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Emergence of communication in embodied agents: co-adapting communicative and non-communicative behaviours

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In this paper, I discuss in which conditions a population of embodied and situated agents that have to solve problems that require co-operation might develop forms of ritualized interaction and communication. After reviewing the most relevant literature, I shall try to identify the main open research problems and the most promising research directions. More specifically, I shall 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 behavioural and cognitive capabilities that are crucial for the development of forms of communication of different complexity.

Keywords: Communication; Language evolution; Adaptive behaviour

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. Cangelosi and Parisi 1998, Steels 1999); (b) how a structured form of communication can emerge from a simpler unstructured communication system (e.g. Kirby 2001, Cangelosi and Parisi 2001); and (c) language acquisition and transmission (e.g. Billard and Dautenhahn 1999, Steels and Kaplan 2001, Sugita and Tani 2004). This paper, instead, will focus on the more general question of how a population of embodied and situated agents that have to solve a given problem might develop forms of interaction and communication that enhance their adaptive capabilities.

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) depend on the adaptive function of communication. Similarly, the type of communication system that might self-organize in a population of interacting agents will depend strongly on the type

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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 of developing 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 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 an important prerequisite for the development of individual cognitive abilities.

We are interested in models in which individuals, besides rich signalling and interaction capabilities, also have a rich sensory and motor non-communicative repertoire that might allow them to improve their ability to solve their 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 might individuals 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 of relying 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 in which communication signals are structured. Forms of communication might range from simple continuous broadcast 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 consist 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 goals of this paper are to identify the main open research problems and the most promising research directions. In the next section, the most relevant experimental work will be reviewed briefly. In section 3, the crucial cognitive and behavioural capabilities that agents should have or should be able to develop in order to develop complex forms of communications will be described. In section 4, I shall try to identify the conditions that might lead to the emergence of effective embodied and communicating agents. Finally, conclusions will be presented in section 5.

2. State of the art

In this section, the research works that are more relevant to the perspective outlined in the previous section will be reviewed. In section 2.1, experiments will be reviewed in which agents that are asked to solve simple tasks that require co-operation and co-ordination develop simple forms of ritualized social interactions and/or signalling capabilities. In section 2.2, experiments will be reviewed in which agents interacting according to predetermined ritualized interaction schemes, and able to modify their internal states on the basis of the result of such interactions, develop an ability to categorize successfully external objects according to a self-organized shared vocabulary and ontology. The aim of this section is not 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 co-operation and co-ordination has been provided by Quinn and co-workers (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 provided only with proximity sensors (that also allowed robots to avoid colliding with one another), therefore do not have dedicated communication channels. Robots' controllers consist of continuous time recurrent neural networks. Evolved individuals are able to solve the co-ordination problem by communicating through a sequence of sensorimotor interactions. For instance, in a simple case described by Quinn (2001), two evolved agents co-ordinate 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 backwards and forwards in order to compensate A's movements; and (4) once agent A faces agent B with its front, it reverses its 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 infra-red 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 to 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 jerky movement of the couple.

(4) Finally (from generation 370 onwards), agents display an ability to reverse in response to sustained proximity. This new reversing behaviour, which allow agents to start moving in a co-ordinated manner, capitalizes 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 case of simple forms of communication. For the purpose of this paper, it is sufficient to say that I shall attribute a communication value to all actions or sequences of actions that, by influencing the sensorimotor 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 four mobile robots were evolved for the ability to aggregate and to move together towards a light target (Baldassarre *et al.* 2002, 2003). Robots were provided with two motors controlling the two wheels, a speaker continuously emitting a sound, infra-red sensors, and directional microphones. As in the case of the Quinn's experiments described earlier, evolved individuals display an ability to co-ordinate 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 being constituted of 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 (2004) showed how robots develop communication abilities and a vocabulary including four signals that influence both the motor and signalling behaviour of other robots. Simulated robots are asked to find and remain on two feeding areas by equally subdividing themselves between the two areas. The team consists of wheeled robots provided with infra-red sensors, sound sensors and actuators controlling the two wheels and the sound speaker. The neural network controller consists of a simple perceptron in which sensory neurons are directly connected to motor neurons.

In this experiment: (1) the number, the form and the meaning of signals (i.e. the effects of signals on other agents) are not determined directly or indirectly 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 co-operating agents. Di Paolo (2000) reported the results of a set of experiments in which two simulated agents moving in an arena had been evolved for the ability to approach each other and to remain close together as long as possible. Agents were 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 $\pm 45°$ with respect to the frontal side of the agent that detects the intensity of the sound; and (4) a continuous time recurrent neural controller with four internal neurons. Evolved agents successfully approached each other by later remaining close to one another. Moreover:

(1) Evolved individuals self-stimulated themselves through their own sounds. By reducing agents' capacity to hear their own sounds, in fact, the author observed that agents' performance deteriorated.
(2) The intensity of sounds produced by the two agents had a marked rhythmical shape that resulted from the interactions of the two agents. After some time, in fact, signals were phase-locked at some value near perfect anti-phase and the movements of the two robots became highly co-ordinated. This co-ordination 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 were unable to trigger the same type of co-ordination process.

In a related work, Iizuka and Ikegami (2003a, 2003b) evolved two populations of simulated agents living in couples in an unstructured arena that should exchange their roles (chaser/evader) so as to produce a form of turn-taking behaviour. Chasing and evading are defined as staying or not staying behind the other agent, respectively. Individuals were tested in couples (with couples consisting of individuals taken from the two different populations). Evolving agents were provided with a feed-forward neural network with three layers, including: (1) three sensory neurons encoding the other agent's relative position and orientation and three context units whose activation value was copied from that of the activation state of three additional output units at time $t-1$; (2) 10 internal neurons; and (3) two motor neurons encoding the desired speed of the two wheels and three additional output units that were used to predict the activation state of the three sensory units at time $t+1$. Evolving agents were selected for the ability to alternate their roles and to predict each other's behaviour. Individuals were evaluated in pairs and each individual of a population was evaluated, in different trials, with all the individuals of the other population. The sensory state at time $t+1$ was used to compute a prediction error that was then used to change the connection weights according to the backpropagation learning algorithm.

The analysis of the results obtained 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 subsequent 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 able 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-taking 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, the results obtained seem to indicate that the ability to predict the other agent's behaviour might constitute an important prerequisite for the possibility to develop effective turn-taking behaviour.

Overall, these experimental results demonstrate how individuals selected for the ability to perform a co-operative task might develop not only 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, 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 rich situations is an open research issue that will be discussed in section 3 and 4.

2.2 *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 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.

The environment consists of an open-ended set of geometrical figures (objects) pasted on to 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 and 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) the development of an effective lexicon and ontology shared within the population (i.e. a lexicon and an ontology that allow 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 the configuration of objects located on the white board).

Agents are provided with hand-crafted sensory pre-processing routines and with predefined motor skills and schemata of interactions. Sensory pre-processing routines consist of: (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; (3) software routines that allow the hearer to receive as input the sequence of words produced by the speaker. Motor skills consist of, 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. Schemata of interactions consist, for example, of: (1) routines that create a new word with its tentative associated meaning in the vocabulary of the hearer when it hears a word that 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; and (3) a routine that updates the communication success rate associated to words, etc.

What results from the changes in agents' internal structures occurring during agents' 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 average, the more they use this word and the more success this word has.

In a subsequent 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 at 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 vary significantly on the basis of the robot/head/objects' 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 labels 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 produced previously. 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 to 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 ritualized 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 behaviour of agents is rather predetermined and fixed. This prevents the possibility of exploiting a co-adaptation between communicative and non-communicative forms of behaviour. Moreover, this makes these models unsuitable for solving general co-cooperative problems (e.g. co-operatively explore an unknown area) or for studying how ritualized interactions, language games and vocabularies might have originated.

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

Understanding how a team of embodied agents might develop complex forms of communication and a shared communication language that enable them to co-operate and co-ordinate is a formidably complex enterprise. The research works reviewed in the previous section show how several aspects that might allow this goal to be achieved 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 at only 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 shall discuss which characteristics might represent important prerequisites for the emergence of complex forms of communication 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 communicative 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. In the short term, it is reasonable to assume that progress might be achieved only by predefining, in the starting conditions, crucial elements or capacities that, although in theory could emerge spontaneously in the course of the process, in practice would be very unlikely to do so. These elements or capacities might consist of agent's predetermined architectural constraints, learning algorithms, interaction schemata, etc. From this point of view, the problem becomes that of identifying the crucial minimal set of prerequisites that might trigger the emergence of complex forms of interaction and communication.

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, some of the potential advantages of integrating an evolutionary and a learning process will be discussed briefly.

Artificial evolution, by requiring only 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 shown clearly 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 increase their performance. However, combining with additional evolved mechanisms able to transform sensory information into teaching or reinforcement signals (Ackley and Littman 1991, Nolfi and Parisi 1997), or able to channel changes on the basis of genetically encoded constraints (Floreano and 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 behavioural capabilities and to an ability to select on the fly the right strategy on the basis of the current environmental circumstances (Nolfi and Parisi 1997, Nolfi and Floreano 1998, Floreano and 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 canalize learning in the right direction; and/or (2) an inherited tendency to behave in a way that maximizes the chance of being 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 (Nolfi 2002c).

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

3.2 *Agents' sensorimotor 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 shall not discuss here the possibility of co-evolving/co-adapting the body and the control system of agents, although this possibility certainly provides potential advantages (Harvey *et al.* 1994, Sims 1995, Bongard and Pfeifer 2003). Rather, I shall try to identify general criteria that the experimenter might follow in determining a suitable sensorimotor 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 *et al.* 1998, Nolfi 2002a, Nolfi and Marocco 2002, Beer 2003, Nolfi in press). Moreover, the possibility of interacting with the environment by producing simple stereotyped behaviour might allow agents indirectly to detect complex environmental regularities (Nolfi and Marocco 2002, Nolfi in press). In other words, rich sensing capabilities might be more likely to be 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 really to exploit sensorimotor co-ordination 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 were provided with motors controlling the pan-tilt movement of the camera. However, given that the motor behaviour of these agents was predefined and fixed, the way in which they interacted 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 sensorimotor 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 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 losing, later on, their original non-social function) might play an important role in the emergence of communication (I shall come back to this issue in sections 3.4 and 4). 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 specific type of sensors and actuators and some specific sensorimotor modalities might potentially have a strong communication potentials. This is the case, for example, of the sensorimotor structures that allow pointing, detection of pointing (e.g. gazing, head movements, arm and finger movements, etc.).

Moreover, some types of sensors and actuators or sensorimotor 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; and (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 sensorimotor 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 based only on current sensory states), the development of more complex forms of communication might require much more complex 'cognitive' abilities.

Two basic prerequisites 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 of forming categories based on single sensory states and the ability to generalize on the basis of these categories have been successfully modelled (Cangelosi and Parisi 1998, Steels 1999, Steels and Kaplan 2001, Marocco *et al.* 2003), the possibility of forming categories based on regularities that can be detected only 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 take into account aspects such us the duration of an event or the sequence in which different events occur that can be detected only by looking at 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 prerequisite for solving this problem, see Nolfi (2002b), Gers *et al.* (2002) and De Croon *et al.* (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 2004). For an attempt to model categorization as a bi-directional co-ordination between the dynamics resulting from the agent/environment interaction and the agent's own internal dynamics, see Di Paolo (2000) and Iizuka and Ikegami (2004).

The emergence of complex forms of communication might also require other more complex cognitive capacities, such as the ability to predict the sensorimotor 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.* 2004), etc. The latter 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 probably 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 detail in the next section.

3.4 *Interaction/communication protocols*

The adaptive potential of social interaction/communication depends significantly 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 agents' behaviours, thus preventing or delaying the ability of these agents to accomplish their current tasks.

The utility of communication thus depends on agents' ability to regulate their communication acts on the basis of a suitable interaction/communication protocol and, specifically:

(1) Agents' ability to limit communication acts (e.g. signalling behaviours) to those that are useful for 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 the content of 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 needs of target agents.
(3) The ability to approach other agents in order to: communicate or to receive communicative information, select good learning experiences, or to achieve joint shared attention (on the last aspect, see Billard and Dautenhahn 1999).
(4) The ability to regulate the communication flows by taking turns (Iizuka and Ikegami 2003a, b) or, more generally, the ability to carry out communication behaviours consisting of sequences of bi-directional communication acts.
(5) The ability to increase communication success through a ritualized 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. In simple communication forms, such as signalling of danger situations, in which few different signals are needed to communicate the relevant information, communication acts occur only sporadically and 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 for any communication protocols.

4. Open research problems: identifying the conditions that might lead to the emergence of communicating embodied agents

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 shall try to identify the conditions that might lead to the emergence of complex forms of interaction and communication. Given the difficulty of the enterprise, the goal is not to attempt to answer 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 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 the previous section focused on the former issue, this section will focus on the latter.

As I claimed in the Introduction, the attempt to evolve communication without explicitly rewarding it is crucial to allowing 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 categorize sensorimotor 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 (1991: 661) suggested 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'. 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 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.
(b) 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 to interact socially properly. Moreover, information related to the internal states of an individual might indirectly provide compact cues on the previous experiences of that individual.
(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 regard 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 co-operation) 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 be more likely to be expected in a team of homogeneous rather than non-homogeneous agents. As shown by Haynes and Sen (1996a, b) 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 react appropriately to received signals (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 interpret correctly mutants' signals, will decrease. This selective advantage gathered by the mutant individuals at the expense 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 provides only an adaptive advantage for the receivers, see Oliphant (1996). For a demonstration of how the evolutionary dynamics might lead to an unstable 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, 2005).

As demonstrated in several experimental studies, however, other factors might counterbalance 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' neural controller determine both the motor and signalling behaviour of the agent and receive both sensory and communicative information (Cangelosi and Parisi 1998); and (3) agents (provided with the same neural architecture as 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 counterbalance the lack of direct benefit for signalling and the advantage for individuals to deceive, these two factors will 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), which differ with respect to the complexity of the problem, we can see that, while in the former the constraint on agents' neural architecture was enough, in the latter communication emerged only 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, for mating signals (for an example of how this type of communication might emerge in a population of artificial agents, see Werner and Dyer (1991)).

Finally, these adaptive problems do not affect (or at least are much less important in) cases in which agents are homogenous and are selected on the basis of their collective performance (Baldassarre *et al.* 2002, 2003, Quinn *et al.* 2003, Marocco and Nolfi 2004). 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.

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 examples of how cultural evolution might lead to the emergence of an ability from scratch through variations arising during social imitation and selective reproduction, see Hutchins and Hazlehurst (1991, 1995) and Denaro and Parisi (1996)). Cultural transmission and evolution play a central role in human language, but they also play 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), which have different characteristics and operate at different time-scales.

The issue of how artificial evolution, online adaptation and social learning techniques might be combined effectively 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 already been proposed and investigated (Nolfi and Floreano 1999, Nolfi 2002c), the study of social learning in situated agents is an area that is gathering 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 and 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 skills through learning (at least in the case in which interacting agents have an interest in co-operating). As a second example, we should consider that acquiring skills from different agents potentially allows 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 co-operating and communicating through a self-organizing process is an extremely ambitious goal. Achieving this goal, in fact, implies understanding which initial conditions might lead to the emergence of 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 of integrating into a single model important aspects that are currently studied in isolation in different models indicate that the time is now ripe for investigating this challenging problem without necessarily relying on short-cuts or simplifications (e.g. models in which communication involves 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 behaviours 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 sensorimotor experiences, and how explicit communication can be facilitated, complemented and sometimes substituted by behavioural and physical cues.

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