Toward communication

First imitations in infants, low-functioning children with autism and robots*

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Adopting a functionalist perspective, we emphasize the interest of considering imitation as a single capacity with two functions: communication and learning. These two functions both imply such capacities as detection of novelty, attraction toward moving stimuli and perception-action coupling. We propose that the main difference between the processes involved in the two functions is that, in the case of learning, the dynamics is internal to the system constituted by an individual whereas in the case of communication, the dynamics concerns the system composed by the perception of one individual coupled with the action of the other.

In this paper, we compare the first developmental steps of imitation in three populations: typically developing children, children with autism, and robots. We show evidence of strong correlations between imitating and being imitated in typical infants and low-functioning children with autism. Relying on this evidence, the robotic perspective is to provide a generic architecture able not only to learn via imitation but also to interact as an emerging property of the system constituted by two similar architectures with a different history.

Keywords: Communication, Imitation, Development, Infant, Children with autism, Autonomous robot/s

Psychologists do not use a consistent definition of imitation. For instance, they say that neonates imitate because they are able to perform perception-action coupling (i.e. they react to a seen movement through performing a matched movement), and that children with autism do not imitate because they are not able to reproduce complex programs of actions or to defer imitation. What they

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call genuine imitation is the ability to imitate new strategies and programs of actions (Heyes, 2001): A definition used before the introduction of a developmental perspective in the study of imitation (Aronfreed, 1969).

These hesitations on how to define imitation plead in favour of the idea that imitation is not a unitary phenomenon. There is a large body of psychological and neuroimaging experiments that have demonstrated that perception of action shares some common neural and cognitive mechanisms with action generation, action simulation, action recognition and, to some extent, action imitation (Decety & Grezes, 1999). These results are highly relevant to the understanding of the mechanisms involved in imitation. On the basis of this data, neuroscientists have proposed the concept of shared motor representations (Georgieff & Jeannerod, 1998).

We propose to take advantage of this evidence to carefully examine the hypothesis that there is a hierarchy of mechanisms involved in different types of imitation which all have in common reacting to the perception of goal-directed movements or actions by the production of similar behaviours. This view takes into account the implication of new findings in neurobiology by Rizzolatti and colleagues (Fadiga, Fogassi, Pavesi & Rizzolatti, 1995; Iacoboni et al., 1999; Rizzolatti, Fadiga, Fogassi & Gallese, 2002) who discovered in the monkey, and then in the human, premotor cortex a class of neurons that they have called 'mirror neurons' because they discharge when an action upon an object is performed or observed. This neuronal capacity to resonate to actions may be involved in high-level imitations, insofar as it does not necessarily lead to the production of the action observed: when mirror neurons discharge for actions, a neural activity is evoked, which corresponds to the representation of the neural activity generated by the effective production of the action observed. According to Rizzolatti and colleagues (2002), mirror neurons that discharge for actions upon objects (F5 neurons) are the best known example of the mirror resonance system, but there are also neurons that discharge when simple movements are performed as well as when they are observed. The resonance of the latter may explain low-level imitations such as social facilitation, stimulus enhancement and neonatal imitation.

The distinction proposed by Rizzolatti et al. (2002) leads us to draw a continuum between uncontrolled and intentional matching responses to an action, rather than to exclude from the definition of imitation those matching behaviours that are not informed by the intention to imitate. The recent perspective held by Byrne and Russon (Byrne & Russon, 1998) also avoids a clear-cut distinction. They do not deny the label of imitation to certain behaviours but rather distinguish between two levels of imitation: a low-level imitation regrouping primary matching behaviours and a high-level imitation regrouping creative insights about interesting goals. Dautenhahn and Nehaniv (2002), and Mitchell (2002) also share the view of a continuum in a hierarchy of imitation levels.

Adopting a bottom-up perspective, we investigated how infants and low-functioning children with autism develop low-level imitations, while we explored in parallel which implementations are needed for autonomous robots to develop the same kind of low-level imitations. A bottom-up perspective, however, represents just part of our common interdisciplinary approach. So as to pin the colours of our mast, we need to add that we share a functionalist perspective (Nadel & Revel, 2003).

A functionalist perspective in the study of imitative development is not a wide-spread focus among psychologists. While modern psychologists investigate the developmental role of emerging imitative capacities (as did Piaget, 1945, for deferred imitation) and elaborate models about the cascading effects of their development (Meltzoff & Gopnik, 1993), little attention is given to the functional use of these capacities by the developing infant in her everyday life. When we read about studies on infant imitation, we may often be forgiven the impression that imitation matters a great deal more to developmental psychologists than to infants (Roessler, 2002). This would be a misleading conclusion: indeed, what could explain the fact that imitation increases exponentially throughout the first two years of human life (Yando, Seitz & Zigler, 1978) if there is not a growing benefit for the infant to engage in imitation? The infant's behaviour is not solely a preparation for the future, it is also and mainly a means for current adaptation (Nadel, 1986; 2002). Which type of adaptation may be fulfilled by imitation?

Imitation has long been viewed by behaviourists as prompted by purposes of learning: the "look-at-me and do-like-me" procedure is a key technique for elementary academic and other kinds of acquisitions. Imitation was defined as learning without incentives and without trial and error (Bandura, 1971). Nowadays, a number of developmentalists contribute to document the major adaptive role of imitation as cultural learning (Tomasello, 1998).

An interesting first step toward the idea that the uses of imitation may differ according to the developmental constraints and current adaptive needs of the developing infant was made by Yando, Seitz and Zigler (1976). These authors proposed a two-factor theory where level of cognitive development and motivation were the essential factors in play in the development of imitation.

Motives for imitating, they said, differ significantly with age. Yes, but it remains to know for which purpose. In the early eighties, a few voices started to propose that imitation has two functions: a cognitive and a social function (Užgiris, 1981), or a learning and a communicative function (Nadel-Brulfert & Baudonnière, 1982). Several researchers have been involved in the exploration of the possible origin of the communicative function of imitation. Among them, Maratos (1973), Pawlby (1977), and Užgiris (1981) certainly pioneered the field. They have shown that just a few weeks after birth, imitation includes turn-taking between partners (Maratos, 1973; Užgiris, Broome & Kruper, 1989). At birth, the frequency of imitation has been suggested to have a predictive value for face-to-face interaction at 3 months (Heimann, 1991). Kugiumutzakis and colleagues (1999), inspired by Trevarthen (1999), have shown the efficiency of an interactive context in the early production of imitation. Nadel (1986) has shown that young infants take advantage of the fact that imitation involves two roles: imitator and model. Two-year-olds use these two roles alternately, so as to take turns and switch roles (Nadel, 2002). Partners coordinate their tempo in order to achieve synchrony between the model and the imitator's activity. This leads to long-lasting exchanges that are possible in no other way before the onset of language.

The distinction between two functions of imitation may appear meaningless, since imitation is social in nature and always requires social embeddedness. We will argue that the outcomes of imitation as learning are radically different from the outcomes of imitation as communication. Learning via imitation benefits the individual, the group or the species, but does not imply sharing anything with the model. In contrast, when one communicates with a partner via imitation, it benefits the two partners in as much as imitation generates changes in both of them (Nadel, 1999). In other words, the one who is imitated and the one who imitates form a new dynamic system, an evolving system of similarities built on the basis of two different repertoires from the interaction of which emerge new possibilities for each party. This developmental perspective revealed a need to enlarge the focus of interest for imitation in robotics.

Until recently, roboticists have mainly been interested in the learning function of imitation: a simple way for a robot to learn from another, and a means to boost learning speed in a population of robots (Berthouze et al., 1998; Kuniyoshi, 1994; Schaal, Atkenson, & Vijayakumar, 2000). If different members of a population of robots can learn not only by themselves but also from each other, this could drastically reduce the complexity of the learning task by allowing the spread of knowledge about a given task over the entire population.

Thus, each member can benefit from the knowledge of the others and integrate this knowledge into its own abilities. This is a case of observational learning, which can in turn speed up the learning of subsequent tasks by the individual. However, even if embedded in a social environment, imitation here does not link individuals through interaction.

One of the pioneers of an approach focused on robotic interaction is Dautenhahn (1995), who has proposed an architecture in which one robot follows a "teacher" (another robot) using a simple sensory-motor rule in order to minimize its energy loss. Practically, this rule simply consists of maintaining contact with a moving object. By acting this way, the robot performs the same movements as the "teacher" robot and thus « looks as if » it is imitating. Our model of architecture has different main features: it tends to reduce the discrepancies between what it sees and what it does (Gaussier et al., 1998), which leads it to perform what is seen. This results in a perception-action coupling. How to interface two self-developing robots with similar architectures and different history, so that the two functions of imitation can emerge?

This question was at the origin of the interdisciplinary program presented in this paper.[1] Roboticists started to examine how two of their generic architectures can develop low-level imitations, and then take turns imitating and being imitated by each other. Simultaneously, developmentalists were involved in comparative studies of imitative development in healthy infants and children with autism. Why this comparison? If there are biological conditions constraining the development of imitation, then we should find a unique hierarchy of behaviours in two contrasted cases of development. At a low level of functioning, children with autism, like newborns, may produce perception-action coupling and imitate simple movements that they see without an intention to do so, and without taking account of whether or not these behaviours are intentional ones. Similarly, they may have covert or unspecified responses to their being imitated. At a higher level of functioning, children with autism may be able to reproduce the goal of a model. In order to assess the necessary conditions for a low-level use of the communicative function of imitation, we planned to confront the development of imitating and being imitated in healthy young infants and low-functioning children with autism, with the development of imitating and being imitated in two robots of similar architecture.

Although the human and robotic approaches were continuously developed in parallel, it appeared to be easier to organize the paper in two parts, one devoted to the human development, and the second to robotic development of imitation.

1. Human aspects of imitative development

Based on numerous studies, we now have a precise description of what the newborn is able to imitate. Newborns imitate mainly three facial gestures: tongue protrusion, mouth opening and eye blinking, and two vocal sounds (Kugiumutzakis, 1993). This has been shown mostly in an experimental context (Meltzoff & Moore, 1983 et seq.) but also in a naturalistic context of social interaction (Kugiumutzakis, 1999). Field and colleagues have also found imitation of primary facial expressions (Field, Woodson, Greenberg, & Cohen, 1982). We have less information about what they are able to imitate a few weeks later. Despite the ever growing number of studies, there is a persisting paucity of research accounting for a developing diversity of imitations throughout the first weeks of life. Indeed, follow-up studies of imitative capacities from birth to 6 months have mostly been aimed at testing whether or not neonatal imitation disappears around month three or are maintained throughout the first six months of life (see Anisfeld, 1996 for a review). They have thus repeatedly modelled tongue protrusion and mouth opening, and for some of them eye blinking, to 6-, 8- or 26- week-olds exactly as they have done with 1-day-olds (Field, Goldstein, Vega-Lahr & Porter, 1986; Kugiumutzakis et al., 1999; Legerstee, 1991; Meltzoff & Moore, 1992). This however does not document the emergence of an enlarged variety and complexity of imitations. Moreover, there exists no developmental studies on the development of imitation recognition. To go a step further, we explored the imitative behaviours of 2-month-olds involved in a televised face-to-face interaction with their mothers.

1.1 Imitating and being imitated in 2-month-olds

Infants' imitations, and their reactions to being imitated, were studied through the use of an experimental situation where the partners interact via audio-video monitors, as explained in Figure 1.

Such a face to face situation was expected to generate exclusive attention to the partner, in both infant and mother, and thus to favour micro-contingent behaviours such as imitations. It allows also to obtain very good records of the infant's and mother's behaviour.

Population

Ten volunteer dyads of French Caucasian mothers with their 9-week-olds (5 girls and 5 boys), all full term and with a normal NBAS score (Brazelton &

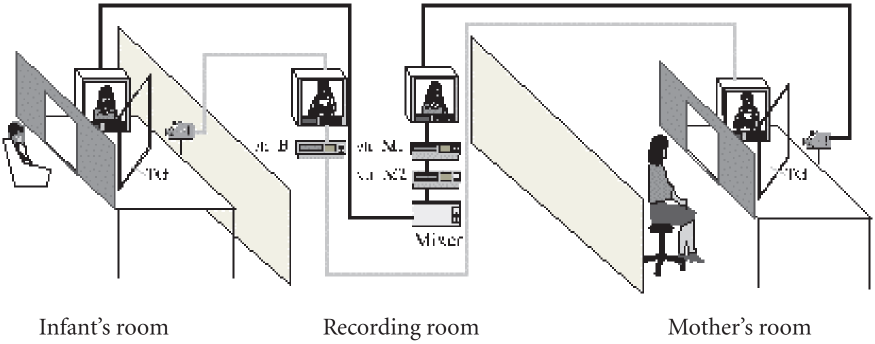

Figure 1. Teleprompter device generating non-contingent communication. The device allows a seamless shift from contingent to non-contingent maternal communication. Three independent rooms were used, one for the infant, one for the mother and one for recording. The device records mother and infant's frames and sends to the mother her infant's face, arms, hands and torso frame and sounds while the infant sees the mother's face, arms, hands and torso, and hears her voice. The design records independently the mother's frames so as to send them later to the infant: as these frames are not dependent on how the infant behaves, they are sequences of non-contingent communication.

Nutget, 1995) participated in the study. Mothers and fathers had given their written informed consent.

Design and Procedure

Mothers and infants sat comfortably in two different rooms. They could see and hear each other via audio-video monitors. Infants sat in a baby-seat facing the reflected image of a large TV monitor, at a distance of 40 centimetres. A character, Mickey Mouse, was presented first to the infants so as to calibrate their focal vision to the screen. The mothers sat in an arm-chair facing the reflected image of a large TV monitor. They could regulate their distance to the infant by moving backward or forward on their seat. They were informed that the situation involved the presentation to the infant of a replayed episode of their former communication: the beginning and the end of this episode were signalled to the mothers by a green light. Mothers were asked to make and maintain contact with their infant. Since no toy was available, the natural way for the mother to interact was to smile, speak, look at the infant, clap hands, make faces etc., and of course, imitate the infant. Sessions lasted from 2 to 4 minutes (mean length: 3 minutes) depending on the delay before mother and infant make eye contact and mother interacts with the infant.

Coding

Infant and mother behaviours were coded using a video-computer interfacing system created by Kervella and Nadel (1998), so as to present simultaneously on the monitor the infant's and the mother's digitized single frames along with the two coding grids. The frames were synchronized according to a LED visual signal. The time unit was: 40/100th second, which means that for each 40/100th second, two stable frames were automatically presented to the coder, one showing the mother and the other the infant. The coding grid consisted of six lists of items. Each list (look, facial expressions, head/torso, arm/hand, mouth, sound) was exhaustive, which means that it was always possible to describe the frame with one of the items. Within each list (representing a behavioural category), the items were exclusive so that each frame could only be described by one item. Two independent coders were trained to code expressive facial patterns in babies (Oster, in press) and infant eye contact calibration.

By directly comparing the coding of the mother and of the infant, we detected the imitative behaviours. A behaviour was defined as imitative if it resulted in a behavioural change leading to a matching of the partner's behaviour within 3 frames (i.e. 120/100th second) following a change in the partner's behaviour. We are aware of the fact that this strict definition may underestimate the number of imitations in both mothers and infants, but it allows us to have a firm definition of what is considered as imitation.

Results

a. imitation during the full contingent episode of TV face-to-face interaction

A total of 45 infants' gestural imitations were found. Nine out of 10 infants imitated something during the 120 seconds of TV interaction with their mothers but the frequency of imitation was very different from one child to another, ranging from 19 to 1. Bodily imitations included head movements ($n=30$), arm/hand movements ($n=4$), torso movements ($n=1$), facial expressions ($n=8$), and two 'tonguing'. Although the time-unit was taxing, we were unable to specify in 14 cases who imitated whom, even looking frame by frame to the action of each partner: those imitations all concerned head movements.

All mothers imitated their infants. All imitated while their infants were gazing at them. The imitations were mostly bodily movements: head ($n=30$), arm ($n=5$), torso ($n=3$) and facial expressions ($n=10$). Three mothers imitated their infant's mouth opening one time. One mother imitated a sound.

These results show that mouth movements are not an important part of 2-month-olds' capacity to imitate and of their mothers' selection of movements to imitate. This statement questions the relevance of the unique experimental use of tongue protrusion to explore an infant's capacity to imitate throughout the six first months of life.

b. imitation recognition

Mothers always imitated their infants while they were gazing at them: it follows that the infants saw their mother's imitations. Did they perceive them as such? For further information, we analysed the infants' behaviour whilst they were imitated: they were often staring, smiling or vocalising at their mother, but such social behaviours are also found during non-imitative interactions and cannot be considered as specific responses to being imitated.

A first indication that something about being imitated is perceived can be found in the highly positive correlation between the mother's and the infant's frequency of imitations (Pearson $r = .77$, $p < .01$): the most imitative infants had the most imitative mothers and the reverse was also true. Additionally, 5 infants out of 10 demonstrated reciprocal imitation, i.e. imitated their mother after their mother had imitated them. This may be an index of an early sensitivity to being imitated.

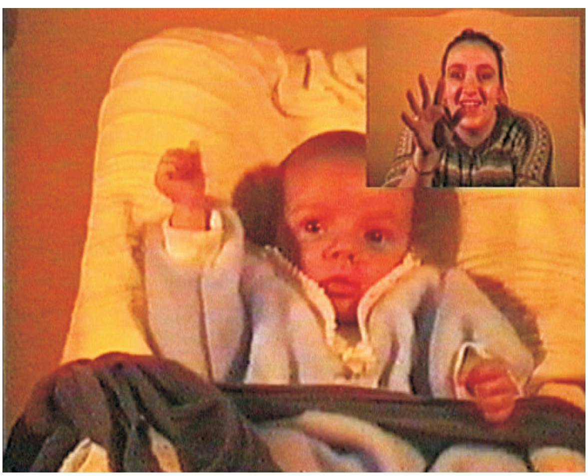

Figure 2. Imitation of mother by a 2-month-old. This infant's imitation of the mother was preceded by an imitation of the infant by the mother.

c. Comparing imitation during contingent versus non-contingent similar episode

An early sensitivity to being imitated was also inferred from the comparison of infant imitation when the infant faced her contingent mother to when she faced the same episode this time replayed, thus non-contingent. In the case of non-contingency, the mother of course does not imitate the ongoing behaviour of her infant. What happens then? Infants imitated, at a mean rate of 1 imitation per 10 seconds, the gestures of their contingent mothers (M number of imitations: 3.2, for a 30-second-episode), whilst they imitated almost nothing during the non-contingent episode (M number: .3) [Student $t(9) = 2.95$, $p < .01$]. The significant difference in the amount of imitation of the infant in the two conditions of contingency indicates that maternal behaviour is not the main determinant of imitation. The fact that the mother does not imitate the infant certainly explains at least partly the very low arousal of imitative behaviour during the non-contingent episode. This fits the speculations developed by Rizzolatti and colleagues (2002) about the possible early role of low resonance mechanisms. The rounds of reciprocal imitations that Pawlby (1977) and Užgiris and colleagues (1989) found at 12 weeks in naturalistic situations gives a convergent picture of an early intertwining between imitating and being imitated.

1.2 Imitating and being imitated from 3 to 12 months

We conducted a follow-up of three infants from 3 months up to 12 months.

Procedure

The same familiar experimenter met the infants at their home every two weeks for a 10-minute- session. The experimenter and the infant had identical sets of baby toys. A fixed digital camera filmed the interaction. During the first 5 minutes, the experimenter modelled simple movements when the infant was gazing at her. She modelled the three classical facial movements (tongue protrusion, mouth opening and eye blinking), and added expressive and non expressive movements of the face. When the infant demonstrated her first capacities to use hands on a board, the experimenter added simple actions such as scratching a spoon on a table. When the infant demonstrated the ability to grasp things, the experimenter added simple familiar actions with or without objects, and unfamiliar actions with and without objects. In the second part of the session, the experimenter imitated the infant's gestures.

Results

a. imitation

The 3-month-old infants were able to imitate a motor trajectory toward a given part of their body. We also found they were able to imitate different head positions and face movements such as cheek movements, previously described by Fontaine (1986). At 5 months, we found evidence of imitations of various movements of mouth, nose, arms, hands and fingers, and we noticed the first imitations of simple actions such as tapping hand on table. After 6 months, infants imitated a large variety of familiar actions like rolling, pushing, and pulling an object, as well as unfamiliar actions such as tearing paper. As already noted long ago by Piaget (1945), this growth of imitation coincides with the sensorimotor development of the infant. It allows the infant to learn a number of new procedures that combine in complex actions simple gestural schemes already stored as a motor repertory. The important fact however is that now infants imitate goal-directed actions and will soon start understanding a model's goal (Meltzoff, 1999). This would correspond to the higher level of resonance described by Rizzolatti et al. (2002) and would be beyond the current capacities of our robot.

In order to explore the hypothesis of a continuing development of matching behaviours, we have compiled classical data investigating imitative development during the 21 first months of life, to which we have added the results of our experimental study with 2 month-olds and the information drawn from a follow-up study including 3 infants meeting the same experimenter every 2 weeks, from 3 months to 12 months. Table 1 presents the information gathered from these three sources.

Table 1. Imitation: developmental steps

1.	**Birth:** facial imitation (Meltzoff & Moore, 1983; Kugiumutzakis, 1999; Field et al., 1982)
2.	**1 month:** Imitates head movements
3.	**2 months:** Imitates facial expressions, head, arm, hand, neck, torso movements (Nadel & Potier, 2000)
4.	**3 months:** Imitates goal-directed movement to body
5.	**4 months:** Imitates a sequence of bodily movements
6.	**6 months:** imitates simple goal-directed actions with objects (Barr et al., 1996 ; Dunst, 1980 ; Meltzoff, 1985)
7.	**12 months:** Imitates a sequence of goal-directed actions (Barr et al., 1996; Dunst, 1980)
8.	**9–15 months:** Imitates the model's goal (Meltzoff, 1995)
9.	**18–21 months:** Imitates as an invitation to communicate (Nadel, 2002)

Table 2. Recognition of being imitated: Developmental steps

1.	**Birth:** Reacts by gazing
2.	**1 month:** Reacts by smiling
3.	**2 months:** Reacts by reciprocal imitation (Nadel & Potier, 2000)
4.	**5 months:** Reacts by loud and repeated laughs (Nadel & Potier, 2000)
5.	**6 months:** Reacts by staring alternatively at the object and at the imitator, stops acting
6.	**9–15 months:** Reacts by controlling, testing the imitator (Meltzoff, 1990)
7.	**18–21 months:** Understands imitation as an intention to communicate (Nadel, 2002)

b. imitation recognition

At 5 months, we found strong emotional reactions to being imitated like staring and bursting into laughter. At 7 months, an active involvement in being imitated was observed: the infants looked back and forth between a partner's movements and their own movements, and stopped activity in awaiting the partner's activity. Emotional reactions were accompanied by looking alternately to a partner's movement and to one's own movement, and waiting for the partner's movement before moving again. After 9 months the infants were able, as Meltzoff (2002) noted, to test the experimenter's intention to imitate via a variety of procedures like change of object handled, change of activity, change of tempo. Meanwhile, the communicative function of imitation does not stay unchanged. Around 9 months, the imitative rounds where mother and infant repeat the same action one after the other are more and more often initiated by the infant (Pawlby, 1977; Užgiris et al., 1989). This progress accounts for an emerging use of communicative rules, that requires a monitoring of being imitated.

Table 2 summarizes the main steps of the development of recognition of being imitated that we observed and that were also documented by other authors.

All steps of being imitated show a parallel development with the developmental steps of imitation. To summarize, it takes about 9 months for an infant to become able to monitor being imitated and to imitate goals rather than procedures. A few months later, after 18 months of age, infants are able to monitor their own actions, and control the other's actions in order to coordinate both: they alternately model new actions to the other and imitate the other. When taking turns they propose novel topics (i.e. actions that had still not been performed together) that enrich the ongoing interaction. Turn taking now implies switching roles.

2. Development of imitation in low-functioning children with autism

Using our description of the main developmental steps of imitation in the first months of life, we have started an exploration of imitative capacities in children with autism. Such an exploration is needed, since results in this area are controversial: some authors claim that children with autism have specific impairments in the domain of imitation (Rogers & Pennington, 1991; Rogers, 1999), whereas others say that the imitative deficits are not specific to autism but more generally include children with different developmental impairments (Roy, Elliott, Dewey, & Square-Storer, 1990), with dysphasia (Cermak, Coster & Drake, 1980) and more generally with language impairments (Smith & Bryson, 1994, 1996). Still others deny noticeable imitative deficits in young children with autism compared to young typical children (Charman & Baron-Cohen, 1995; Nadel et al., 1999). Most of all, we need a description of children's imitative capacities according to their developmental age and their motor repertory. Indeed, what is striking when we observe low-functioning children with autism is how poor their motor production skills are and how rarely gestures are functionally aimed at using different properties of objects, namely their inter-modal qualities. Such a lack of attraction for novel experiences may extensively limit the building of strong and automatic motor representations, but does not prevent low-level imitations.

The relatively late diagnosis of autism (not earlier than 9 months to-date) suggests that early motor development is not impaired or at least not specifically impaired. We thus postulate the integrity of basic perception-action coupling in low-functioning children with autism.

Material and Procedure

Following our procedures with typical infants, we rearranged a familiar room with two identical sets of attractive objects. We adopted a three-episode procedure. During the first episode, the experimenter modelled attractive actions with objects, according to an experimental protocol. The child with autism was free to imitate the actions or not. In a second episode, the experimenter imitated all actions or gestures displayed by the child and in a third episode the experimenter again modelled a variety of actions according to the experimental protocol, this time asking the child to imitate her. The sessions lasted around 10 minutes, depending on the child's first involvement in the task. A hidden mobile camera filmed child and experimenter.

Population

Ten girls and 13 boys with autism, aged 3 to 7 years, diagnosed as such with the DSMIV (APA, 1996) and CARS (Schopler, Reichler, & Rochen-Renner, 1988), participated in the study. Their developmental ages evaluated with PEPr (Schopler et al., 1988) and the revised Binet-Simon Scale (Zazzo et al., 1966), varied from 6 months to 65 months.

Coding

A coder blind to the goal of the research and a trained user of our task analysed independently the records second by second to find the imitations recognizable as such, and their level in the hierarchy of typical imitative development (shown in Table 1). For example, a child may be capable of low level imitations, such as: "put a spoon in a bowl", but also of higher imitations of unfamiliar actions such as "open an umbrella, hold it upside down, put in a balloon and toss it". All the actions imitated will be summed up to get the percentage of successful imitations (score) but only the higher kind of imitation will be considered to fix the developmental level.

The coders also analysed the child's response to being imitated. These responses inform about the developmental level of imitation recognition that the child has achieved: for instance, the child's testing of the imitator (staring at the imitator plus changing behaviour, changing object, changing tempo…) is the index of explicit recognition, but the child's turn taking between being imitated and imitating is quoted as recognition of communicative imitation. The global Kappa agreement between the two coders was .81 for imitation and .85 for imitation recognition.

Results

Figure 3a presents the imitation score and the developmental level of imitation achieved by each child with autism. The developmental level represents the higher normal stage of imitation that was performed by the child (for example, tap on the table with a spoon). The imitation score takes into account the number of times that the child imitates successfully. All children with autism were able to imitate at least simple familiar actions as 6-to-9 month-olds do. If we take as a criterion the mental age of children with autism instead of their chronological age, the developmental path of imitation is similar to the typical developmental path described earlier (see Table 1). This is consistent with the idea that children with autism are not specifically impaired in imitation. The significant correlation between mental age and imitation level (Spearman

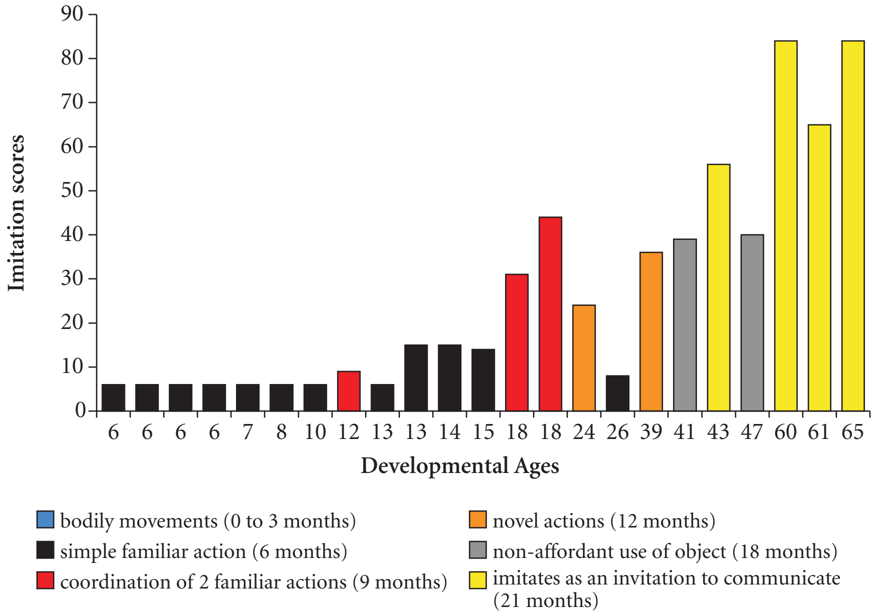

Figure 3a. Imitation scores of children with autism of different developmental ages. The histogram combines two informations: the color informs about the higher developmental level of imitation achieved by each child and the score informs about the percentage of imitation performed, whatever the level.

$r = +857$, $p < .001$) supports this position.

Figure 3b presents the developmental level of imitation recognition achieved by each of the 23 children with autism. Note that the developmental steps of imitation recognition in children with autism parallel typical developmental steps of imitation recognition as described in Table 2.

There was a significant relationship between the level of imitation and the level of imitation recognition ($\chi^2 = 9.88$, $p < .01$). For instance, those children who were good imitators all recognized being imitated. This is a good index of a parallel development of the two facets of imitation, reinforcing the hypothesis that the communicative function of imitation emerges very early from the intermesh of imitating and being imitated. Neuroimaging findings (Decety et al., 2002) support this hypothesis in as much as they show a large overlap in brain activation during 'imitating' and 'being imitated' conditions.

Altogether, the correlated development of imitating and being imitated in typical infants and children with autism, the similarity of brain activation during imitating and being imitated, and the mirror neurons' discharge during

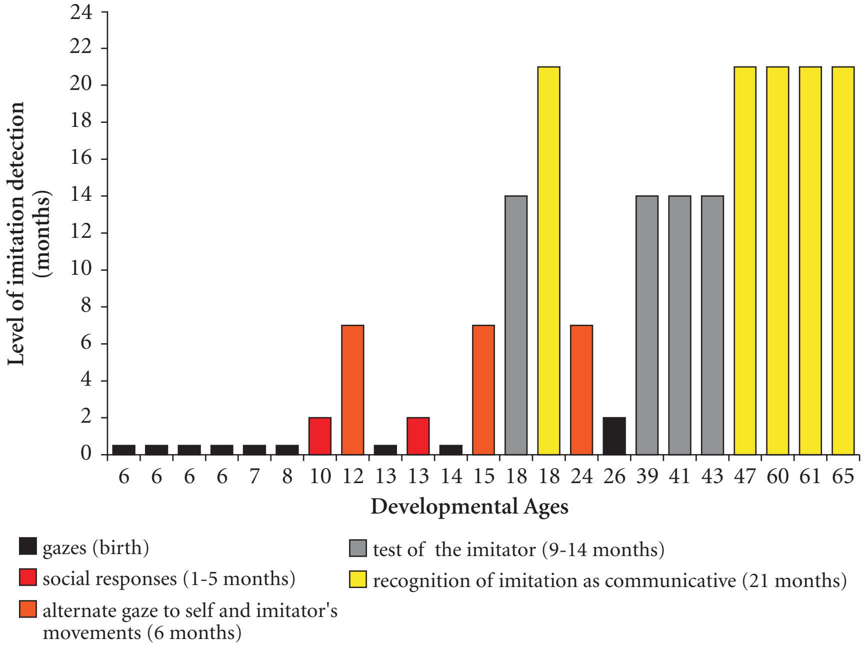

Figure 3b. Levels of imitation recognition of children with autism. The color informs about the higher developmental level of imitation recognition achieved by each child.

observation of actions upon objects, all these facts suggest a common origin to learning and communication via imitation. The observation of an action facilitates the reproduction of this action (observational learning) and attracts the attention of the model towards the imitator: this could lead to a circular repetition of the same action by the two partners. In robotic words, the dynamics of interaction between the two systems would converge on a cyclic attractor, exhibiting only turn-taking abilities. Exploring the transition to role-switching, the roboticists could give hints to model how role switching can emerge from turn-taking, and help developmentalists explain the process that leads to achieve communication through similarity.

3. Robotic aspects of imitative development

Actions such as reaching and grasping a visible object, moving or pushing it toward a given place, imitating very simple gestures or actions, are all difficult tasks for an autonomous robot. These tasks often refer to specific aims and algorithmic solutions. Far from building optimal solutions to a given problem, our aim is rather to provide a generic architecture that could easily deal with various tasks, whatever their devices (mechanical arms with different shapes, physics and dynamics). The visuo-motor control architecture that we propose is built as a perception-action loop (Gaussier & Zrehen, 1995; Revel & Gaussier, 2003; Quoy, Banquet & Daucé, 2000). If imitation is based on perception-action coupling, imitation should be a "natural" field of application for this architecture (Andry et al., 2000, 2001; Gaussier et al., 1998; Moga & Gaussier, 1999). Inspired by developmental findings, our attempt here is to provide a generic architecture able not only to learn via imitation but also to interact as an emerging property of the system.

First step "motor-babbling": Learning visuo-motor associations

We propose a simple control architecture that is able to learn the associations between perceptions (vision and proprioception) and actions in order to provide efficient control to robots of various mechanical complexities (Figure 4).

For our experiments, we use Koala robots equipped with 180 degrees pan and tilt monocular camera "heads" (no stereo vision). The mechanical arms are 5 Degrees Of Freedom (DOF) Katana robotic arms, allowing redundant movements in the working space (the same point within the working space can be accessed by multiples configurations of the arm).

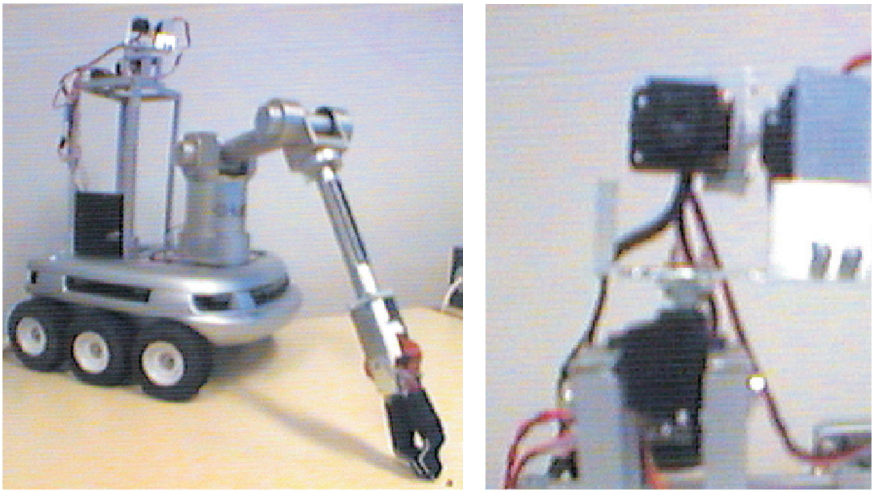

Figure 4. A Katana robotic arm and a home-made pan tilt camera (right) are mounted on a mobile Koala robot (left).

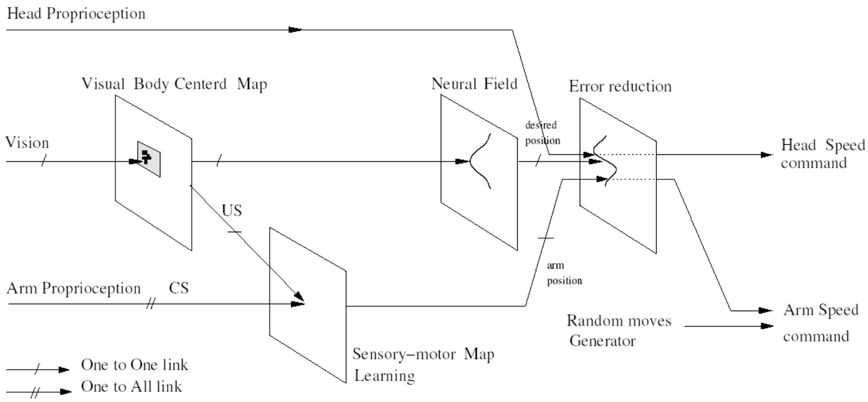

Figure 5. The simplified architecture. Proprioception of the arm and vision from the CCD camera are merged in a sensory-motor map composed of clusters of neurons. This map learns the visuo-motor associations using vision as an Unconditional Stimulus (US). After learning, the arm proprioception, acting as a Conditional Stimulus (CS) triggers the correct activity of the sensory-motor map and can be used to compute the right movement to reach a possible target using the Neural Field (NF) dynamic properties.

Two main perceptive pathways process information coming from vision and arm proprioception. They are merged in a sensory-motor map that learns the visuo-motor associations. Visual information triggers a dynamical attractor centered on the stimulus. The direct output of the attractor is then used to compute the motor command of all the devices of the robot (i.e. motors of the head and joints of the arm). Perceptions are processed in a 2-D camera-centered space. The results of this computation are then simply projected on a 2-D body-centered map of neurons representing the whole visual working space (Figure 5).

To allow the association of multiple proprioceptive vectors with a single visual perception, we use a new kind of sensory-motor map, composed of small clusters of neurons. Each cluster of this map associates a single connection from one neuron of the visual map with multiple connections from the arm's proprioception. Visual information is considered as the Unconditional Stimuli (US) that controls the learning of a particular pattern coming from the proprioceptive input, the Conditional Stimuli (CS). It is important to notice that both motor commands and proprioceptive information are coded in the visual field (in relation with the position of the arm in the visual space).

The winner cluster will represent the "visual" response associated with the

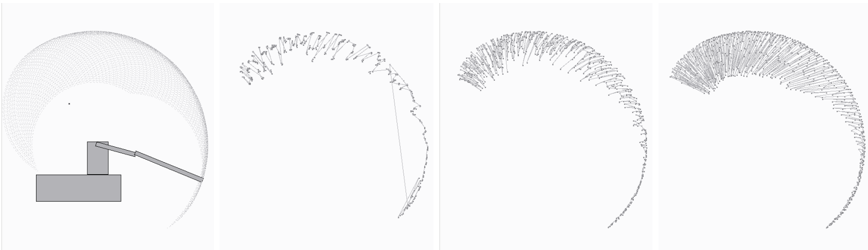

Figure 6. Example of visuo-motor learning of our autonomous robot.

proprioceptive input presented. Thus, many proprioceptive configurations are able to activate the same "visual impressions", while close visual responses can be induced by very different proprioceptive inputs, thanks to the independence between each cluster.

During the learning phase, which can be compared to a kind of "motor babbling", the robot performs movements at random and learns to associate visual positions with the corresponding proprioception and resulting movement, as Figure 6 shows. During this phase, the robot is put in a "quiet" environment, far from possible ambiguous distractors (learning with distractors would require many more presentations to detect the stable part of the sensory-motor associations). After learning, each visual perception is correlated with the corresponding proprioception, and the robot's controller acts as a "homeostat" producing movements allowing it to keep a consistent perceptual state (that minimizes the error between visual and proprioceptive information) in the visual field as well as in the proprioception field. We consider this "motor babbling" phase as the very first step of the development of our architecture for imitation.

Second step: Low-level imitation as a side effect of perception ambiguity

Once the first step is achieved, there is nothing to add to the architecture for imitative capabilities to emerge, if we consider the two following principles :

1. The perception is fundamentally ambiguous
2. The robot is a homeostat tending to reduce the error between its visual perception and its proprioception (it can be seen as visuo-motor reflex).

Given these generic principles, the imitative behaviour is nothing more than a side effect due to the perceptual limitation of the system. An elementary imitative behaviour can be triggered by exploiting the ambiguity of the perception: using only movement detection, the system cannot differentiate its own "body" from another moving target, such as, for instance, a moving hand (see

Figure 7, right). If we now shift the head horizontal motor direction with respect to the robot's body proprioception, we can ensure that the robot's arm is not in the field of view of the camera. Thus, a hand moving in front of the camera will be associated to the robot's own arm (perception ambiguity). Due to the discrepancy between vision and proprioception, the generated error will induce movements of the robotic arm that lead it to reproduce the movements of the human hand. Thus, an imitative behaviour emerges.

Using the setup described earlier, Andry and colleagues (2001) have shown that the robot can imitate several kinds of movements (square or circular trajectories, up and down movements, see Figure 8). During the experiment, the 3 main DOF of the arm were freed, allowing movements in all the working space. The experimenter was naturally moving his/her arm in front of the robot's camera making simple vertical or horizontal movements, squares, or circles. The camera rapidly tracked the hand and reproduced in real time the hand's perceived trajectory. The use of neural fields ensures a reliable filtering of movements and a stable, continuous tracking of the target by the head and the arm of the robot.

Getting for free the double function of imitation: Learning and communication
We are now interested in the overall dynamics of the interaction between two

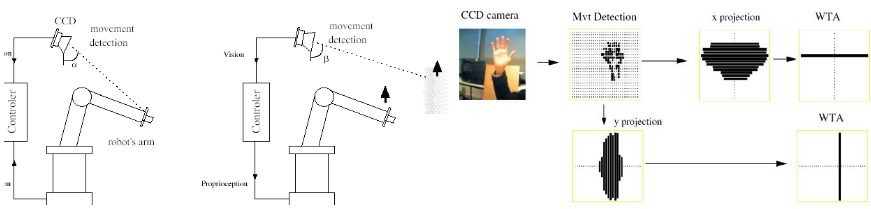

Figure 7. Illustration of a low-level imitation mechanism. In a first step, a neural controller learns the visuo-motor associations within the workspace. During the learning phase, the workspace is explored generating movements at random. After learning, a simple shift of the camera (angle θ) leads to a confusion between the user's moving hand and the robot's own arm (test phase). This confusion generates an error that the controller tries to reduce by moving the arm the same way as the hand. The system thus "imitates" the human hand's trajectory. Right: Example of end point tracking (here a hand) using movement detection. The movement detection (on the center) is computed from the image flow (here, the experimenter was waving his forearm). The activity of the 2-D map is projected on two 1-D maps of neurons. Then, each projection map is connected to a WTA (Winner-Take-All mechanism) computing the position of the maximum of movement in the scene (computation performed at 20 images/sec).

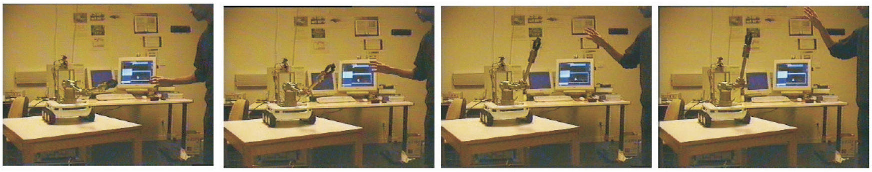

Figure 8. Real time imitation of simple vertical gesture. To obtain a low-level imitation, we simply shift the head's position with the body and the arm (shift = 90 degrees). Thus, a perceived movement is interpreted as an error, inducing corrective movements of the arm: an imitation emerges.

similar autonomous controllers with perception and action groups interconnected, in order to understand which minimal features need to be added to our architecture to get to a higher level of imitation. In order to simplify the problem, tests were performed in simulation. Perception and Motor groups are highly simplified (binary values). The output of the first autonomous controller is connected to the input of the second one, and vice versa: this simulates perfect perceptions of the other's action (see Figure 9). If one system imitates the other, each system perceives exactly the reproduction of its own production and thus can believe that it is perceiving its own production.

What is noticeable here is that we now consider three dynamical systems:

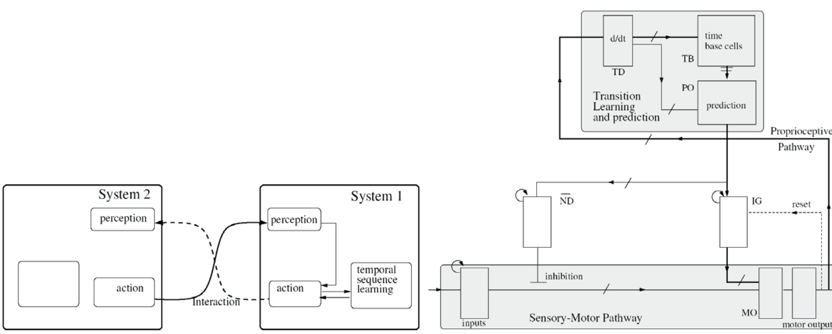

Figure 9. The model of sequence learning by imitation. The system is designed as a PerAc block. The "transition learning and prediction" mechanism is a perception level modulating the "sensory-motor pathway". Introduction of new elements allows synchronization between agents. "Non novelty detection" (ND) and Integration (IG) groups are used to control the internal dynamic of the system. Perception is then acting as an addition of energy on the system, triggering the corresponding action earlier. Between two systems producing the same sequence, the effect of connecting action to perception induces a step by step adjustment of the sequence production until synchronization.

two "one-body" systems composed of the two similar neural controllers, and one "two-body" system composed of the two systems in interaction. Besides, if we add learning capacities to neural controllers we can have the intuition that the dynamics of the whole system, which represents the dynamics of the interaction, is modulated by the learning capabilities of each system. After a while, both systems should evolve in order to make the whole system converge to a global attractor: by learning at an individual level, the whole system converges in a stable interaction — a prerequisite for communication.

Third step: Imitating a trajectory of movements

During the second developmental step of imitation, we have shown that the robot was able to reproduce a complex trajectory performed by a human experimenter. We then wondered how it could learn this sequence of movement from another identical system.

Banquet and colleagues (1998) have developed a neural network allowing a robot to learn to predict its next action according to the execution of the previous one and to the current context. Such an architecture would allow the robot to reproduce a sequence of actions with a precise timing. But this mechanism is not sufficient to allow two autonomous robots to learn from each other. Let us then suppose that the two robots use a "transition learning and prediction" mechanism (for details, see Andry et al., 2000; Gaussier et al., 1998, Moga & Gaussier, 1999).

If a given system already knows one sequence of action (for example transitions 1→2, 2→3, 3→1), and the other one knows nothing, the first robot will produce action 1. By construction, this action is recognized by the second robot, that will reproduce it. Unfortunately, the first robot will perceive this action and will have the problem of choosing between reproducing the imitated action or continuing its own sequence (risking a dead lock if the perceived information is dominant). A strong inhibition of the direct sensory-motor pathway must be introduced in the "model". Hence we have to solve the problem of when to control inhibition, depending on the role of the robot (imitator or model). This problem becomes even more crucial and interesting, if both systems have already learnt sequences of actions: thus are both potential models and imitators. Hence the problem of demonstrating a known sequence or of learning a demonstrated sequence is directly related to the inhibition of the sensory-motor link.[2]

The inhibition should therefore be partial only: the input signal must not be strong enough to induce motor reaction, and must nevertheless be present in order to modulate the motor production. Here, "modulate" stands for taking a relevant perception into account in order to change the timing of the sequence. Precisely, the perception of a given action could help to accelerate the triggering of the corresponding action by the system. Minor improvement of the architecture permits to obtain the modulation of the speed reproduction, in the manner of a Phase Locking Loop (PLL). The acceleration mechanism is based on the following idea: acceleration is due to a fusion between an anticipatory information of the next motor event, and the perception of this motor event. In other words, if the system "knows" in advance the next action to perform, an incoming perception of this precise action could trigger it earlier. Two mechanisms are involved. First, a modification of the connections between time base (TB on Figure 9) and PO groups (a standard conditioning) permits to have an early prediction of the next transition. If a given action is perceived after its prediction, then it will increase the potential of the corresponding MO neuron, overshooting the threshold earlier: the system accelerates.

Yet, if these systems are obviously interacting, are they communicating? According to Nadel et al. (1999), communication emerges if two systems create something together that would not exist if each system had been alone. In a work in progress, we claim that the same architecture can exhibit communicative capabilities without any new add-on. Let us suppose two systems "S1" and "S2" with the same neural architecture but with a different history: "S1" may have learned to reproduce a rhythm with frequency f1 and "S2" with frequency f2≠f1. What happens then when each one interacts with the other and how can this be formalized in the dynamical system context? If f1 and f2 are "close" to each other (according to a given metric) both S1 and S2 should try to reproduce each other's tempo. Both tempos evolve and we can guess they both converge to a new dynamical attractor with a new tempo T3 that has been reached by adapting slightly each entity's own attractor. We could then say that S1 and S2 communicate since they have created a new tempo by interacting with each other.

Next steps: Making the "will" to communicate explicit

In the previous configuration, after the two robots had learnt to interact, the system that they formed converged on a dynamical attractor producing rhythm. In this context, each prediction of one robot finds an echo in the production of the other (and can be related to self-production): the two-robot-system has converged on a definite cycle and nothing "unpredictable" (thus nothing informative) can occur. One way to create novelty via interacting is to modulate perceptual inhibition according to the internal motivation of each system in order for the system to be more or less receptive to what the other produces. The result is that the robot becomes either a "producer" (i.e. a system that *wants* to "be imitated") or an "observer" (i.e. a system that *wants* to imitate). Now two roles are defined: producer or observer, and these roles are transitory roles to be switched by the two robots as "conversational" turns. It must be noticed that these turns are very different from the previous step in which systems were simply doing the same thing one after the other, as observed in imitative rounds of 3-month-old infants with their mothers.

Work in progress (Prepin, 2003) has shown that a dynamical system made of the interaction of two systems embedding such a "will to communicate" can converge so as to present a rhythmic alternation between a phase in which one system is producing and the other is observing, and the reverse condition: it is interesting to see this behaviour as comparable to "role switching" behaviours observed in children, where taking turns implies proposing to the other something new to imitate and then to become an imitator in response to the other's proposal of something new to imitate (Nadel, 2002).

Concluding comments

The option of our interdisciplinary work was to adopt a bottom-up perspective where imitation is seen as an emerging property of an innate capacity to couple perception to action. We privileged the hypothesis that this emerging capacity develops continuously, ranging from low level imitations that do not require an explicit representation of the goal to fulfill, to high level imitations defined as mental operations that process the relationships between actions and goals. We focused on early stages of low-level imitations in order to acknowledge a possible parallel development of three imitative entities: typically developing infants, atypically developing children and generic architectures built as a perception-action loop.

Above the objective to document this point, we had the main focus to explore the idea that imitation consists of one single set of capacities serving two different functions: learning and communication. Although it has been argued by developmentalists (Užgiris, 1981) that the learning and the social function of imitation are intermeshed, little work, if any, has been devoted to a demonstration of this functional relationship. As a support to what remains an opinion more than a demonstration, the psychological literature in the field does not show a clear-cut distinction between the development of learning and the development of interacting through imitation. However, the intermeshing of imitating and being imitated from which the core communicative function of imitation originates, is not captured by the classical though vague claim that imitation is social in nature (after all, learning mostly occurs within a social context).

We need to take seriously the role of turn-taking and role switching from imitating to being imitated if we intend to avoid the confusion between social embeddedness and interindividual exchange and sharing. That was and still remains the ultimate goal of the robotic part of this interdisciplinary program.

In its first developmental steps, due to the property of its perceptive system, the robot processes any movement seen as if it was its own. This perceptual error results in an imitation (i.e. imitating corrects the discrepancy between movement seen and movement done). From this can emerge both the capacity to learn new actions and the capacity to link one's perception to the other's action rather than to one's own action. This does not imply distinguishing between self and other. Such a demonstration may inspire developmental psychologists. It may well be that, at first, when imitated, the very young infant takes the behaviour seen as being hers, which will result in reciprocal imitation if the movement seen does not match exactly the movement done. Through imitation, this will lead the infant to distinguish between two classes of perception that Russell (1996) proposes to be at the origin of the sense of agency: those perceptions that are a by- product of one's own action and intention, and perceptions coming from the external world, that you cannot modify at will. For synchronous imitation generates a unique phenomenon with multiple outcomes: seeing ones' intentions acted through the behaviour of the other.

Notes

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1. This program was supported by a grant of the Ministry or Research, Cog 156, Interdisciplinary Program of Cognitive Sciences.

2. With the long term perspective of building an architecture able to share complex motor sequences and take turns, Andry and Gaussier conceived the following experiment: two systems had learnt the same sequence of actions (for example transitions 1→2, 2→3, 3→1 are learned, allowing the production of the sequence 1, 2, 3, 1, 2, … and so on). The solution developed is inspired by the "entrainment" phenomenon observed by Huygens (1665), in which two pendulum clocks placed on the same support synchronize themselves ("clock synchronization"). Here, perception is similar to the physical wave transmitted by the support, and must allow the addition of some energy to the system in order to trigger the motor output earlier. Perception is adding energy to the system's actions. The system produces its sequence independently, and "blindly".

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