging from their interactions, and (3) evolving individuals also display an ability to develop a simple form of communication protocol that allows them to switch signalling behaviours on and off.

Other researchers focused on the emergence of mutual interaction between two cooperating agents. Di Paolo (2000) reported the results of a set of experiments in which two simulated agents moving in an arena have been evolved for the ability to approach each other and to remain close together as long as possible. Agents are provided with: (1) two motors controlling two wheels, (2) a sound organ able to produce sounds with different intensities located in the centre of the agent's body, (3) two sound sensors symmetrically placed at ±45 degrees with respect to the frontal side of the agent that detects the intensity of the sound, and (4) a recurrent dynamical neural controller with four internal neurons. Evolved agents successfully approach each other by later remaining close to one another. Moreover:

(1) evolved individuals self-stimulate themselves through their own sounds. By reducing agents' capacity to ear their own sounds, in fact, the author observed that agents' performance deteriorated.
(2) the intensity of sounds produced by the two agents has a marked rhythmical shape that results from the interactions of the two agents. After some time, in fact, signals are phase-locked at some value near perfect anti-phase and the movements of the two robots become highly coordinated. This coordination between motor and signalling behaviours of the two agents cannot be explained by the ability of one of the two agents to adapt to the behaviour of its partner only, but rather by the achievement of a dynamical co-adaptation process (entrainment). As shown by the author, in fact, non-plastic beacons producing rhythmical signals are unable to trigger the same type of coordination process.

In a related work, Iizuka and Ikegami (2002, 2003) evolved two populations of simulated agents living in couple in an unstructured arena that should exchange their roles (chaser/evader) so as to produce a form of turn-tacking behaviour. Chasing and evading are defined as staying or not staying behind the other agent, respectively. Evolving agents are provided with a feed-forward neural network with three layers including: (1) three sensory neurons encoding the other agent relative position and orientation and three context units whose activation value is copied from that of the activation state of three additional output units at time t-1, (2) ten internal neurons, and (3) two motor neurons encoding the desired speed of the two wheels and three additional output units that are used to predict the activation state of the three sensory units at time t+1. Evolving agents are selected for the ability to alternate their roles and to predict each other's behaviour. Individuals are evaluated in pairs and each individual of a population is evaluated, in different trials, with all the individuals of the other population. The sensory state at time t+1 is used to compute a prediction error that is then used to change the connection weights according to the back-propagation learning algorithm.

The analysis of obtained results shows how in early evolutionary phases agents tend to produce regular turn taking (i.e. the two agents display regular trajectories that allow them to exchange their role periodically). In successive evolutionary phases, instead, agents tend to display chaotic turn-taking (i.e. the two agents display non-geometrical and an always changing trajectory without fixed periodicity). Regular turn-takers are comparatively insensitive to noise (probably due to their simple dynamics) with respect to chaotic turn-takers. However, chaotic turn-takers are better capable to adapt online to the other agent's behaviour with respect to regular turn-takers. Tests made by using passive agents (i.e. agents unable to adapt their behaviour on the fly) showed how the evolved turn-tacking behaviours are not simply forms of oscillator but rather forms of dynamic coupled behaviours resulting from ongoing two-directional interactions.

The visual inspection of the agents' trajectories and the analysis reported above seem to indicate that interesting forms of interactions and communication occur. Moreover, although the role of prediction learning is not analysed in detail, obtained results seem to indicate that the ability to predict the other agent's behaviour might constitute an important pre-requisite for the possibility to develop effective turn-taking behaviour.

Overall, the experimental results above demonstrate how individuals selected for the ability to perform a cooperative task might not only develop forms of communication but also primitive forms of communication protocols that in turn enhance their communication/interaction abilities.

Although these models provide important insights and demonstrate how simple forms of communication might emerge from scratch, however, they only lead to the development of simple forms of communicative and non-communicative behaviours. How these models can be extended in order to deal with more complex and reach situations is an open research issue that will be discussed in section 3 and 4.

### 2.3 How a population of communicating agents might lead to the self-organization of an ontology and a shared lexicon

In the Talking Head experiment, Steels (1999) demonstrated how the interaction between a population of embodied and communicating agents might lead to the self-organization of a shared lexicon as well as a perceptually grounded categorization of the world. Although the goal of this research is not that to observe how communication might emerge as an indirect result of the need to accomplish a collective task, this model represents an important reference point and provides important insights on crucial aspects that are simplified in the models reviewed in the previous section.

In the Talking Head experiment the environment consists of an open-ended set of geometrical figures (objects) pasted on a white board. The population consists of a number of software agents that are sequentially embodied into two robots provided with a pan-tilt camera and a simulated sound auditory and production systems (for a similar model implemented on mobile LEGO robots, see Steels & Vogt, 1997). The two robots look toward the white board and interact by playing a language game in which they assume the role of the speaker and the hearer, respectively. During each game, the speaker identifies a randomly selected object on the white board and produces a word or a sequence of words that should allow the hearer to identify the corresponding object. The hearer then tries to identify the area to which the speaker is referring to by visually pointing to the area itself. The speaker finally responds by pointing to the selected area thus allowing the hearer to identify whether communication was successful or not, and, in the latter case, which was the correct target area. As a result of each game and on the basis of the course of the game (e.g. the fact that the hearer already has in its vocabulary the words produced by the speaker or not, the fact that the hearer did or did not successfully identify the target area), agents modify their internal vocabulary and ontology (i.e. the meaning associated to the words of their vocabulary). The continuation of this process leads to: (a) an increase of successful games (up to almost 100%), and (b) to the development of an effective lexicon and an ontology shared within the population (i.e. a lexicon and an ontology that allows agents to play the language game successfully). Such self-organized lexicon and ontology also fulfils the environmental and body characteristics experienced by the agents (e.g. the discrepancy between the two agents' field of view, the reliability of the robots visual system, the specific type of objects and configurations of objects located on the white board).

Agents are provided with hand crafted sensory pre-processing routines and with predefined motor skills and schemas of interactions. Sensory pre-processing routines consist in: (1) software routines that allow an agent to extract a sequence of perceived objects and their relative properties (such as the horizontal and the vertical position of the object, its average grey scale value, its area, the number of edges etc.) from a visual scene, (2) software routines and position sensors that detect the point to which the speaker robot is visually pointing to, (3) software routines that allow the hearer to receive as input the sequence of words produced by the speaker. Motor skills consist in, for example, a software routine that allows an agent to identify a unique area on the visually perceived scene on the basis of a sequence of words with their associated meanings. Schemas of interactions consist, for example, in: (1) routines that create a new word with its tentative associated meaning in the vocabulary of the hearer when it hears a word that it is not included in its vocabulary, (2) a routine that creates a new word in the vocabulary of the speaker when none of its current words uniquely identify the current selected object of the white board, (3) a routine that updates the communication success rate associated to words, etc.

What results from the changes in agent's internal structures occurring during agent's interactions are: (1) a perceptually grounded categorization of the world (consisting of a lexicon and a corresponding ontology), and (2) the convergence of the population toward a sufficiently shared lexicon and ontology. As an example of word/meaning formation, consider that the horizontal position of an object ranging from 0.0 to 1.0 might be categorized into two categories/words (corresponding, for example, to the two halves of the range) or into finer and finer categories with their corresponding words. As a second example consider that one object (i.e. a red triangle located in the top-left side of the board) might be discriminated in different ways (e.g. by using words that indicate its shape and colour or its position). Finally, consider that the same meaning can be associated with two or more words and two or more words might have the same meaning (both at the level of the single agent or at the level of the population). Indeed, by analysing the frequency of words used to express a single meaning in one experiment, one can observe a struggle in which different words compete until the population settles on a single dominant word. This winner-take-all effect is due to a positive feedback loop between use and success. The more agents prefer a particular word, on the average, the more they use this word and the more success this word has.

In a successive work, Steels and Kaplan (2001) used a similar approach to study how a Sony AIBO robot might acquire a lexicon and a corresponding ontology by a human mediator with whom it plays a similar language game. The use of a mobile autonomous robot (rather than a pan-tilt camera placed on a fixed position as in the case of the Talking Head experiment) introduces significant new complexity from the point of view of the categorization problem given that objects are almost never seen in their entirety and objects' perceived images significantly vary on the basis of the robot/head/object relative positions and orientations. The robot/human interaction is regulated on the basis of a predefined sequence of elementary behaviours (a language game). More precisely:

(1) The human mediator first shows an object to the robot by placing the object in the robot's field of view and by saying "look", a word that helps the robot to focus its attention on the current visual scene. The robot then concentrates on the object by trying to track it and touch it.
(2) The human label the object with a word ("ball" for example).
(3) The robot tries to pronounce the same word. The human mediator then provides a positive feedback (i.e. pronounce the word "yes") or repeats the original word if the word it hears is different from the one it previously produced. If the word is a new one for the hearer robot, it creates a new word in its vocabulary.

(4) The robot stores in its memory a perceived instance of the object and associates it with the corresponding word. The comparison of a new perceived image with the labelled images previously stored later allows the robot to identify and name an object without the help of the human mediator.

As pointed out by the authors, several problems might arise during these human/robot/environment interactions. For example, the robot might have heard a wrong word due to problems with speech recognition or the robot might not have been paying attention to the right object. The impact of these problems, however, is minimized by the interactions with the human mediator regulated by the language game script (i.e. the human mediator repeats the word if it has not been properly understood by the robot or tries to bring the robot's attention on the right object when the robot pays attention to something else). For a related model that addresses how a communication ability can be socially transmitted from a robot with a predetermined lexicon to other robots see (Billard and Dautenhahn, 1999).

These models present two important advantages with respect to the models described in the previous section, namely: (1) the ability to exploit social learning, and (2) the ability to exploit ritualised interactions between agents (language games). The implication of these aspects will be discussed in the next sections. The main limitation of these models is that, aside from the content of communication acts, the behaviours of agents is rather predetermined and fixed. This prevents the possibility to exploit a co-adaptation between communicative and non-communicative forms of behaviour. Moreover, this makes these models not suitable to solve general co-cooperative problems (e.g. cooperatively explore an unknown area) or to study how ritualised interactions, language games and vocabularies might have originated.

## 3. Open research problems: identifying and integrating crucial cognitive/behavioural capabilities

The attempt to model how a population of embodied agents trying to solve problems that require cooperation and coordination might develop complex forms of communication and a shared communication language is a formidably complex enterprise. The research works reviewed in the previous section show how several aspects that might allow to achieve this goal can be modelled (e.g. how signalling behaviours and primitive forms of communication protocols can emerge, how communicative and non-communicative behaviour can co-adapt, how a population of interacting agents might develop a shared lexicon and ontology). However, the modelling of other crucial aspects (e.g. compositional languages and grammar) is only at a very preliminary stage (Steels, 2003a). Moreover, a significant challenge is constituted by the need to integrate aspects that have been successfully modelled in different experimental settings into a single coherent model. In the rest of the paper I will discuss how important that might represent important pre-requisites for the emergence of complex forms of communication can be modelled and how all the necessary aspects might be integrated into a single model.

From an evolutionary and developmental perspective the most straightforward way to approach the issue of how complex forms of interaction and communication can emerge is to start from simple but open-ended models that might lead to the emergence of progressively more complex forms of communication and cognitive capacities. After all, this is how these abilities emerged in natural life. This possibility, however, can reasonably be pursued only as a long-term research goal. On the short term, it is reasonable to assume that progresses might be only achieved by predefining, in the starting conditions, crucial elements or capacities that although in theory could spontaneously emerge in the course of the process, in practice, would very unlikely do so. These elements or capacities might consist of agent's pre-determined architectural constraints, learning algorithms, interaction schemas, etc. From this point of view our problem becomes that of identifying the crucial minimal set of pre-requisites that might trigger the emergence of complex forms of interactions and communications.

## 3.1 Adaptation processes

A fundamental aspect for the emergence of complex interaction and communication abilities is the adaptation process or the combination of adaptation processes selected. The models reviewed in section 2.1 rely on an evolutionary process (i.e. a process based on selective reproduction and random variation) while the models described in section 2.2 rely on a form of ontogenetic learning (i.e. a process in which agents modify their free parameters as a result of their interaction with the physical and social environment). These two forms of adaptive processes have complementary characteristics and can be effectively integrated (see Nolfi and Floreano, 1999). In this section I briefly discuss some of the potential advantages of integrating an evolutionary and a learning process.

Artificial evolution, by only requiring an overall evaluation of the performance of an agent or of a group of agents, is a straightforward method to select solutions in which different characteristics co-evolve and co-adapt. For example, as clearly shown in the models reviewed in section 2.1, it is an effective way to co-evolve communicative and non-communicative behaviours. Learning, on the other hand, by being based on changes introduced as the result of the continuous interaction with the physical and social environment, can potentially exploit the huge amount of information that agents collect through their sensors during their lifetime. This information does not provide direct cues on how agents should change to solve their adaptive problems. However, combined with additional evolved mechanisms able to transform sensory information into teaching or reinforcement signals (Ackley & Littman, 1991; Nolfi & Parisi, 1997) or able to channel changes on the basis of genetically encoded constraints (Floreano & Urzelai, 2001) can lead to powerful ontogenetic adaptive processes.

Evolution and learning operate on different time scales. Evolution is a form of adaptation capable of capturing relatively slow environmental changes that might encompass several generations. Learning, instead, allows an individual to adapt to environmental changes that are unpredictable at the generational level. Indeed, the combination of evolution and learning can lead to an ability to develop the required behavioral capabilities and to an ability to select on the fly the right strategy on the basis of the current environmental circumstances (Nolfi & Parisi, 1997; Nolfi & Floreano, 1998; Floreano & Urzelai, 2001).

More generally, the interaction between evolution and learning deeply alters the dynamics of the two processes so that their dynamic in interaction is very different from their dynamic in isolation. Indeed, evolving plastic individuals tend to develop a predisposition to acquire their capabilities through learning rather than, directly, an ability to behave effectively as in the case of evolving non-plastic individuals. This predisposition to learn may consist of: (1) the presence of starting conditions that canalise learning in the right direction, and/or (2) an inherited tendency to behave in a way that maximizes the chance to be exposed to useful learning experiences. Similarly, while in non-evolving individuals the value of free parameters prior to learning is a constraint that should be overcome, in evolving individuals inherited genetic parameters prior to learning represent an opportunity to be exploited during learning (Nolfi, 2002c).

Finally, as I will discuss in Section 4.3, social learning (i.e. learning from others) might potentially allow evolving individuals to acquire capabilities independently discovered by other different individuals.

## 3.2 Agents’ sensory-motor structure

Another aspect that strongly affects the potential outcome of experiments involving a population of interacting agents is the type of sensors and motors (actuators) with which agents are provided. I will not discuss here the possibility to co-evolve/co-adapt the body and the control system of agents although this possibility certainly provides potential advantages (Harvey et. al., 1994; Sims, 1995; Bongard & Pfeifer, 2003). Rather I will try to identify general criteria that the experimenter might follow in determining a suitable sensory-motor structure.

The first aspect that should be stressed is that sensors and actuators do not have independent functions. Indeed, by interacting with the external environment (i.e. by modifying their own position or orientation with respect to the environment or by modifying the environment itself) agents might greatly simplify the problem of categorizing environmental situations that require different motor reactions (Scheier, Pfeifer & Kunyioshi, 1998; Nolfi, 2002a; Nolfi & Marocco, 2002; Beer, 2003; Nolfi, in press). Moreover, the possibility to interact with the environment by producing simple stereotyped behaviour, might allow agents to indirectly detect complex environmental regularities (Nolfi & Marocco, 2002; Nolfi, in press). In other words, reach sensing capabilities might be more likely obtained by complementing a set of sensors with motors that allow agents to interact with their environment rather than by simply adding additional sensors. It should be noted, however, that to really exploit sensory-motor coordination agents should not only be provided with sensors and effectors but should also be able to modify (through an adaptation process) the relation between sensors and motors. In the Talking Head experiment reviewed in section 2.2, for example, agents are provided with motors controlling the pan-tilt movement of the camera. However, given that the motor behaviour of these agents is predefined and fixed, the way in which they interact with the environment cannot be co-adapted with their current ontology.

A second important aspect that should be stressed is that communicative and non-communicative sensory-motor channels cannot and should not be separated. In fact, elementary behaviours that initially do not have any social functions and that have an impact on the sensory systems of other agents might later on assume a social/communicative function. These forms of pre-adaptations (in which traits evolved for a non-social function later assume a social/communicative function eventually loosing, later on, their original non-social function) might play an important role in the emergence of communication. Indeed, they seems to have played a crucial role in the origin of the communicative behaviour described by Quinn (2001) and reviewed in section 2.1.

The fact that in natural organisms (and probably in self-organizing artificial agents) sensors and actuators tend to have both non-communicative and communicative functions, however, does not imply that some type of sensors and actuators and some sensory-motor modalities might potentially have a strong communication potentials. This is the case, for example, of the sensory-motor structures that allow pointing, detection of pointing (e.g. gazing, head-movements, arms and fingers movements etc.).

Moreover, some types of sensors and actuators or sensory-motor modalities might be especially suited for communication for their ability to convey information ready to be used from other agents. As an example of this category consider pheromone that: (1) by lasting a significant amount of time can be detected over a significant time range, (2) by remaining in the physical area in which it has been synthesized can convey spatial information in a ready to use way, (3) by summing up the trace left by different individuals can provide compact information on what several individuals did.

### 3.3 Cognitive capacities

In addition to suitable sensors and actuators, embodied and communicating agents should be provided with a control system that determines the activity of the actuators on the basis of the current and previously experienced sensory-motor states. Although simple forms of communication might be developed by relying on very simple control systems (e.g. reactive neural networks in which sensory neurons are directly linked with motor neurons and motor actions are only based on current sensory states), the development of more complex forms of communication might require much more complex “cognitive” abilities.

Two basic capabilities that embodied and communicating agents should have are: (1) the ability to form internal categories by mapping sensory patterns or sequences of sensory patterns that require similar motor reactions into similar internal states or into similar internal dynamics, and (2) the ability to generalize, that is the ability to react to new sensory patterns (or sequence of sensory patterns) on the basis of their similarities with previously experienced sensory patterns (or sequence of sensory patterns).

While the possibility to form categories based on single sensory states and the ability to generalize on the basis of these categories have been successfully modelled (Cangelosi & Parisi, 1998; Steels, 1999; Steels & Kaplan, 2001; Marocco et al. 2003), the possibility to form categories based on regularities that can only be detected by looking at how sensory states change in time is still far from being well understood. Consider, for example, cases in which agents have to discriminate different locations of the environment on the basis of the occurrence of different sequences of sensory cues (Nolfi, 2002b), or select moving objects to be caught on the basis of their trajectories (Beer, 2003). To perform these categorization processes agents should be able to takes into account aspects such us the duration of an event or the sequence with which different events occur that can only be detected by looking to how sensory states change in time. For recent results that indicate how the availability of internal states that change at different time rates might represent an important pre-requisite for solving this problem, see (Nolfi, 2002b; Gers, Schraudolph & Schmidhuber, 2002; De Croon, Nolfi & Postma, in press). Recent results also indicate the importance of viewing categories as dynamical internal processes rather than as fixed-point attractors in agents' internal dynamics (Beer, 2003; Sugita and Tani, 2004; Iizuka and Ikegami, in press). For an attempt to model categorization as a bi-directional coordination between the dynamics resulting from the agent/environment interaction and the agent's own internal dynamics see (Di Paolo, 2000; Iizuka and Ikegami, in press).

The emergence of complex forms of communication might also require other more complex cognitive capacities such as the ability to predict the sensory-motor consequences of agents' own actions (Nolfi and Tani, 1999; Clark and Grush, 1999), the ability to predict changes in the physical and social environment, the ability to learn from others or to imitate other agents' behaviour (Billard, 2000; Tani et al., in press) etc. The later issue will be discussed in more details in section 4.3.

An additional interesting aspect that might be investigated is whether the ability to have access to their own communication acts (i.e. talking to themselves [Steels, 2003b]) might improve the ability of agents to communicate and/or the ability to acquire complex cognitive abilities.

Finally, the emergence of complex forms of communication very likely requires selective attention mechanisms and/or an ability to modify communication behaviours on the basis of the potential targets of communication acts. This aspect will be discussed in more details in the next section.

### 3.4 Interaction/communication protocols

The adaptive potential of social interaction/communication significantly depends on the protocol that regulates communication between agents. Indeed, communicative actions might have counter-adaptive effects on other agents' behaviour and on the adaptive capability of the population as a whole. For instance, communication acts might interfere with other agent's behaviours thus preventing or delaying the ability of these agents to accomplish their current tasks.

In general terms, one can expect that the adaptive potential of communication depends on the ability of agents to regulate their communication acts on the basis of a suitable interaction/communication protocol and specifically:

(1) The ability of agents of limiting communication acts (e.g. signalling behaviors) to those that can increase the adaptive capability of the team. Interestingly, this aspect might lead to an

adaptive pressure to use dedicated communication channels (i.e. to detach communication actions from non-communicative behaviours).

(2) The ability to detect the potential target agents of communication and to filter and/or re-code communication so as to provide to receivers relevant, useful, and ready to use information. This ability to modify communication on the basis of receivers' needs might include, for example, the ability to re-code spatial information on the basis of the relative position of the 'speaker' and the 'hearer' or the ability to detect the adaptive needs of target agents.

(3) The ability to approach other agents in order to communicate, to potentially receive communicative information, to select good learning experiences, or to achieve joint shared attention (on the last aspect see Billard & Dautenhahn, 1999).

(4) The ability to regulate the communication flows by taking turns (Iizuka and Ikegami, 2003a, 2003b) or more generally the ability to carry on communication behaviours consisting of several bi-directional communication acts.

(5) The ability to increase communication success through a ritualised form of interaction (Steels, 1999) between communicating agents (e.g. a communication protocol in which the hearer repeats the detected communication signal and waits for a confirmation from the speaker).

(6) The ability to communicate through signals with time-varying properties or sequences of signals structured according to a grammar.

Obviously, the full set of abilities is only required in complex forms of communication. Simple communication forms, such us signalling of danger situations, in which: (1) few different signals are needed to communicate the relevant information, (2) communication acts occur only sporadically, and (3) communication acts have a priority on all other types of activities and are relevant for all members of the population; communication might successfully emerge without the need of any communication protocols.

## 4. Open research problems: identifying the conditions that might lead to the emergence of ECAgents

While in the previous Section I tried to identify the functional components that should be integrated to lead to complex forms of communication, in this section I will try to identify the conditions that might lead to complex forms of interaction and communication. Given the difficulty of the enterprise, our goal is not the attempt to answer to this question, but simply to identify open problems and sketch some interesting research directions.

### 4.1 How communication can emerge as a result of indirect selective pressure

One first important open question concerns whether non-trivial forms of communication can evolve as a result of an indirect selective pressure originating from the need to solve a given adaptive problem. This question involves two aspects: (1) the identification of the structural, cognitive and behavioural prerequisites for the emergence of complex forms of communication, and (2) the identification of the situations (i.e. the class of problems and/or the environmental and social conditions) that might exert an adaptive pressure to communicate. While in the previous section I focussed on the former issue, in this section, I will focus on the latter.

As I claimed in the introduction, the attempt to evolve communication without explicitly rewarding it is crucial to allow the emergence of a self-organization process in which: (a) communication abilities and communication systems are not indirectly predetermined by the experimenter, (b) communicative and non-communicative behaviour can freely co-evolve and co-adapt, and (c) individuals are free to determine the most effective way to categorise sensory-motor information. However, this leaves open the problem of determining the conditions in which indirect selective pressure on communication can be expected.

In their pioneering work on evolution of communication Werner and Dyer (1992) suggest that an evolutionary pressure on agents to communicate should be expected in cases where “animals [agents] have information that other animals needed to know but were not capable of finding out by themselves” (Werner and Dyer, 1992, pp.661). This general hypothesis might be further detailed by identifying the conditions in which this situation occurs. Indeed, we might identify at least the following cases:

(a) Information related to the internal states of an individual beyond the nervous system (e.g. hormones, internal organs, immune system, emotional states etc.). This information might be highly valuable in order to determine how socially interact properly. Moreover, information related to the internal states of an individual might indirectly provide compact cues on the previous sensory-motor experiences of that individual.
(b) Information related to the current sensory state experienced by an individual (e.g. sensory information indicating the presence of a predator). This form of information might be useful to other individuals that, by being located in different positions and orientations or by not being provided with the same sensing capabilities might not have access to it.
(c) Information related to what an agent is going to do (e.g. information related to the action that an agent is going to perform or related to more abstract intentions of an agent).
(d) Information about the external environment collected by an agent during its previous interaction with the environment (e.g. information on the location of a food source that is no longer in the agent’s sight).

Other aspects that might co-determine whether or not an indirect selective pressure on communication could be expected regards the relation between individual and collective interests (an issue that will be discussed in the next section), the nature of the problem (i.e. whether or not the problem requires cooperation), and the relative organization of the interacting agents (whether the problem requires specialization and whether agents can assume different specialized roles). With respect to the last aspect, a selective pressure on the emergence of communication might more likely be expected in a team of homogeneous rather than in non-homogeneous agents. As showed by (Haynes and Sen, 1996a, 1996b) in fact, while agents that are not specialized might need to communicate to negotiate their role on the fly, specialized agents do not need to communicate in order to negotiate their relative roles.

### 4.2 Adaptive factors in the evolution of communication

Beside the problem of determining how a given problem might exert an indirect adaptive pressure on the emergence of communication, we should be able to identify the conditions in which communication might emerge evolutionarily. The emergence of communication in fact, requires the development of two complementary but independent abilities: an ability to produce signals (from the point of view of the signaller) and an ability to appropriately react to received signal (from the point of view of the receiver). When selection operates at the level of individuals, two aspects might prevent the emergence of communication, namely: *the lack of an adaptive benefit for the signaller* and *the conflict between individual and collective interests*.

The first problem is due to the fact that in many cases, also occurring in natural communication (e.g. in the case of alarm calls), signalling behaviours provide an adaptive advantage for the receivers but not direct benefits for the signaller. The lack of an adaptive advantage, from the point of view of the signaller, might prevent the preservation of genetic characters that lead to signalling behaviours even if these behaviours are useful for the receivers and for the group as a whole. The second problem is due to the fact that, even in cases in which communication emerges, the evolved strategies are not stable and are easily invaded by mutant individuals that produce different signals. In this condition in fact, mutant's fitness will remain the same while the fitness of the other members of the population, that are unable to correctly interpret mutants' signals, will decrease. This selective advantage gathered by the mutant individuals to the expenses of the other individuals and of the population as a whole will allow mutant individuals to leave more offspring and will consequently lead to the loss of the ability to communicate. For a simple demonstration of how communication fails to evolve in a population of disembodied agents in which communication only provides an adaptive advantage for the receivers, see Oliphant (1996). For a demonstration of how the evolutionary dynamics might lead to an instable situation in which an ability to communicate periodically evolves and then is lost due to mutant signallers invading the population, see Batali (1995) and Mirolli and Parisi (2004, in preparation).

As demonstrated in several experimental studies, however, other factors might counter-balance these adaptive problems and might lead to the emergence of a stable communication system. For instance a stable communication system emerges in experiments in which: (1) the population is spatially distributed and individuals are more likely to communicate and mate with those close to them (Oliphant, 1996), (2) the same set of internal neurons of agents' controller determine both the motor and signalling behaviour of the agent and receive both sensory and communicative information (Cangelosi and Parisi, 1998), (3) agents (provided with the same neural architecture described above) receive communication signals only from their parents and are allowed to communicate only after a first evolutionary phase in which they can develop their individual capabilities (Marocco et al., 2003). In any case, although these and other ecological factors (see Di Paolo, 1997; Noble et al., 2002) might counter-balance the lack of direct benefit for signalling and the advantage for individuals to deceive, these two factors will in any case tend to prevent the emergence or the preservation of communication. Indeed, if we compare the experiments described in Cangelosi and Parisi (1998) and Marocco et al. (2003) that differ with respect to the complexity of the problem, we can see that why in the former the constraint on agents' neural architecture was enough, in the latter communication only emerged by also restricting communication acts between parents and by allowing individuals to evolve their individual ability before communicating. The question of how complex communication systems can emerge without a direct benefit for the signaller therefore largely remains an open problem.

Obviously, these adaptive problems do not affect (or at least are much less important) in cases in which communication provides an adaptive benefit for both producers and receivers. This is the case, for example, of mating signals (for an example of how this type of communication might emerge in a population of artificial agents, see Werner and Dyer [1991, 1994]).

Finally, these adaptive problems do not affect (or at least are much less important) in cases in which agents are selected on the basis of their collective performance (Baldassarre, Nolfi, and Parisi, 2002, 2003; Quinn et al., 2003; Marocco and Nolfi, in press). Interestingly, a similar situation occurs in colonies of some social insects (e.g. in bees) in which most of the individuals are sterile and in which individuals are very genetically related. For a systematic comparison of the effects on the emergence of communication of the selection schema (individual or team selection) and/or of the level of genetic relatedness among individuals see (Magnenat & Floreano, in preparation).

### 4.3 Social Learning and Culture

Agents might develop an ability to communicate and a shared communication system phylogenetically (i.e. through changes occurring over generations) or ontogenetically (i.e. through changes occurring during agents' lifetime). While in the former case characters that allow communication are encoded genetically and are transmitted and varied during agents' reproduction, in the latter case the characters that allow communication are transmitted and varied through social learning. These two modalities are also referred to with the terms: genetic evolution and cultural transmission or cultural evolution (for an example of how cultural evolution might lead to the emergence of an ability from scratch through variations arising during social imitation and selective reproduction, see Parisi & Denaro [1996]). Cultural transmission and evolution plays a central role in human language but it also plays a role in some forms of animal communication (e.g. in monkeys, squirrels, birds etc., see Wagner et al, 2003). Moreover, when both genetic and cultural factors are present, communication emerges as a result of the interaction between three adaptive processes: genetic evolution, individual learning, and cultural evolution (or social learning) that have different characteristics and operate at different time scales.

The issue of how artificial evolution, online adaptation, and social learning techniques might be effectively combined together is a largely unexplored research area in this field. Indeed, although methods that combine evolutionary and learning algorithms (e.g. evolutionary algorithms with reinforcement learning algorithms or with hebbian learning algorithms) have been already proposed and investigated by several authors (see Nolfi & Floreano, 1999; Nolfi, 2002c), the study of social learning in situated agents is an area that is gathering an increasing research attention but that it is still in its infancy (Lindblom and Ziemke, 2003). For a pioneering attempt to study how the combination of evolution and learning might favour the emergence of communication and a critique of obtained results see MacLennan & Burghardt (1993) and Noble and Cliff (1996).

Advances in social learning techniques and methods for combining evolutionary and social learning might produce significant insights on how complex forms of communication might emerge from the interaction between situated agents. Indeed, social learning has specific features that might greatly enhance agents’ ability to acquire complex skills. As an example of these features we should consider that in social learning agents play two roles (a student role and a teacher role) and consequently might improve both their ability to learn from others and their ability to facilitate other agents’ learning. In other words, agents that learn socially might exploit the fact that the social environment with which they interact during learning, unlike the physical environment, has been co-evolved to favour the ability to acquire adaptive skills through learning (at least in the case in which interacting agents have an interest in cooperating). As a second example, we should consider that acquiring skills from different agents potentially allow individuals to combine several adaptive characters discovered independently by different individuals and resulting from both genetic and ontogenetic variations. Genetic assimilation (Baldwin, 1896; Waddington, 1942) might later assure the genetic fixation of characters previously acquired ontogenetically, where appropriate.

## 5 Conclusions

The attempt to develop agents able to solve collective problems by cooperating and communicating through a self-organizing process is an extremely ambitious goal. Achieving this goal, in fact, imply to understand which initial conditions might lead to the emergence of a complex behavioural, cognitive, and social abilities. Moreover, the attempt to develop these abilities in embodied and situated agents introduces other important challenges (e.g. the need to deal with noisy and incomplete information, the need to extract regularities by integrating information in time, the need to produce sequential behaviours).

Despite this enormous complexity, the promising preliminary results reviewed in this paper and the possibility to integrate into a single model important aspects that are actually studied in isolation in different models indicate that the time is now ripe for investigating this challenging problem without necessarily rely on shortcuts or simplifications (e.g. models in which communication involve the exchange of a predefined list of signals or a pre-specified and fixed meaning-space).

In this paper I have stressed, in particular, the importance of studying models in which communicative and non-communicative behaviour can co-adapt and shape one another. Hopefully, these models will shed light on how useful internal categories can be developed, how they are grounded in the sensory-motor experiences, and how explicit communication can be facilitated, complemented, and sometimes substituted by behavioural and physical cues.

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