

Developmental robotics: a survey

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Abstract. Developmental robotics is an emerging field located at the intersection of robotics, cognitive science and developmental sciences. This paper elucidates the main reasons and key motivations behind the convergence of fields with seemingly disparate interests, and shows why developmental robotics might prove to be beneficial for all fields involved. The methodology advocated is synthetic and two-pronged: on the one hand, it employs robots to instantiate models originating from developmental sciences; on the other hand, it aims to develop better robotic systems by exploiting insights gained from studies on ontogenetic development. This paper gives a survey of the relevant research issues and points to some future research directions.

Keywords: development, embodied cognitive science, robotics, synthetic methodology

1. Introduction

Developmental robotics is an emergent area of research at the intersection of robotics and developmental sciences—in particular developmental psychology and developmental neuroscience. It constitutes an interdisciplinary and two-pronged approach to robotics, which on one side employs robots to instantiate and investigate models originating from developmental sciences, and on the other side seeks to design better robotic systems by applying insights gained from studies on ontogenetic development.¹

Judging from the number of recent and forthcoming conferences, symposia and journal special issues, it is evident that there is growing interest in developmental robotics (Berthouze *et al.* 1999, Weng 2000, Pfeifer and Lungarella 2001, Balkenius *et al.* 2001, Westermann *et al.* 2001, Elman *et al.* 2002, Di Paolo 2002, Prince *et al.* 2002, 2003, Prince and Demiris 2003, EpiRob 2004, ICDL 2004, and this special issue of *Connection Science*). There are at least two distinct driving forces behind the growth of the alliance between developmental psychology and robotics:

- Engineers are seeking novel methodologies oriented toward the advancement of robotics, and the construction of better, that is, more autonomous, adaptable and sociable robotic systems. In that sense, studies of cognitive development can be used as a valuable source of inspiration (Brooks *et al.* 1998, Metta 2000, Asada *et al.* 2001).
- Robots can be employed as research tools for the investigation of embodied models of development. Neuroscientists, developmental psychologists, and also engineers, may

gain considerable insight from trying to embed a particular model into robots. This approach is also known as synthetic neural modelling, or synthetic methodology (Reeke *et al.* 1990, Sandini 1997, Pfeifer and Scheier 1999, Pfeifer 2002, Sporns 2003).

The research methodology advocated by developmental robotics is very similar to that supported by epigenetic robotics. The two research endeavours not only share problems and challenges but are also driven by a common vision. From a methodological point of view both partake of a biomimetic approach to robotics known as biorobotics, which resides at the interface of robotics and biology. Biorobotics addresses biological questions by building physical models of animals, and strives to advance engineering by integrating aspects of animal sensory systems, biomechanics and motor control into the construction of robotic systems (Lambrinos *et al.* 1997, Beer *et al.* 1998, Webb 2001, Sharkey 2003). There is, however, at least one important difference of emphasis between epigenetic robotics and developmental robotics: while the former focuses primarily on cognitive and social development (Zlatev and Balkenius 2001), as well as on sensorimotor environmental interaction (Prince and Demiris 2003), the latter encompasses a broader spectrum of issues, by also investigating the acquisition of motor skills and the role played by morphological development. In the context of this review, the difference will not be stressed any further.

The primary goals of this article are to present an overview of the state-of-the-art developmental robotics (and hence epigenetic robotics), and to motivate the usage of robots as ‘cognitive’ or ‘synthetic’ tools, that is, as novel research tools to study and model the emergence and development of cognition and action. From a methodological point of view, this review is not intended to be critical. Developmental robotics is still in its infancy, and an indication of the pros and cons of specific pieces of research may be premature. We hope, however, that the review will offer new perspectives on certain issues and point out areas in need of further research. The secondary goal is to uncover the driving forces behind the growth of developmental robotics as a research area, and to expose its hopefully far-reaching implications for the design and construction of robotic systems. We advocate the idea that ontogenetic development should not only be a source of inspiration, but also a design alternative for roboticists, as well as a new and powerful tool for cognitive scientists.

In the following section, we make an attempt to trace back the origins of developmental robotics, which we believe are to be found in the rejection of the cognitivist paradigm by many scholars of artificial intelligence. Next, we present our working definition of ontogenetic development, and summarize some of its key aspects. In the following sections, we give an overview of the various current and past research directions (including motivations and goals), show who is doing or has been doing what and to what purpose, and discuss the implications of the developmental approach for robotics research. In the final section, we point to future research directions and conclude.

2. In the beginning there was the body

In an ever-growing number of fields there is an ongoing and intense debate about the usefulness of taking into account ideas of embodiment, i.e. the claim that having a body that mediates perception and affects behaviour plays an integral role in the emergence of human cognition. Scholars of artificial intelligence, artificial life, robotics, developmental psychology, neuroscience, philosophy and other disciplines seem to agree on the fact that brain, body and environment are reciprocally coupled, and that cognitive processes arise from having a body with specific perceptual and motor capabilities

interacting with and moving in the real world (Brooks 1991, Varela *et al.* 1991, Thelen and Smith 1994, Hendriks-Jensen 1996, Clark 1997, Beer *et al.* 1998, Lakoff and Johnson 1999, Pfeifer and Scheier 1999, Sporns 2003). This paradigm stands in stark contrast to the mind-as-computer metaphor advocated by traditional cognitive science, according to which the body is seen as an output device that merely executes commands generated by a rule-based manipulation of symbols that are associated with an internal representation of the world (Newell and Simon 1976, Fodor 1981). Perception is largely seen as a means of creating an internal representation of the world rich enough to allow reasoning and cognizing to be conceptualized as a process of symbol manipulation (computer program), which can take place entirely in the mind. One of the most unfortunate consequences of the mind-as-computer metaphor for cognitive science and artificial intelligence in general, and for developmental psychology and robotic research in particular, has been the tacit acceptance of a strong separation between cognitive structure (i.e. symbols and representations), the software operating on that structure (i.e. mechanisms of attention, decision making and reasoning) and the hardware on which to implement the software (Brooks 1991, Thelen and Smith 1994, Pfeifer and Scheier 1999, Bates and Elman 2002). Another assumption of the cognitivist research paradigm was a denial of the importance of ontogenetic development by rationalists-nativists (Keil 1981, Chomsky 1986). In the field of language acquisition, for instance, Chomsky theorized that all languages derive from a universal grammar, somehow encoded in our genome. The purpose of development and learning was merely to fine-tune some parameters to a specific language. The same cognitivist approach also hypothesized accurate, symbol-based representations of the real world (Newell 1990), as well as task-specific models of information processing and reasoning (Pylyshyn 1984).

Out of dissatisfaction with the direction in which (cognitive) psychology was heading, and to overcome the limitations inherent in the rather artificial distinction of the developmental phenomena into domain-specific competencies and modules (Fodor 1983), Masao Toda (1982) proposed the study of ‘fungus eaters’, i.e. simple but nevertheless complete and autonomous creatures endowed with everything needed to behave in the real world. Around the same time Braitenberg (1984) defined the ‘law of uphill analysis and downhill synthesis’,² and argued for the introduction of a novel methodology in psychology, which he called ‘synthetic psychology’. Two similar approaches followed: ‘synthetic neural modelling’ (Reeke *et al.* 1990), which attempts to correlate neural and behavioural events taking place at multiple levels of organization; and the ‘synthetic methodology’ (Pfeifer and Scheier 1999), a wider term that embraces the whole family of synthetic approaches. The shared common goal of synthetic approaches is to seek an understanding of cognitive phenomena by building physical models of the system under study. Typically, they are applied in a bottom-up way: initially, a simple system (e.g. with a small number of sensors) is built and explored, then its complexity is successively increased (e.g. by adding sensors) if required to achieve a desired behaviour.

The extension of the synthetic methodology to include development is a conceptually small step. First, development is a process during which changes in all domains of function and behaviour occur from simple to complex (see section 3.1). Therefore, it is reasonable to assume that its key aspects can be captured by means of a bottom-up synthetic approach. Second, cognitive development cannot be isolated from the body in which it is instantiated and from the real world in which it is embedded, and with which the body physically interacts. As a matter of fact, the traditional approach (based on the computer metaphor) has ultimately failed to address the intimate linkage between brain, body and environment, and to study behavioural and neural changes typical of ontogenetic

development that are important for the emergence of cognition. The construction of an artificial system through the application of a ‘developmental synthetic methodology’, however, is not straightforward. An adequate research methodology as well as a good set of design principles supporting such a methodology are still open research issues, one possible reason being the difficulty in disentangling the complex notion of development itself, which is—as we shall show in the following section—multifaceted, non-linear, complex and yet to be fully understood.

The central tenet of embodied cognition is that cognitive and behavioural processes emerge from the reciprocal and dynamic coupling between brain, body and environment. Since its inception, this view has spawned paradigm changes in several fields, which in turn have influenced the way we think about the role of embodiment for the emergence of cognition. Ballard (1991), for instance, introduced the concept of animate or active vision, which states—roughly speaking—that visual processes can be simplified if visual sensing is appropriately intertwined with acting and moving in the world (see also Churchland *et al.* 1994). By employing active vision, problems such as figure/ground segmentation or estimation of shape from shading become well-conditioned. The paradigm change expresses how action and motor control contribute to the improvement of perceptual abilities. Biological systems are not passively exposed to sensory input, but instead interact actively with their surrounding environment. Thus, accordingly, the ‘Holy Grail of artificial intelligence’, that is, a computerized general vision system, has to be viewed as strictly dependent on the availability of a controllable body coupled to a less controllable world. In a similar vein, Brooks (1991) showed that behaviour does not necessarily have to rely on accurate models of the environment, but rather might be the result of the interaction of a simple system with a complex world. In other words, there is no need to build enduring, full-scale internal models of the world, because the environment can be probed and reprobated as needed. More recently, Pfeifer and Scheier (1994) argued that a better global understanding of the perception–action cycle might be required—contrary to our intuition.³ The authors proposed an alternative view that breaking up perception, computation and action into different subsystems might be too strong a commitment. In other words, the minimal unit of processing should be a complete perception–action cycle. Neurophysiology too contributed to the paradigm change. Emblematic was the discovery of visually responsive motor neurons supporting the hypothesis of an intimate coupling between vision and action in the definition of higher cognitive abilities, such as object and action recognition (Di Pellegrino *et al.* 1992, Gallese *et al.* 1996). Also fascinating, along the same line of research, is the link between action and language proposed by Rizzolatti and Arbib (1998), who argued that the visuo-motor neurons found in the area *F5* of monkeys are most probably the natural homologue of the Broca’s area of humans.

3. Facets of development

Ontogenetic development is commonly seen as a process of change whereby appropriate biological structure and skills emerge anew in an organism through a complex, variable and constructive interplay between endogenous and environmental factors (Johnson 1997). Unlike development and maturation, which involve species-typical growth, and changes at the level of cell, tissue and body, learning is experience-dependent, and is often characterized by a relatively permanent change of behaviour resulting from exercise and practice (e.g. Chec and Martin 2002). The debate nowadays gravitates around the precise nature of the interaction between learning and development. There are at least three leading views. The first one is closest to the one of Piaget (1953), and sees learning capitalizing on the achievements of development. The interaction is

unidirectional, and learning cannot occur unless a certain level of development has been achieved. The second view is bidirectional and states that learning and development are mutually coupled, in the sense that the developmental process enables, limits, or even triggers learning, and learning in turn advances development (Kuhl 2000). The third, more radical, view, which accommodates continuity and change under the theoretical umbrella of dynamic systems theory (Thelen and Smith 1994), suggests erasing the boundaries between development and learning altogether, while considering ‘dynamics’ at all levels of organization (molecular, cellular, structural, functional, and so on). We do not take any position in this or other debates. We are convinced, however, that using robots as tools for scientific investigation might provide a route to disentangle open issues—such as the nature of the interaction between development and learning. An additional advantage of the proposed methodology is that we can simply build various assumptions into the system and perform tests as we like—no ethical issues involved. The latter point is perhaps a less obvious, but equally important, justification for this area of research. It is relatively straightforward, for instance, to build pathological conditions into a robot’s sensory, motor and neural systems (e.g. by lesioning or augmenting its sensorimotor apparatus). Thus, robotic models cannot only help elucidate principles underlying normal (healthy) development, but they may also provide insight into disease and dysfunction of brain, body and behavioural processes.

In the remainder of this section, we review several important facets (components) of ontogenetic development, and give pointers to some of the pertinent literature. The reader should bear in mind that we do not intend to give an exhaustive account of biological development. Both our choices of what to include and what to discard are therefore limited and biased by our beliefs of what is deemed important and what is not. However, we do intend to convey the message that these seemingly disparate facets of development are closely intertwined and that—if taken into account during the design and construction of artificial systems—they can represent a valuable source of inspiration. We also point out that many of these aspects can and should be conceptualized as principles for the design of intelligent developmental systems. A set of generalized principles for agent design can be found in Pfeifer (1996) and in Pfeifer and Scheier (1999). For quick reference, we have summarized the list of facets in table 1.

3.1. *Development is an incremental process*

By assuming a certain level of abstraction, development in virtually any domain (e.g. nervous system, motor apparatus, cognition) can be described as a sequence of stages through which the infant advances. Indeed, the idea that development may be an incremental process is not novel, and had already been proposed by Jean Piaget in his theory of stages of cognitive development more than 50 years ago (e.g. Piaget 1953), as well as by Eleanor Gibson (1988), who suggested decomposing infant exploration into three distinct phases. The apparent stage-like nature of development, however, by no means implies stable underlying processes, characterized by a well-ordered, discontinuous and incremental unfolding of clearly defined stages (as suggested by Piaget). Thelen and Smith (1994) give evidence for the opposite: depending on the level of observation, development is messy and fluid, full of instabilities and non-linearities, and may even occur with regressions. There may be rapid spurts, such as the onset of babbling, as well as more protracted and gradual changes, such as the acquisition of postural control. Various systems (e.g. the perceptual and the motor system) do not even change at the same rate. This list of properties is a clear indication of how challenging the study of developmental changes is. An additional difficulty arises from the fact that those changes are both qualitative (e.g. transition from crawling to walking) and quantitative

Table 1. Facets of development at a glance.

Facet	Synopsis	References
Incremental process	Prior structures and functions are necessary to bootstrap later structures and functions	Piaget (1953), Thelen and Smith (1994)
Importance of constraints	Early constraints can lead to an increase of the adaptivity of a developing organism	Bushnell and Boudreau (1993), Elman (1993), Hendriks-Jensen (1996), Turkewitz and Kenny (1982)
Self-organizing process	Development and learning are not determined by innate mechanisms alone	Goldfield (1995), Kelso (1995), Thelen and Smith (1994)
Degrees of freedom	Constraining the movement space may be beneficial for the emergence of well co-ordinated and precise movements	Bernstein (1967), Goldfield (1995), Sporns and Edelman (1993)
Self-exploration	Self-acquired control of body dynamics	Angulo-Kinzler (2001), Goldfield (1995), Thelen and Smith (1994)
Spontaneous activity	Spontaneous exploratory movements are important precursors of motor control in early infancy	Piek (2002), Prechtl (1997)
Prospective control, early abilities	Predictive control is a basic early competency on top of which human cognition is built	Meltzoff and Moore (1997), Spelke (2000), Von Hofsten <i>et al.</i> (1998)
Categorization, sensorimotor co-ordination	Categorization is a fundamental ability and can be conceptualized as a sensorimotor interaction with the environment	Edelman (1987), Thelen and Smith (1994)
Value systems	Value systems mediate environmental saliency and modulate learning in a self-supervised and self-organized manner	Sporns and Alexander (2002)
Social interaction	Interaction with adults and peers is very important for cognitive development	Baron-Cohen (1995), Meltzoff and Moore (1977), Vygotsky (1962)

(e.g. increase of muscle–fat ratio). Another important characteristic of the developmental progression is that later structures build up on less complete and less efficient prior structures and their behavioural expressions. In other words, the former structures provide a background of subskills and knowledge that can be reused by later ones. The mastery of reaching, for instance, requires adequate gaze and head control, and a stable trunk support, the latter being even more important for fine manipulation (Bertenthal and Von Hofsten 1998). Finally, we point out the absence of a central executive behind this developmental progression. In other words, development is largely decentralized and exhibits the properties of a self-organizing system (see section 3.3).

3.2. *Development as a set of constraints*

The notion of initial constraints or of ‘brake’ on development is often invoked in order to explain developmental trajectories (Harris 1983, Bushnell and Boudreau 1993). Examples of constraints present at birth in many vertebrate species (e.g. rats, cats, humans) are the limitations of the organism’s nervous system (such as neural connectivity and number of neuronal cells) and of its sensory and motor apparatus (such as reduced visual acuity and low muscle strength). Because each developmental step somehow establishes the boundary conditions for the next one, a particular ability cannot emerge if any of the capacities it entails is lacking. Thus, particular constraints can act (metaphorically speaking) as a brake on development. These rate-limiting factors (as they are also called sometimes) are not necessarily a bad thing. Turkewitz and Kenny (1982) pioneered the theoretical position that early morphological limitations and constraints can lead to an increase of the adaptivity of a developing organism (see also Bjorklund and Green 1992). That is, the immaturity of the sensory and the motor system, which at first sight appears to be an inadequacy, is of advantage, because it effectively decreases or eliminates the ‘information overload’ that otherwise would most certainly overwhelm the infant. According to this hypothesis, the limited acuity of vision, contrast sensitivity and colour perception of neonates (Slater and Johnson 1997: 126) may actually improve their perceptual efficiency by reducing the complexity of the environmental information impinging on their visual system (for additional examples, see Hendriks-Jensen 1996). Following similar lines of argumentation, several other researchers have suggested that processing limitations of young learners, originating from the immaturity of the neural system, can actually be beneficial for learning itself (Newport 1990, Elman 1993, Westermann 2000, Dominguez and Jacobs 2003). In other words, constraints can be interpreted as particular instances of ‘ontogenetic adaptations’, that is, unique adaptations to the environment throughout development, which effectively simplify the world and hence facilitate learning (Bjorklund and Green 1992).

3.3. *Development as a self-organizing process*

A fundamental characteristic of self-organization is that structured patterns or global order can emerge from local interactions between the components constituting a system, without the need for explicit instructions or a central programme (see also section 3.1). In this sense, development largely unfolds in a self-organized fashion. The earliest actions of human infants, for instance, are spontaneous and exhibit the typical properties of a self-organizing system (Sporns and Edelman 1993, Thelen and Smith 1994, Goldfield 1995). A growing body of evidence has shown that the control of movements of particular (exploratory) actions is not determined by innate mechanisms alone, but emerges from the dynamics of a sufficiently complex action system interacting with its surrounding environment (Bernstein 1967, Kelso and Kay 1987, Taga 1991, 1995, Goldfield 1995). In other words, the dynamics of the interaction of infants and their surroundings modulates the ever-changing landscape of their exploratory activities. The intrinsic tendency to co-ordination or pattern formation between brain, body and environment is often referred to as entrainment, or intrinsic dynamics (Kelso 1995). Gentaro Taga (1991), for instance, was able to show that rhythmic movements (in his case, walking) can emerge from what he called a ‘global entrainment’ among the activity of the neural system, the musculo-skeletal system and the surrounding environment. Another vivid illustration of a dynamically self-organized activity was provided by Thelen (1981). She found that the trajectory and the cyclic rhythmicity of kicks displayed by human infants and the intrinsic timing of the movement phases was the ‘result of cooperative

(and local) interactions of the neuro-skeletal muscular system within particular energetic and environmental constraints' (Thelen and Smith 1994: 79).

Processes of self-organization and pattern formation are not confined to the learning and the development of movements but are essential features of biological systems at any level of organization (Kelso 1995). Iverson and Thelen (1999), for instance, invoked entrainment and other principles of dynamic co-ordination typical of self-organized behaviour to explain the developmental origins of gestures that accompany the expression of language in speech; Edelman (1987) hypothesized that perceptual categorization—one of the primitives of mental life—arises autonomously through self-organization; and finally, even the amazing complexity of the brain has been proposed to be the result of a process of self-organized ontogenesis (von der Malsburg 2003).

3.4. *Degrees of freedom and motor activity*

Perhaps not surprisingly, movements of infants lack control and co-ordination compared with those of adults. The co-ordination of movements (in particular in humans) is very poor at birth and undergoes a gradual maturation over an extended period of postnatal life. Examples of this developmental progression are crawling (Adolph *et al.* 1998), walking with support (Haehl *et al.* 2000), walking (Thelen and Smith 1994: 71), reaching and grasping (Streri 1993). Despite the fact that the musculo-skeletal apparatus is a highly non-linear system, with a large number of biomechanical and muscular degrees of freedom,⁴ and in spite of the potential redundancy of those degrees of freedom in many movement tasks (i.e. the activation of different muscle groups can lead to the same movement trajectory), well-co-ordinated and precisely controlled movements emerge. This 'degrees of freedom problem', first pointed out by Bernstein (1967), has recently attracted a lot of attention (Vereijken *et al.* 1992, Sporns and Edelman 1993, Zernicke and Schneider 1993, Goldfield 1995). A possible solution to the control issues raised by the degrees of freedom problem, that is, how—despite the complexity of the neuro-musculo-skeletal system—stable and well-co-ordinated movements are produced, was suggested by Bernstein himself. His proposal is characterized by three stages of change in the number of degrees of freedom that take place during motor skill acquisition. Initially, in learning a new skill or movement, the peripheral degrees of freedom (the ones further from the trunk, such as wrist and ankle) are reduced to a minimum through tight joint coupling (freezing of degrees of freedom). Subsequently, the restrictions at the periphery are gradually weakened so that more complex movement patterns can be explored (freeing of degrees of freedom). Eventually, preferred patterns emerge that exploit reactive phenomena (such as gravity and passive dynamics) so as to enhance efficiency of the movement. The strong joint coupling of the first phase has been observed in spontaneous kicking in the first few months of life (Thelen and Fischer 1983), and is thought to allow infants to learn without the interference of complex, unco-ordinated motor patterns.

Recently, the straightforward, but rather narrow and unidirectional view of the nature of change in the number of controlled degrees of freedom proposed by Bernstein has been contended—in adult studies (Spencer and Thelen 1999, Newell and Vaillancourt 2001), as well as in infant studies (Haehl *et al.* 2000). These recent observations seem to indicate that, while according to Bernstein's framework biomechanical degrees of freedom only increase (as a consequence of practice and exercise), there can be—depending on the task—an increase or decrease of the number of degrees of freedom. Despite such counter evidence, Bernstein's proposal bears at least two important messages, which fit very nicely into the above discussion: (a) the presence of initial constraints that are gradually lifted; and (b) the emergence of co-ordinated movements from a dynamic

interaction (via external feedback and forces) between the maturing organisms and the environment.

3.5. *Self-exploratory activity*

Scaffolding by parents and caretakers (see section 3.10), as well as active exploration of objects and events, have been acknowledged to be of crucial importance for the developing infant (Piaget 1953, Gibson 1988, Rochat 1989, Bushnell and Boudreau 1993). Little attention, however, has been paid to the understanding of what sort of information is available to infants as a result of their self-exploratory acts. Self-exploration plays an important role in infancy, in that infants' 'sense of the bodily self' to some extent emerges from a systematic exploration of the perceptual consequences of their self-produced actions (Rochat 1998, Rochat and Striano 2000). The exploration of the infants' own capacities is one of the primary driving forces of development and change in behaviour, and infants explore, discover and select—among all possible solutions—those that seem more adaptive and efficient (Angulo-Kinzler 2001: 363). Exploratory actions, traditionally thought to be actions focused on the external world, may as well be focused on the infants' own action system (Von Hofsten 1993). Infants exploring their own action system or their immediate surroundings have been observed to perform movements over and over again (Piaget 1953). Newborn infants, for instance, have been observed to spend up to 20% of their waking hours contacting their face with their hands (Korner and Kraemer 1972). In analogy to vocal babbling, this experiential process has also been called 'body babbling' (Meltzoff and Moore 1997). By means of self-exploratory activities, infants learn to control and exploit the dynamics of their bodies (Thelen and Smith 1994, Goldfield 1995, Smitsman and Schellingerhout 2000). The nature of these dynamics differs from infant to infant (each infant has a unique set of abilities, muscle physiology, fat distribution, and so on), and depends on the dynamics of the interaction with the environment, which in turn varies from task to task. Self-exploration can also be conceptualized as a process of soft-assembly,⁵ i.e. a process of self-organization (see section 3.3) during which new movements are generated and more effective ways of harnessing environmental forces are explored, discovered and selected (Schneider *et al.* 1990, Schneider and Zernicke 1992, Goldfield 1995).

3.6. *Spontaneous activity*

Spontaneous movements have been recognized as important precursors to the development of motor control in early infancy (Thelen 1995, Forssberg 1999, Taga *et al.* 1999, Piek 2002). One of their main functions is the exploration of various musculo-skeletal organizations, in the context of multiple constraints, such as environment, task, architecture of the nervous system, muscle strength, masses of the limbs and so forth (see sections 3.2 and 3.5). Well co-ordinated movement patterns emerge from spontaneous neural and motoric activity as infants learn to exploit the physical properties of their bodies and of the environment. In fact, foetuses (as early as 8–10 weeks after conception) and newborn infants display a large variety of transient and spontaneous motoric activity, such as general movements⁶ and rhythmical sucking movements (Precht 1997), spontaneous arm movements (Piek and Carman 1994), stepping and kicking (Thelen and Smith 1994). An interesting property of spontaneous movements is that although they are not linked to a specific, identifiable goal, they are not mere random movements. Instead, they are organized, right from the early days of postnatal life, into recognizable forms. Spontaneous kicks in the first few months of life, for instance, are well-co-ordinated movements characterized by a tight joint coupling between the hip, knee and ankle joints (Thelen and Fischer 1983, Thelen and Smith 1994), and by short phase lags between the

joints (Piek 2001: 724). As hypothesized by Sporns and Edelman (1993), spontaneous exploratory activity may also induce correlations between certain populations of sensory and motor neurons, which are eventually selected as a task is consistently accomplished or a goal attained. The same authors also proposed three concurrent steps of how the development of sensorimotor co-ordination may proceed: (a) spontaneous generation of a variety of movement patterns; (b) development of the ability to sense the consequence of the self-produced movements; and (c) actual selection of a few movements. We note that the ultimate ‘availability’ of good sensorimotor patterns is connected to the degrees of freedom problem: the latter can be achieved only if the range of in principle possible movements is constrained by initially reducing the number of available degrees of freedom (see section 3.4).

3.7. *Anticipatory movements and early abilities*

Throughout development infants acquire and refine the ability to predict the sensory consequences of their actions and the behaviour of external objects and events (e.g. the ‘when’ and ‘where’ of a forthcoming manual interception of an object passing by). Optimally, this ability allows movements to be adjusted prospectively rather than reactively in response to an unexpected perturbation (Von Hofsten 1993, Adolph *et al.* 2000). Two types of control strategies are employed to control anticipatory movements: predictive and prospective control (e.g. Peper *et al.* 1994, Regan 1997). In predictive control the current perceptual information is used to predict the sensory activation at a future point in time. Prospective control, on the other hand, relies on the sensory (or perceptual) information associated with a particular action as the action unfolds over time, and is thus based on a close coupling between information and movement.

Predictive and prospective control are in place early in development. Infants as young as 1 month, for instance, are able to compensate for head movements with zero lag between head and eye movements (Bertenthal and Von Hofsten 1998, Von Hofsten *et al.* 1998). Predictive control is important because of the intrinsic time delays of the sensorimotor system (visual feedback can take up to 150 ms to be processed by the cortex, for instance). An example where infants make use of prediction is gaze-following. During gaze control there are at least two situations during which predictive control is important: for the prediction of the motion of visual targets, and for the prediction of the consequences of relative movements between body parts (e.g. movement of the head with respect to the eyes).

Prediction clearly supports the idea that the brain forms so-called ‘internal forward models’—instances of internal models, which have been hypothesized to exist in the cerebellum (Miall *et al.* 1993), and whose biological and behavioural relevance has been confirmed by recent experiments (e.g. Mussa-Ivaldi 1999, Wolpert *et al.* 2001). Forward models are ‘neural simulators’ of the musculo-skeletal system and the environment (Clark and Grush 1999, Grush 2003, Wolpert *et al.* 2003), and thus allow prediction of the future state of the system given the present state and a certain input (a state specifies a particular body configuration).

The ability to make predictions is part of what Spelke (2000) refers to as ‘core initial knowledge’, that is, a set of basic competencies on top of which human cognition is built. High-level cognitive functions, such as planning and shared attention, for instance, can be interpreted with respect to their capability of predicting the consequences of chains of events. The large number of behavioural predispositions that have been discovered, and which are part of the core knowledge, show that infants are not mere blank slates waiting to be written on (Thelen 1981, Johnson 1997, Meltzoff and Moore 1997, Iverson and Thelen 1999, Spelke 2000).

3.8. *Categorization and sensorimotor co-ordination*

Categorization is the ability to make distinctions in the real world, i.e. to discriminate and identify sensory stimulations, events, motor acts, emotions, and so on. This ability is of such fundamental importance for cognition and intelligent behaviour that a natural organism incapable of forming categories does not have much chance of survival (unless the categories are innate, but then they are not flexible). For example, the organism will not be able to discern food and non-food, peer and non-peer, and so forth. Categorization is an efficient and adaptive initial step in perceiving and cognizing, as well as a base for most of our conceptual abilities. Our daily interactions with the physical world and our social and intellectual lives rely heavily on our capacity to form categories (Lakoff 1987), and so does cognitive development (Thelen and Smith 1994). Most organisms are therefore endowed with the capacity to categorize perceptually and discriminate behaviorally an extraordinary range of environmental stimuli (Edelman 1987).

Evidence from developmental psychology supports the idea that perceptual categorization and concept formation are the result of active exploration and manipulation of the environment (e.g. Piaget 1953, Gibson 1988, Bushnell and Boudreau 1993, Streri 1993). That is, while sensation and perhaps certain aspects of perception can proceed without a contribution of the motor apparatus, perceptual categorization depends upon the interplay between sensory and motor systems. In other words, categorization is an active process, which can be conceptualized as a process of sensorimotor-co-ordinated interaction of the organism with its surrounding environment (e.g. discrimination of textures and size of objects by exploratory hand movements). It is through such interaction that the raw sensory data impinging on the sensors may be appropriately structured and the subsequent neural processing simplified. The structure induced in the sensory data is important—perhaps critical—in establishing dynamic categories, and may be a consequence of the correlation of movements and of time-locked external (potentially multimodal) sensory stimulation (Thelen and Smith, 1994: 194). We conclude that the absence of self-produced movements can affect the development of cognitive abilities and skills. Children with severe physical disabilities, for instance, have limited opportunities to explore their surroundings; and this lack of experience affects their cognitive and social development.

3.9. *Neuromodulation, value and neural plasticity*

Neuromodulatory systems are small and compact groups of neurons that reach large portions of the brain. They include the noradrenergic, serotonergic, cholinergic, dopaminergic and histaminergic cell nuclei (Edelman 1987, 2001). In mammals, the importance of these modulatory neurotransmitter systems vastly outweighs the proportion of brain space they occupy, their axons projecting widely throughout the cerebral cortex, hippocampus, basal ganglia, cerebellum and spinal cord (Dickinson 2003, Hasselmo *et al.* 2003). One of the primary roles of neuromodulatory systems is the configuration and tuning of neural network dynamics at different developmental stages (Marder and Thirumalai 2002). Another important role of these systems in brain function is to serve as ‘value systems’ that either gate the current behavioural state of the organism (e.g. waking, sleep, exploration, arousal), or act as internal mediators of value and environmental saliency. That is, they signal the occurrence of relevant stimuli or events (e.g. novel stimuli, painful stimuli, rewards) by modulating the neural activity and plasticity of a large number of neurons and synapses (Friston *et al.* 1994). Value systems have several properties: (a) their action is probabilistic, i.e. they influence big populations of neurons; (b) their activation is temporally specific, that is, their effects are transient and short-lasting; and (c) spatially uniform, i.e. they affect widespread regions of the

brain, while acting as a single global signal (Sporns and Alexander 2002). Other implementations of value systems, e.g. in other species, are also possible (Dickinson 2003).

Value systems play a pivotal role in adaptive behaviour, because they mediate neural plasticity and modulate learning in a self-supervised and self-organized manner. In doing so, they allow organisms to learn autonomously via self-generated (possibly spontaneous) activity. In a sense, value systems introduce biases into the perceptual system, and therefore create the necessary conditions for learning and the self-organization of dynamic categories. The action of value systems can be either genetically predetermined, such as in behaviours that satisfy homeostatic and appetitive needs, or it can incorporate activity and experience-dependent processes (Sporns 2004). The two flavours of value are also known as innate and acquired value (Friston *et al.* 1994).

3.10. *Social interaction*

Interactions with adults and peers (scaffolding, tutelage, and other forms of social support) as well as mimetic processes such as mimicry, imitation and emulation are hypothesized to play a central role in the development of early social cognition and social intelligence (Whiten 2000, Meltzoff and Prinz 2002). The presence of a caregiver to nurture children as they grow is essential because human infants are extremely dependent on their caregivers, relying upon them not only for their most basic needs but also as a guide for their cognitive development (Vygotsky 1962, Lindblom and Ziemke 2003). It is important to note that, in terms of development, interaction with objects and interaction with peers bear two completely different valences (Nadel 2003). Through interaction with inanimate objects infants acquire information ‘statically’ and maybe learn the ‘simple’ physics that entails the objects’ behaviour. During peer-to-peer or infant–adult interaction, however, infants are engaged in a complex communicative act, involving the interaction of two complex dynamical systems mutually influencing (and modifying) each other’s behaviour.

A fundamental type of interaction between infants and adults is scaffolding. The concept of scaffolding, whose roots can be found in the work of Vygotsky (1962), was introduced by Wood *et al.* (1976) and refers to the support provided by adults to help children bootstrap cognitive, social and motor skills. As the child’s confidence increases, the level of assistance is gradually reduced. In other words, scaffolding helps to structure the environment in order to facilitate interaction and learning. Scaffolding by a more capable caregiver or imitation of a peer can reduce distractions and bias explorative behaviours toward important environmental stimuli. The caregiver can also increase or decrease the complexity of the task. This issue is akin to the concept of ‘sensitive periods’ (Bornstein 1989, Gottlieb 1991), that is, particular intervals of time during which infants are especially responsive to the input from their caregivers and hence more apt to acquire skills.

From a very early age, infants are endowed with the necessary means to engage in simple, but nevertheless crucial social interactions (e.g. they show preferences for human smell, human faces and speech (Johnson 1997, Nadel and Butterworth 1999)—see also section 3.7), which can be used by the caregiver to regulate and shape the infant’s behaviour. Joint or shared attention, i.e. the ability to attend to an object of mutual interest in the context of a social exchange, is already observed in 6-month-old infants (Butterworth and Jarrett 1991). Meltzoff and Moore (1977) reported on the early ability of very young infants to imitate both facial and manual gestures. Indeed, early and non-verbal imitation is a powerful means for bootstrapping the development of communication and language. Developmental psycholinguists such as Fernald (1985) provided compelling evidence for what sort of cues preverbal infants exploit in order to recognize affective communicative intent in infant-directed speech (motherese).

Basic social competencies are the background on which more complex social skills develop, and they represent yet another way to facilitate learning (see section 3.1). The reliance on social contact is so integrated in our species that it is hard to imagine a completely asocial human. Severe developmental disorders that are characterized by impaired social and communicative development, such as autism (Baron-Cohen 1995), can give us a glimpse of the importance of social contact (Scassellati 2001: 30).

3.11. *Intermediate discussion*

In summary, despite being some sort of unfinished version of a fully developed adult, infants are well adapted to their specific ecological niche. As suggested in the discussion above, development is a process during which the maturation of the neural system is tied to a concurrent and gradual lifting of the initial limitations on sensory and motor systems. The state of immaturity that at first sight appears to be an inadequacy in fact plays an integral role during ontogeny, and results in increased flexibility, and faster acquisition of skills and subskills. Innate abilities, such as prospective control or pre-wired motor patterns (Thelen 1981), can also speed up skill acquisition by providing a 'good' background for the learning of novel skills. The difficulty of learning particular tasks can be further reduced by shaping development via appropriate social exchanges and scaffolding by adults.

The various aspects of development exposed in this section are obviously highly interdependent and cannot be considered in isolation. Spatiotemporally co-ordinated movement patterns (section 3.4), for instance, arise spontaneously and in a self-organized fashion from the interaction among brain, body and environment, and are—at least in part—the result of an entrainment between these three components (sections 3.6 and 3.3). In general, autonomous and self-organized formation of spatiotemporal patterns is a distinguishing trait of 'open nonequilibrium systems', that is, of systems in which 'energy' flows: (a) from one region of the system to another (the system is not at equilibrium); and (b) in and out of the system (the system is open) (e.g. Haken 1983, Kelso 1995).

Category learning (section 3.8) represents another example of the interdependency between the proposed developmental aspects because it lends itself well to an interpretation as a dynamic process during which, through interaction with the local environment, patterns of behaviour useful for category formation self-organize (section 3.3). Moreover, in analogy with the development of patterns of motor co-ordination in motor learning (section 3.4), it is possible to conceptualize the emergence of perceptual categories as a modification of degrees of freedom: mechanical degrees of freedom (i.e. number of joints and muscles) in the case of motor learning and sensorimotor or perceptual degrees of freedom (i.e. categories) in the case of category formation. The self-organization of categories is directed by neural and bodily constraints (section 3.2) as well as by value systems (section 3.9), which not only introduce the necessary biases for learning to take place, but also modulate it, by evaluating the consequences of particular actions. Hence, they constitute the engine of exploration and represent a *conditio sine qua non* for category learning, for social interactions (section 3.10) and for directing self-exploratory processes (section 3.5).

Self-exploration and self-learning, in turn, are strongly dependent on spontaneous movement activity (section 3.6). This sort of activity, albeit not oriented toward any functional goal (such as reaching for an object, or turning the head in a particular direction), leads to the generation of sensory information across different sensory modalities correlated in time, which gives infants the possibility of learning to sense and predict the consequences of their own actions through self-exploration. For example, take an

infant spontaneously waving her hand in front of her eyes and touching her face. Over time, this sort of activity generates associations of the sensory information that originates from outside the body (called exteroception, e.g. vision, audition or touch) with the one coming from inside the body (or proprioception, e.g. vestibular apparatus or muscle spindles), and a sense of bodily self can emerge (Rochat and Striano 2000).

As can be seen from these few examples, every aspect of development is affected simultaneously by other ones. This coupling makes their investigation challenging, and modelling a difficult enterprise. We contend that embodied models and robotic systems represent appropriate scientific tools to tackle the interaction and integration of the various aspects of development. The construction of a physical system forces us to consider: (a) the interaction of the proposed model with the real world; and (b) the interaction and the integration of the various subcomponents of the model with each other. This way of thinking has spurred, since its inception, a growing number of research endeavours.

4. Research landscape

In this section, we present a survey of a variety of research projects that deal with or are inspired by developmental issues. Table 2 gives a representative sample of investigations and is not intended as a fully comprehensive account of research related to developmental robotics. For the inclusion of a study in table 2, we adopted the following two criteria:

- The study had to provide clear evidence for robotic experiments. That is, we did not include computer-based models of real systems, avatars, or other simulators. This choice is not aimed at discrediting simulations, which indeed are very valuable tools of research. In fact, we acknowledge that physical instantiation is not always an absolute requirement, and that simulations have distinct advantages over real-world experiments, such as the possibility for extensive and systematic experimentation (Ziemke 2003, Sporns 2004). If the goal, however, is to model and understand development and how it is influenced by interaction with the environment, then robots may represent the only viable solution. Whereas a simulation can impossibly capture all the complexities and oddities of the physical world (Brooks 1991, Steels 1994, Pfeifer and Scheier 1999), robots—by being ‘naturally’ situated in the real world—are the only way to guarantee a continuous and real-time coupling of body, control and environment.
- The study had to show a clear intent to address hypotheses put forward in either developmental psychology or developmental neuroscience. The use of connectionist models, reinforcement or incremental learning applied to robot control alone—without any link to developmental theories, for instance—did not fulfil this requirement.

Despite the admittedly rather restrictive nature of these two requirements, we were able to identify a significant number of research papers satisfying them. In order to introduce some structure in this rather heterogeneous collection of papers, we organized the selected articles of table 2 according to four primary areas of interest (see table 3):

- (1) *Socially oriented interaction*: this category includes robotic systems in which social interaction plays a key role. These robots either learn particular skills via interaction with humans or with other robots, or learn to communicate with other robots or humans. Examples are: language acquisition, imitation and social regulation.

Table 2. Explicitly invoked developmental facet(s).

Developmental facets	Link to development, representative publication	References
Value systems, neural plasticity	Postnatal cortical plasticity (Kato <i>et al.</i> 1991)	Almassy <i>et al.</i> (1998)
Social interaction, importance of constraints	Early imitation (Nadel and Butterworth 1999)	Andry <i>et al.</i> (2002)
Sensorimotor co-ordination	Reflexive behaviour (Piaget 1953)	Berthouze <i>et al.</i> (1997)
Self-exploration, sensorimotor categorization	Reflexive behaviour (Piaget 1953)	Berthouze <i>et al.</i> (1998)
Self-exploration	Self-exploration	Berthouze <i>et al.</i> (1998)
Social interaction	Infant-caregiver interactions (Bullock 1979)	Breazeal and Scassellati (2000)
Social interaction	Prosodic pitch contours (Fernald 1985)	Breazeal and Aryananda (2002)
Prospective control, sensorimotor co-ordination	Visuo-haptic exploration, control of reaching (Berthier <i>et al.</i> 1996)	Coehlo <i>et al.</i> (2001)
Social interaction	Proto-language development (Vygotsky 1962)	Dautenhahn and Billard (1999)
Social interaction, early abilities	Active intermodal matching (Meltzoff and Moore 1997)	Demiris (1999)
Neural plasticity	Neurotrophic factors (Purves 1994)	Elliott and Shadbolt (2001)
Social interaction	Joint attention (Butterworth and Jarrett 1991)	Kozima and Yano (2001)
Categorization, neural plasticity	Homeostatic plasticity mechanism (Turrigiano and Nelson 2000)	Krichmar and Edelman (2002)
Social interaction, self-exploration	Early imitation, body babbling (Meltzoff and Moore 1997)	Kuniyoshi <i>et al.</i> (2003)
Degrees of freedom, value systems	Freezing/unfreezing of degrees of freedom (Bernstein 1967)	Lungarella and Berthouze (2002c)
Self-organization, self-exploration	Bouncing, entrainment (Goldfield <i>et al.</i> 1993)	Lungarella and Berthouze (2003)
Stage-like process, value	Infant reaching behaviour (Diamond 1990)	Marjanovic <i>et al.</i> (1996)
Stage-like process, value	Infant reaching behaviour (Konczak <i>et al.</i> 1995)	Metta <i>et al.</i> (1999)
Social interaction	Mirror systems (Gallese <i>et al.</i> 1996)	Metta and Fitzpatrick (2003)

(Continued)

Table 2. Continued.

Developmental facets	Link to development, representative publication	References
Social interaction, importance of constraints	Joint visual attention	Nagai <i>et al.</i> (2002)
Sensory-motor co-ordination, self-organization	Category learning (Thelen and Smith 1994)	Pfeifer and Scheier (1997)
Social interaction, stage-like process	Model of joint attention (Baron-Cohen 1995)	Scassellati (1998)
Categorization, sensorimotor co-ordination	Explorative behaviours (Rochat 1989)	Scheier and Lambrinos (1996)
Categorization, value systems, neural plasticity	Perceptual categorization (Edelman 1987)	Sporns <i>et al.</i> (2000)
Value systems, neural plasticity	Neuromodulatory system (Schultz 1998)	Sporns and Alexander (2002)
Social interaction	Eye–arm co-ordination	Stoica (2001)
Social interaction, early abilities	Proto-linguistic functions (Halliday 1975)	Varshavskaya (2002)
Value system	NA	Weng <i>et al.</i> (2000)
Social interaction, self-organization	Contingent maternal vocalization (Pelaez-Nogueras <i>et al.</i> 1996)	Yoshikawa <i>et al.</i> (2004)

NA, not available.

- (2) *Non-social interaction*: this category comprises studies that are characterized by a direct and strong coupling between sensory and motor processes, and the surrounding local environment, which do not involve any interaction with other robots or humans. Examples are: learning to grasp, visually-guided manipulation, perceptual categorization and navigation.
- (3) *Agent-related sensorimotor control*: this category organizes studies that investigate the exploration of bodily capabilities, changes of morphology (e.g. perceptual acuity, or strength of the effectors) and their effects on motor skill acquisition, and self-supervised learning schemes not specifically linked to a functional goal. Examples are: self-exploration, categorization of motor patterns, learning to swing or bounce.
- (4) *Mechanisms and processes*: this category contains investigations that address mechanisms or processes thought to increase the adaptivity of a behaving system. Examples are: developmental plasticity, value systems, neurotrophic factors, Hebbian learning, freezing and unfreezing of mechanical degrees of freedom, increase or decrease of sensory resolution and motor accuracy, and so on.

The borders of the proposed categories may not be as clearly defined as this classification suggests, and instances may exist that fall in two or more of those categories; or even worse, these categories may appear arbitrary and *ad hoc*. We believe, however, that a

Table 3. Representative examples of developmentally-inspired robotics research.

Subject area	Goal/focus	Robot	References
Socially oriented interaction	Early imitation	MR + AG	Andry <i>et al.</i> (2002)
	Social regulation	AVH	Breazeal and Scassellati (2000)
	Regulation of affective communication	AVH	Breazeal and Aryananda (2002)
	Proto-language development	MR	Dautenhahn and Billard (1999)
	Early imitation	AVH	Demiris (1999)
	Joint visual attention	UTH	Kozima <i>et al.</i> (2002)
	Joint visual attention	UTH + MR	Nagai <i>et al.</i> (2002)
	Joint visual attention	UTH	Scassellati (1998)
	Eye–arm co-ordination, imitation	RA	Stoica (2001)
Non-social sensorimotor interaction	Early language development	AVH	Varshavskaya (2002)
	Vocal imitation	RS	Yoshikawa <i>et al.</i> (2004)
	Saccading, gaze fixation	AVH	Berthouze and Kuniyoshi (1998)
	Visuo-haptic exploration	HGS	Coelho <i>et al.</i> (2001)
	Visually-guided pointing	UTH	Marjanovic <i>et al.</i> (1996)
	Visually-guided reaching	UTH	Metta <i>et al.</i> (1999)
	Visually-guided manipulation	UTH	Metta and Fitzpatrick (2003)
Agent-related sensorimotor control	Indoor navigation	MR + AG	Weng <i>et al.</i> (2000)
	Self-exploration, early abilities, categorization	AVH	Berthouze <i>et al.</i> (1998)
	Self-exploration, early imitation	UTH + MR	Kuniyoshi <i>et al.</i> (2003)
	Pendulation, morphological changes	HD	Lungarella and Berthouze (2002c)
Mechanisms	Bouncing, entrainment	HD	Lungarella and Berthouze (2003)
	Behavioural interaction, neural plasticity	MR + AG	Almasy <i>et al.</i> (1998)
	Sensorimotor categorization, self-organization	AVH	Berthouze and Kuniyoshi (1998)
	Sensory deprivation, neural plasticity	MR	Elliott and Shabolt (2001)

(Continued)

Table 3. Continued.

Subject area	Goal/focus	Robot	References
	Invariant object recognition, conditioning	MR + AG	Krichmar and Edelman (2002)
	Categorization, value	MR + AG	Pfeifer and Edelman (1997)
	Categorization, cross-modal associations, exploration	MR + AG	Scheier and Lambrinos (1996)
	Categorization, conditioning, value	MR + AG	Sporns <i>et al.</i> (2000)
	Neuromodulation, value	MR + AG	Sporns and Alexander (2002)

AVH, active vision head; UTH, upper-torso humanoid; MR, mobile robot; HD, humanoid; HGS, humanoid grasping system; UTH + MR, upper-torso humanoid on mobile platform; MR + AG, mobile robot equipped with arm and gripper; RS, robotic system.

grouping into four primary interest areas is meaningful for the following reasons. First, the individual categories refer to different contextual situations, that is, while interactions in a social context typically involve one or more persons or robots, interactions that are not socially-oriented and agent-related control do not. Second, movements performed during a social-related interaction have a communicative purpose, e.g. language, or gestures. Non-social sensorimotor interactions as well as agent-related control, however, do not bear any communicative value (unless an object is used as a means of communication). As stated previously, evidence from developmental psychology suggests that interaction with peers and interaction with objects bear completely different valences. Third, unlike non-social sensorimotor interactions whose primary purpose is the active exploration or manipulation of the surrounding environment, agent-related sensorimotor control is mainly concerned with the exploration of the agent's own bodily capabilities. Examples from studies into human development (mainly concerned with motor development) are: rhythmical stereotypes (Thelen 1981), general movements (Prechtl 1997), crawling (Adolph *et al.* 1998), and postural control (Hadders-Algra *et al.* 1996, Bertenthal and Von Hofsten 1998).

Finally, we note that the last category (mechanisms) groups mechanisms and processes that are valid for whatever content domain—be it socially- or not socially-oriented interaction, or agent-related sensorimotor control. Most of the studies surveyed in this paper employed a number of mechanisms and processes either explicitly or implicitly. Hebbian learning and neurotrophic factors, for instance, are general mechanisms of plasticity. Similarly, value systems can modulate different types of learning, and guide the self-organization of early movements. We believe that these mechanisms might form a good basis on which to build a general theory of developmental robotics.

4.1. *Socially-oriented interaction*

Studies in social interaction and acquisition of social behaviours in robotic systems have examined a wide range of learning situations and techniques. Prominent research areas include shared (or joint) attention, low-level imitation (that is, reproduction of simple

and basic movements), language development and social regulation (for an overview and a taxonomy of socially interactive robots, see Fong *et al.* (2003)). Adopting a developmental stance within this context may indeed be a good idea.

Brian Scassellati (1998), for instance, advocated the application of a developmental methodology as a means of providing a structured decomposition of complex tasks, which ultimately could facilitate (social) learning. Scassellati (2001) described the early stages of the implementation in a robot of a hybrid model of shared attention, which in turn was based on a model of the development of a ‘theory of mind’⁷ proposed by Baron-Cohen (1995). Despite the simplicity of the robot’s behavioural responses and the need for more complex social learning mechanisms, this study represents a first step toward the construction of an artificial system capable of exploiting social cues to learn to interact with other robots or humans. Another model of joint attention was implemented by Nagai *et al.* (2002). The model involved the development of the sensing capabilities of a robot from an immature to a mature state (achieved by means of a gradual increase of the sharpness of a Gaussian spatial filter responsible for preprocessing the visual input), and a change of the caregiver’s task evaluation criteria, through a decrease of the task error leading to a positive reward for the robot. Along a similar line of research, Kozima and Yano (2001) studied a ‘rudimentary’ or early type of joint visual attention displayed by infants. In this case, the robot was able to roughly identify the attentional target in the direction of the caregivers’s head only when it could simultaneously see both the caregiver and the target.

Joint attention is but one factor on which social interaction relies. An architecture of mutually regulatory human–robot interaction striving at integrating various factors involved in social exchanges was described by Breazeal and Scassellati (2000). The aim of the suggested framework was to include perception, attention, motivations and expressive displays, so as to create an appropriate learning context for a social infant-like robot capable of regulating on its own the intensity of the interaction. Although the implementation did not parallel infant development exactly, the authors claimed that the design of the system was heavily inspired by the role motivations and facial expressions play in maintaining an appropriate level of stimulation during social interaction of infants with adults (Breazeal and Scassellati 2000). Human–robot interaction was also the focus in Dautenhahn and Billard (1999), where the authors described an example of emergence of global interaction patterns through exploitation of movement dynamics. The experiments performed were based on an influential theory of cognitive development advocated by Vygotsky (1962), which proposes that social interactions are essential for the development of individual intelligence. For a recent review of Vygotsky’s theory of cognitive development and its relation to socially-situated artificial intelligence, see Lindblom and Ziemke (2003).

Socially-situated learning can also be guided by robot-directed speech. In such a case, the robot’s affective state—and as a consequence its behaviour—could be influenced by verbal communication with a human caregiver. It is perhaps less obvious, but equally important, to note that there is no need to associate a meaning to what is said. Breazeal and Aryananda (2002), for instance, explored recognition of affective communicative intent through the sole extraction of particular acoustic cues typical of infant-directed speech (Fernald 1985). This represents an instance of non-verbal interaction in which emotional expressions and gestures used by human caretakers shape how and what preverbal infants learn during social exchanges. Varshavskaya (2002) applied a behaviour-based approach to the problem of early concept and vocal label acquisition in a sociable anthropomorphic robot. The goal of the system was to generate the kind of vocal output that a pre-linguistic, 10–12 month-old infant may produce; namely, emotive

grunts, canonical babblings, which include the syllables required for meaningful speech, and a formulaic proto-language (some sort of preverbal and pregrammatical form of the future language). In the author's own words, most inspirational for the design of the proto-language acquisition system was the seminal work by Halliday (1975). Dautenhahn and Billard (1999) also investigated the synthesis of a robotic proto-language through interaction of a robot with either a human or a robotic teacher. They were able to show how language can be grounded via a simple movement imitation strategy. 'More preverbal' was work done by Yoshikawa *et al.* (2004), who constructed a system—consisting of a microphone, a simplified mechanical model of the human vocal tract and a neural network—that had to learn to articulate vowels. Inspired by evidence that shows how maternal vocal imitation leads to the highest rates of infant vocalization (Pelaez-Nogueras *et al.* 1996), the artificial system was trained by having the human teacher imitate the robotic system.

Recently, developmentally inspired approaches to robot imitation have received considerable attention (Demiris, 1999, Andry *et al.* 2002, Dautenhahn and Nehaniv 2002, Kuniyoshi *et al.* 2003). Typically, in robot imitation studies the robot imitates the human teacher or another robot. This relationship was turned upside down by Stoica (2001), who showed that imitation of the movements of a robotic arm by a human teacher could naturally lead to eye–arm co-ordination as well as to an adequate control of the arm—see also Yoshikawa *et al.*'s (2004) work on speech generation. Many authors have suggested a relatively straightforward two-stage procedure. First, the artificial system learns to associate proprioceptive or other motor-related sensory information to visual sensory information and then, while imitating, it exploits the acquired associations by querying for the motor commands that correspond to the previously perceived sensory information. An example of a different approach was reported by Demiris and Hayes (2002), who developed a computational architecture of early imitation used for the control of an active vision head, which was based on the active inter-modal matching hypothesis⁸ for early infant imitation proposed by Meltzoff and Moore (1997). The author also gives an overview of previous work in the field of robotic imitation (for similar surveys, see Schaal 1999, Breazeal and Scassellati 2002).

Learning by imitation offers many benefits (Demiris 1999, Schaal 1999, Demiris and Hayes 2002). A human demonstrator, for instance, can teach a robot to perform certain types of movements by simply performing them in front of the robot. This strategy drastically reduces the amount of trial-and-error for the task that the robot is trying to accomplish and consequently speeds up learning (Schaal 1999). Furthermore, it is possible to teach new tasks to robots by interacting naturally with them. This possibility is appealing because it might lead to open-ended learning not constrained by any particular task or environment.

All studies reviewed thus far presuppose in one way or another a set of basic sensorimotor skills (such as gazing, pointing or reaching) deemed important for social exchanges of any kind. Stated differently, for embodied systems to behave and interact—socially and non-socially—in the real world, an appropriate co-ordination of perception and action is necessary. It is becoming commonly accepted that action and perception are tightly intertwined, and that the refinement of this coupling is the outcome of a gradual developmental process (e.g. Thelen and Smith 1994). The following subsection will review studies that attempt to deepen our understanding of the link between perception and action in a non-social context.

4.2. *Non-social interaction*

Sensing and acting are tied to each other. Accurate motor control would not be possible without perception and, vice versa, purposive vision would not be feasible without

adequate control of actions. In the last decade or so, neurophysiologists have been discovering a number of multi-sensory and sensorimotor areas. Building models of the processing performed by those areas might be a challenging research endeavour but, more importantly, it should cast definitive doubts on the way the problem of perception has traditionally been understood by the artificial intelligence community, that is, as a process of mapping sensory stimulation on to internal symbolic representations (particularly as young children presumably do not have well-developed ‘symbols’⁹). We have already given some hints that this has changed. More work is certainly required in order to get a better grasp of the mechanisms of perception and how they are linked to action.

The co-ordination of action and perception is of particular importance for category learning. Traditionally, the problem of categorization has been investigated by employing disembodied categorization models. A growing body of evidence supports, however, a more interactive, dynamic and embodied view of how categories are formed (Lakoff and Johnson 1999, Pfeifer and Scheier 1999, Nolfi and Floreano 2000). In essence, as suggested by Dewey (1896) more than a century ago, categorization can be conceptualized as a process of sensorimotor co-ordinated bodily interaction with the real world. Embodied models of categorization are not passively exposed to sensory data, but through movements and interaction with the environment they are able to generate ‘good’ sensory data, for example by inducing time-locked spatiotemporal correlations within one sensory modality or across various sensory modalities (Pfeifer and Scheier 1997, Lungarella and Pfeifer 2001, Te Boekhorst *et al.* 2003).

Categorization of objects via real-time correlation of temporally contingent information impinging on the haptic and the visual sensors of a mobile robot was achieved by Scheier and Lambrinos (1996), for instance. The suggested control architecture employed sensorimotor co-ordination at various functional levels—for saccading on interesting regions in the environment, for attentional sensorimotor loops and for category learning. Sensorimotor activity was also critical in work performed by Krichmar and Edelman (2002), who studied the role played by sensory experience for the development of perceptual categories. In particular, the authors showed that the overall frequency and temporal order of the perceptual stimuli encountered had a definite influence on the number of neural units devoted to a specific object class. This result is confirmed by research on experience-dependent neural plasticity (see Stiles 2000, for a recent view).

A few other examples of the application of a developmental approach to the acquisition of visuo-motor co-ordinations exist. Marjanovic *et al.* (1996), for instance, were able to show how acquired oculomotor control (saccadic movements) could be reused for learning to reach or point toward a visually identified target. A similar model of developmental control of reaching was investigated by Metta *et al.* (1999). The authors concluded that early motor synergies might speed up learning and considerably simplify the problem of the exploration of the workspace (see also Pfeifer and Scheier 1997). They also pointed out that control and learning should proceed concurrently rather than separately—as is the case in more traditional engineering approaches. These studies complement those on the development of joint attention, discussed in the previous section. Berthouze and colleagues employed the tracking of a pendulum to teach an active vision head simple visual skills such as gaze control and saccading eye movements (Berthouze *et al.* 1997, Berthouze and Kuniyoshi 1998). Remarkably, the robot even discovered its ‘own vestibulo-ocular reflex’. The approach capitalized on the exploitation of the robot–environment interaction for the emergence of co-ordinated behaviour. Non-social, object-related sensorimotor interaction was also central in the study performed by Metta and Fitzpatrick (2003). Starting from a reduced set of hypotheses, their humanoid

system learned—by actively poking and prodding objects (e.g. a toy car or a bottle)—to associate particular actions with particular object behaviours (e.g. a toy car rolls along if pushed appropriately, while a bottle tends to roll sideways). Their results were in accordance with the theory of affordances by Gibson (1977).

A different research direction was taken by Coehlo *et al.* (2001). They proposed a system architecture that employed haptic categories and the integration of tactile and visual information in order to learn to predict the best type of grasp for an observed object. Relevant in this case is the autonomous development of complex visual features starting from simple behavioural primitives.

Weng *et al.* (2000) reported on a developmental algorithm tested on a robot, which had to learn to navigate on its own in an unknown indoor environment. The robot was trained interactively, that is, online and in real time, via direct touch of one of the 28 touch sensors located on the robot's body. By receiving some help and guidance from a human teacher, the algorithm was able automatically to develop touch-guided motor behaviours and, according to the authors, some kind of low-level vision.

4.3. *Agent-related control*

As discussed in section 3.5, self-exploration plays a salient role in infancy. The emergence and tuning of sensorimotor control are hypothesized to be the result of the exploration of the perceptual consequences of infants' self-produced actions (Rochat and Striano 2000). Similarly, an agent may attain sensorimotor control of its bodily capabilities by autonomous exploration of its sensorimotor space. A few instances of acquisition of agent-related control in robots exist.

Inspired by findings from developmental psychology, Berthouze *et al.* (1998) realized a system that employed a set of basic visuo-motor (explorative) behaviours to generate sensorimotor patterns, which were subsequently categorized by a neural architecture capable of temporal information processing. Following a similar line of research, Kuniyoshi *et al.* (2003) developed a visuo-motor learning system whose goal was the acquisition of neonatal imitation capabilities through a self-exploratory process of 'body babbling' (Meltzoff and Moore 1997). As in Berthouze *et al.* (1998), the proposed neural architecture was also capable of temporal information processing. An agent-related (not object-related) type of categorization was also reported by Berthouze and Kuniyoshi (1998). The authors used self-organizing Kohonen maps to perform an unsupervised categorization of sensorimotor patterns, which emerged from embodied interaction of an active vision system with its environment. The self-organization process led to four sensorimotor categories consisting of horizontal, vertical and 'in-depth' motions, and an unclearly defined, intermediate category.

Morphological changes (e.g. body growth, changes of visual acuity and visual resolution) represent one of the most salient characteristics of an ongoing developmental process. Lungarella and Berthouze (2002a) investigated the role played by such changes for the acquisition of motor skills by using a small humanoid robot that had to learn to pendulate, i.e. to swing like a pendulum. The authors attempted to understand whether physical limitations and constraints inherent to body development could be beneficial for the exploration and selection of stable sensorimotor configurations (see also Turkewitz and Kenny 1982, Bjorklund and Green 1992). In order to validate the hypothesis, Lungarella and Berthouze (2002a, b) performed a comparative analysis between the use of all bodily degrees of freedom from the very start and the progressive involvement of all degrees of freedom by employing a mechanism of developmental freezing and unfreezing of degrees of freedom (Bernstein 1967). In a follow-up case study (Lungarella and Berthouze 2002c), the same authors investigated the hypothesis that inherent adaptivity

of morphological changes leads to behavioural characteristics not obtainable by mere value-based regulation of neural parameters. The authors were able to provide evidence for the claim that, in learning a motor task, a reduction of the number of available bio-mechanical degrees of freedom helps to stabilize the interplay between environmental and neural dynamics (the way patterns of activity in the neural system change with time). They showed that the use of all available degrees of freedom from the start reduced the likelihood of the occurrence of physical entrainment, i.e. mutual regulation of body and environmental dynamics. In turn, lack of entrainment led to a reduced robustness of the system against environmental perturbations. Conversely, by initially freezing some of the available degrees of freedom, physical entrainment and thus robust oscillatory behaviour could occur.

Another instance of agent-related sensorimotor control was reported by Lungarella and Berthouze (2003). Inspired by a study of how infants strapped in a *Jolly Jumper* learn to bounce (Goldfield *et al.* 1993), the authors performed a series of experiments with a bouncing humanoid robot (see figure 1), aimed at understanding the mechanisms and computational principles that underly the emergence of movement patterns via

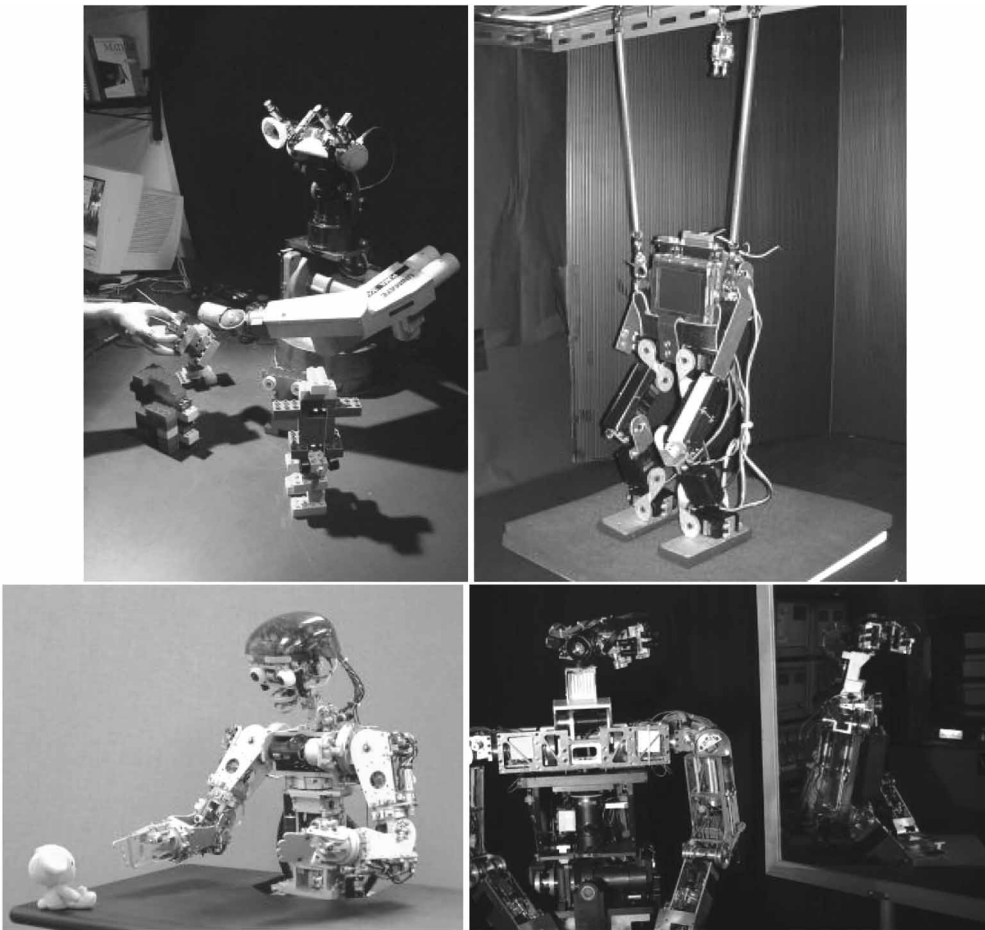


Figure 1. Examples of robots used in developmental robotics. From left to right, top to bottom: BabyBot (LiraLab), BabyBouncer (AIST), Infanoid (CRL), COG (MIT).

self-exploration of the sensorimotor space (such as entrainment). The study showed that a suitable choice of the coupling constant between limb segments, as well as of the gain of the sensory feedback, induced a reduction of the movement variability and an increase in bouncing amplitude, and led to movement stability. The authors attributed the result to the entrainment of body and environmental dynamics. Taga (1995) reported a similar finding in the case of biped walking.

4.4. *Mechanisms and processes*

A few mechanisms, such as freezing and unfreezing of degrees of freedom, or physical entrainment, have already been discussed in the previous section. Other developmentally relevant mechanisms exist. Some of them are related to changes in morphological parameters, such as sensor resolution and motor accuracy, some of them affect neural parameters, such as the number of neurons constituting the neural system. Dominguez and Jacobs (2003) and Nagai *et al.* (2002), for instance, describe systems that start with an impoverished visual input whose quality gradually improves as development (or learning) progresses. In this section, we discuss two additional mechanisms.

4.4.1. *Value system.* Learning is modulated by value systems. A learning technique in which the output of the value system modulates learning itself is called value-based or value-dependent learning. Unlike reinforcement learning techniques (which provide an interesting set of computational principles), value-based learning schemes typically specify the neural mechanisms by which stimuli can modulate learning and by which organisms sense the consequences of their actions (Sporns 2003, 2004, see also Pfeifer and Scheier 1999: chapter 14). Another difference between the two learning paradigms is that typically—in reinforcement learning—learning is regulated by a (reinforcement) signal given by the environment, whereas in value-based learning, the (value) signal is provided by the agent itself (self-teaching). A number of value systems have been realized in robotic systems. In those implementations the value system either plays the role of an internal mediator of salient environmental stimuli and events (Scheier and Lambrinos 1996, Almassy *et al.* 1998, Sporns *et al.* 2000, Krichmar and Edelman 2002, Sporns and Alexander 2002), or is used to guide some sort of exploratory process (Lungarella and Berthouze 2002c, Steels 2003).

Almassy *et al.* (1998) constructed a simulated neural model embedded in an autonomous real-world device, one of whose four components was a ‘diffuse and ascending’ value system. The value signals were used to modify the strength of the connections from the neurons of the visual area to the ones of the motor area. One of the results of these value-dependent modifications was that, without any supervision, appropriate behavioural actions could be linked to particular responses of the visual system. A similar model system was described by Krichmar and Edelman (2002). Compared with previous work, the modelled value signal had two additional features: a prolonged effect on synaptic plasticity; and the presence of time delays (Krichmar and Edelman 2002: 829). Another instantiation of a value system is described by Scheier and Lambrinos (1996) and Pfeifer and Scheier (1997). In this case, the output of the value system was used to modulate Hebbian learning—yet another crucial mechanism. Essentially, the robot was allowed to learn only while it was exploring objects. Sporns and Alexander (2002) tested a computational model of a neuromodulatory system¹⁰—structurally and functionally similar to the mammalian dopamine and noradrenaline system—in an autonomous robot. The model comprised two neuromodulatory components mediating the effect of rewards and of aversive stimuli. According to the authors, value signals played a dual role in synaptic plasticity, in that they not only had to modulate the strength of the

connection between sensory and motor units, but they were also responsible for the change of the response properties of the value system itself.

In contrast to the previous cases, where the value system was used to modulate learning, in Lungarella and Berthouze (2002c) the value system was employed to guide the exploration of the parameter space associated with the neural system of a robot that had to learn to pendulate.

4.4.2. *Developmental plasticity.* Plasticity is an important ontogenetic mechanism that contributes to the adaptivity of brain, body and behaviour in response to internal and external variations. The developing brain, for instance, is continuously changing (in terms of number of neurons, number of interconnections, wiring patterns, synaptic plasticity, and so on) and these changes are in part experience-dependent. Such neural plasticity gives our neural circuitry the potential to acquire (given appropriate training) nearly any function (O’Leary *et al.* 1994). A similar characteristic holds for plasticity of body and behaviour.

The study of a neural model incorporating mechanisms of neural plasticity was conducted by Almassy *et al.* (1998) (for more examples, see Sporns 2004). In particular, the authors analyzed how environmental interactions of a simulated neural model embedded in a robot may influence the initial formation, the development and the dynamic adjustment of complex neural responses during sensory experience. They observed that the robot’s self-generated movements were crucial for the emergence and development of selective and translation-invariant visual cortical responses because they induce correlations in various sensory modalities. Another result was the development of a foveal preference, that is, the system showed ‘stronger visual responses to objects, presented closer to the visual fovea’ (Almassy *et al.* 1998: 358).

A further example of synthetic neural modelling is illustrated in Elliott and Shadbolt (2001). The authors studied the application of a neural model, featuring ‘anatomical, activity-dependent, developmental synaptic plasticity’ (Elliott and Shadbolt 2001: 167), to the growth of sensorimotor maps in a robot whose task was to avoid obstacles. They showed that the deprivation of one or two (infrared-light) receptors could be taken care of by a mechanism of developmental plasticity, which according to the authors would allow the nervous system to adapt to the body as well as to the external environment in which the body resides.

4.5. *Intermediate discussion*

We can make a number of observations. Almost 40% of the studies reviewed (11 out of 29) fell in the category labelled ‘social interaction’ (see table 3). Apparently, this category constitutes a primary direction of research in developmental robotics. This result is confirmed by the fact that, lately, a lot of attention has been directed toward designing socially interactive robots. In a recent and broad overview of the field, Fong *et al.* (2003) tried to understand the reasons behind the growing interest in socially interactive robotics. They concluded that ‘social interaction is desirable in the case robots mediate human–human (peer-to-peer) interactions (robot as persuasive machine) or in the case robots function as a representation of, or representative for, the human (robot as avatar¹¹)’. It is plausible to assume that in order to acquire more refined and advanced social competencies, e.g. deferred imitation,¹² a robot should undergo a process of progressive development of its social skills analogue to the one of humans. Fong and his colleagues share the same opinion.

It is further interesting to note that many of the studies considered here examine to some extent the sensorimotor competence in interacting with the local environment—in particular, basic visuo-motor competencies such as saccading, gaze fixation, joint

attention, hand–eye co-ordination and visually-guided reaching. Brooks (2003) stressed the ‘crucial’ importance of basic social competencies (e.g. gaze direction or determination of gaze direction) for peer-to-peer interactions. Early motor competencies are a natural prerequisite for the development of basic social competencies. We were able, however, to single out only a few studies that have attempted to go beyond pointing, reaching, or gazing, i.e. early motor competencies. This issue is closely related to the notoriously hard problem of learning to co-ordinate the many degrees of freedom of a potentially redundant non-linear physical system and, indeed, imitation learning may represent a suitable route to its solution (Schaal 1999). Another way out of the impasse may be to exploit processes of self-exploration of the sensorimotor system and its intrinsic dynamics. The usage of self-exploration is explicitly advocated in four of the studies surveyed (Berthouze *et al.* 1998, Andry *et al.* 2002, Lungarella and Berthouze 2002c, Kuniyoshi *et al.* 2003), and presumably has been employed implicitly also in other ones.

From a developmental perspective, learning multi-joint co-ordinations or acquiring complex motor skills may benefit from the introduction of initial morphological (sensor, motor and neural) constraints, which over time are gradually released (Scassellati 2001, Lungarella and Berthouze 2002b, Nagai *et al.* 2002). In the same context, mechanisms of physical and neural entrainment, that is, mutual regulation between environment and the robot’s neural and body dynamics, as well as value-based self-exploration of body and neural parameters, deserve further investigation. A pioneering attempt to capitalize on the coupling between the body, neural and environmental dynamics was promoted by Taga (1991). In his model of biped walking, he showed how movements could emerge from a global entrainment¹³ among the activity of the musculo-skeletal system and the surrounding environment. The study was performed, however, only in simulation. Williamson (1998) used two real robot arms to investigate a similar issue. He claimed that his approach would allow one to achieve general oscillatory motion and more complex rhythmic tasks by exploitation of the coupled dynamics of an oscillator system and the arm dynamics (Williamson 1998: 1393). Two obvious shortcomings of his investigation were the absence of learning and of a developmental framework. Lungarella and Berthouze (2002c, 2003), building on previous research, attempted to capitalize on the interplay between neural plasticity, morphological changes and entrainment to the dynamics of body and task.

Autonomy, a thorny concept without a generally accepted definition (e.g. Pfeifer and Scheier 1999), is another research theme in need of further investigation. Loosely speaking, an autonomous system must be self-contained and independent from external control. Thus, in such a system the mechanisms and processes that mould local structure to yield global function must reside entirely within the system itself (Sporns 2003). Autonomy is no easy feat. An autonomous robot should also be endowed with an initial set of values and drives, i.e. motivations or needs to act and interact with the environment. The role of the value system and of the motivational system is to mediate learning, promote parameter exploration, drive action selection and regulate social interactions (Blumberg 1996, Breazeal and Scassellati 2000). Concerning the value system, an important issue will have to be addressed in future work, that is, how specific or general the system of values and motivations needs to be in order to bootstrap adaptive behaviour. In current implementation, values and motivations are relatively simple: light is better than no light, or seek face-like blobs while avoiding non-face-like blobs. In essence, the issue boils down to the choice of the initial set of values and drives. But how much has to be predefined, and how much should be acquired?

Finally, we note that while the spectrum of outstanding research issues as well as the complexity of the available robots have considerably increased over the past few years,

not many ‘developmentally inspired’ reconnaissance tours into unexplored research directions have been started yet. There is, for instance, only one single study on navigation that tried to employ developmental mechanisms (Weng *et al.* 2000), and there are no studies at all on robot locomotion!

5. Developmental robotics: existing theoretical frameworks

Early theorization of developmental robotics can be traced back to work on behaviour-based robotics, physical embodiment, situatedness and sensorimotor coupling with the environment (Brooks 1991, Brooks and Stein 1994, Rutkowska 1995). *En route* to understanding human intelligence by building robots, Sandini *et al.* (1997) were among the first to recognize the importance of taking into account development. They called their approach ‘developmental engineering’. As in traditional engineering, the approach is directed toward the definition of a theory for the construction of complex systems. The main objective is to show that the adoption of a framework of biological development can be successfully employed for constructing artificial systems. Metta (2000) pointed out that this methodology can be envisaged as some sort of new tool for exploring developmental cognitive sciences. Such a new tool could have a similar role to the one that system and control theory had for the analysis of human movements. The authors investigated some of the aspects of visuo-motor co-ordination in a humanoid robot called *Babybot* (see figure 1). Issues such as the autonomous acquisition of skills, the progressive increase of the task complexity (by increasing the visual resolution of the system) and the integration of various sensory modalities were also explored (Panerai *et al.* 2002, Natale *et al.* 2002). Recently, the same group also produced a manifesto of developmental robotics outlining various aspects relevant to the construction of complex autonomous systems (Metta *et al.* 2001). The article maintained that the ability of recognizing progressively longer chains of cause–effect relationships could be one possible way of characterizing learning in an ‘ecological context’, because in a natural setting no teacher can possibly provide a detailed learning signal and enough training data (e.g. in motor learning the correct activation of all muscles, proper torque values, and so on). For another recent manifesto of developmental robotics, see Elliott and Shadbolt (2003).

Around the same time as Sandini, Ferrell and Kemp (1996) as well as Brooks (1997) argued that development could lead to new insights into the issues of cognitive and behavioural scaling. In an article titled ‘Alternative essences of intelligence’, Brooks *et al.* (1998) explored four ‘intertwined key attributes’ of human-like intelligent systems, that is, development, embodiment, social interaction and multisensory integration. They made the following assumptions (implicitly negating three central beliefs of classical artificial intelligence): (a) human intelligence is not as general purpose as usually thought; (b) it does not require a monolithic control system (for the existence of which there is no evidence); and (c) intelligent behaviour does not require a centrally stored model of the real world. The authors, drawing inspiration from developmental neuroscience and psychology, performed a series of experiments in which their humanoid robot(s) had to learn some fundamental sensorimotor and social behaviours (see also section 4). The same group also tried to capitalize on the concept of bootstrapping of skills from previously acquired skills, i.e. the layering of new skills on top of existing ones. The gradual increase in complexity of task-environment, sensory input (through the simulation of maturational processes), as well as motor control, was also explored in tasks such as learning to saccade and to reach toward a visually identified target (Marjanovic *et al.* 1996). Scassellati (1998, 2001) proposed that a developmental approach in humans and in robots might provide a useful structured decomposition

when learning complex tasks—or in his own words, ‘building systems developmentally facilitates learning both by providing a structured decomposition of skills and by gradually increasing the complexity of the task to match the competency of the system’ (Scassellati 2001: 29).

Another example of the novel and developmentally inspired approach to robotics was given by Asada *et al.* (2001). The authors proposed a theory for the design and construction of humanoid systems called ‘cognitive developmental robotics’. One of the key aspects of cognitive developmental robotics is to avoid implementing the robot’s control structure ‘according to the designers’ understanding of the robot’s physics’, but to have the robot acquire its own ‘understanding through interaction with the environment’ (Asada *et al.* 2001: 185). This methodology departs from traditional control engineering, where the designer of the system imposes the structure of the controller. In cognitive developmental robotics in particular, and in developmental robotics in general, the robot has to get to grips with the structure of the environment and behaviour, rather than being endowed *a priori* with an externally designed structure. Cognitive developmental robotics also points at how to ‘prepare’ the robot’s environment to progressively teach the robot new and more complex tasks without overwhelming its artificial cognitive structure. This technique is called scaffolding, and parents or caretakers often employ it to support, shape and guide the development of infants (section 3.10).

A last example of existing theories in developmental robotics is ‘autonomous mental development’ (Weng *et al.* 2001). Autonomous mental development differs from the traditional engineering paradigm of designing and constructing robots in which the task is ‘understood by the engineer’ because the machine has to develop its own understanding of the task. According to this paradigm, robots should be designed to go through a long period of autonomous mental development, from ‘infancy to adulthood’. Autonomous mental development relegates the human to the role of teaching and supporting the robot through reinforcement signals. The requirements for a truly mental development include being non-task-specific, because the task is generally unknown at the design time. For the same reason, the artificial brain has to develop a representation of the task, which could not be possibly embedded in advance into the robot by the designer.

6. Discussion

One of the big outstanding research issues on the agenda of researchers of artificial intelligence and robotics is how to address the design of artificial systems with skills that go beyond ‘single-task’ sensorimotor learning. The very search for flexible, autonomous and open-ended multi-task learning systems is, in essence, a particular re-instantiation of the long-standing search for general-purpose (human-like) artificial intelligence. In this respect, developmental robotics does not differ from other approaches, and embraces a variation on the same theme. Yet—as some other scholars of the field—we speculate that the ‘rapprochement’ of robotics and developmental psychology may represent both a crucial element of a general constructive theory for building intelligent systems and a prolific route to gain new insights into the nature of intelligence.

The modern view on artificial intelligence notwithstanding (e.g Pfeifer and Scheier 1999), ‘hand designing’ autonomous intelligent systems remains an extremely difficult enterprise—so challenging that the artificial intelligence community is starting to resign itself to the fact that with the current models of intelligence it may even be impossible in principle. In fact, many to date believe that all proposed frameworks may have multiple shortcomings. It is probably false to assume, for instance, that by merely simulating enough of the right kind of brain, intelligence will ‘automagically’ emerge. In other words, enough quantitative change may not necessarily lead to a qualitative change

(e.g. De Garis *et al.* 1998). It is likely that some fundamental principles still remain to be understood. Brooks (1997, 2003), for instance, has hypothesized that our current scientific understanding of living things may be lacking some yet-to-be-discovered fundamental mathematical description—Brooks calls it provocatively the ‘juice’—that is preventing us from grasping what is going on in living systems. We believe that a developmental approach may provide a way to tackle gracefully the problem of finding Brooks’s juice. The mere observation that almost all biological systems—to different extents—mature and develop, bears the compelling message that development is the main reason why the adaptivity and flexibility of organic compounds transcend those of artificial systems. In this sense, the study of the mechanisms underlying postnatal development might provide the key to a deeper understanding of biological systems in general and of intelligent systems in particular. In other words, although it might be interesting from an engineering perspective, we have not yet succeeded in designing intelligent systems that are able to cope with the contingencies of the real world—the reason being that we do not yet understand many of the mechanisms underlying intelligent behaviour. Thus, we are basically trying to learn from nature that in millions of years of evolution has come up with ontogenetic development. In a possible next step, the designer commitments could be pushed even further back (evolutionarily speaking), by designing only the mechanisms of genetic regulatory networks and artificial evolution, and letting everything evolve (Nolfi and Floreano 2000).

But what can a developmental approach do? Can it help us construct intelligent machines? The rationale is that having a complex process (development) gradually unfold in a complex artificial system (e.g. humanoid robot) can inform our understanding of an even more complex biological system (e.g. human brain). Development is a historical process, in the course of which—through mutual coupling and through interaction with the environment—new and increasingly complex levels of organization appear and disappear. That is, adult skills do not spring up fully formed but emerge over time (see section 3.1). Thus, at least in principle, it should be possible to decompose the developmental progression into a sequence of increasingly complex activity patterns that facilitate learning from the point of view of the artificial system, and analysis and understanding on the side of the designer. Moreover, development provides constraints and behavioural predispositions that, combined with a general state of ‘bodily immaturity’, seem to be a source of flexibility and adaptivity (see sections 3.2 and 3.7). Newborn infants, for instance, despite being restricted in many ways, are tailored to the idiosyncrasies of their ecological niche—even to the point of displaying a rich set of adaptive biases toward social interaction. Another contribution to the adaptivity of the developing system comes from its morphological plasticity, i.e. changes over time of sensory resolution, motor accuracy, mass of muscles and limbs, and so on.

The message conveyed is one of the basic tenets of a developmental synthetic methodology: the designer should not try to engineer ‘intelligence’ into the artificial system (in general an extremely hard problem); instead, he or she should try to endow the system with an appropriate set of basic mechanisms for the system to develop, learn and behave in a way that appears intelligent to an external observer. As many others before us, we advocate the reliance on the principles of emergent functionality (Rutkowska 1994) and self-organization (see section 3.3), which are essential features of biological systems at any level of organization.

According to Rosen (1991), the formulation of a theory about the functioning of ‘something’ (e.g. living cells, artificial neural networks, and so forth) entails at least two problems. The first one, called the ‘physiology problem’, relates to the mechanisms that underlie the functioning of this ‘something’. The second one, the ‘construction

problem', addresses the identification of the basic building blocks of the system. This identification is extremely difficult because in general it is not obvious which of the many possible decompositions is the correct one for describing the system as a whole. Here, development comes to the rescue. During ontogenesis the different factors (the building blocks) are integrated into a functioning whole (the system). By studying how a system is actually assembled, we have automatically (by default) a suitable decomposition. The understanding acquired from comprehending development can be applied to both situations, that is, it can help us solve both the physiology as well as the construction problem. A real understanding of 'life itself' (borrowing from Rosen) might come only through the formulation of a constructive theory.

As is evident from the survey given above, two important aspects of living systems that developmental robotics has to date not addressed sufficiently are *morphology* and *materials*. In order to understand cognition, however, we cannot confine our investigations to the mere implementation of control architectures and the 'simulation' of morphological changes (see Pfeifer 2000). If robots are to be employed as 'synthetic tools' to model biological systems, we need also to consider physical growth, change of shape and body composition, as well as material properties of sensors and actuators.

In this respect, despite not being explicitly inspired by developmental issues, the field of modular reconfigurable robotics is of some relevance for developmental robotics (e.g. Rus and Chirikjian 2001). Murata *et al.* (2001), for instance, provided a taxonomy of reconfigurable, redundant and regenerative systems, and maintained that this kind of machine represents the ultimate form of reliable systems. Ideally, these systems should be able to produce any element in the system by themselves. To date, there are no working examples of such systems. It is interesting to note that the description given by Murata *et al.* bears some resemblance to the definition of 'autopoietic' systems given by Maturana and Varela (1992): 'An autopoietic system is organized as a network of processes of production (synthesis and destruction) of components such that these components (a) continuously regenerate and realize the network that produces them, and (b) constitute the system as a distinguishable unity in the domain in which they exist' (see also Beer 2003, Luisi 2003). An example of an autopoietic system is the cell, which is constituted of a membrane and of the machinery for protein synthesis. From the point of view of applications, the relevance of robots that have self-repair capabilities, or that can adapt their body shape to the task at hand, is evident; indeed, the robotics community has recently started to address these issues (Hara *et al.* 2003, Teuscher *et al.* 2003). From a theoretical point of view, however, it will be important to develop computational paradigms capable of describing and managing the complexity of a robot body that changes over time.

As far as material properties are concerned, current technology lacks many of the characteristics that biology has; that is, durable, efficient and powerful actuators (e.g. in terms of power–volume and weight–torque ratios), redundant and adaptive sensory systems (e.g. variable density of touch receptors), as well as mechanical compliance and elasticity. Thus, the search for novel materials for actuators and sensors will play a pivotal role. A few of these issues are being investigated for the current generation of humanoid robots (for a review, see Dario *et al.* 1997), and will become more compelling as the robots will start moving 'out of the research labs'. Take haptic perception (i.e. the ability to use touch to identify objects), for instance. Owing to the technological difficulties involved in the construction of artificial skin sensors, most researchers do without this ability, or de-emphasize its importance in relation to vision, audition, or proprioception. In many respects, however, haptic perception—even more than vision—is directed toward the coupling of perception and action. Moreover, the integration of haptic and

visual stimulation is absolutely essential for the development of cognition (e.g. visuo-haptic transfer, that is, the ability to co-ordinate information about the shape of objects from hand to eyes seems already to be present in newborns (Streri and Gentaz 2003)).

7. Future prospects and conclusion

A list of future research directions that are worth pursuing needs to include autonomous learning—where autonomous is intended in its strongest connotation, that is, as learning without a direct intervention from a human designer (of course, this does not exclude interaction with a human teacher). A key aspect of autonomous learning is the study of value systems that gate learning, and drive exploration of body dynamics and environment. We postulate that robots should acquire solutions to contingent problems through autonomous exploration and interaction with the real world: generating movements in various situations, while experiencing the consequences of those movements. Those solutions could be due to a process of self-assembly, and thus would be constrained by the robot's current intrinsic dynamics. Common (not necessarily object-related) repetitive actions displayed by human infants (poking, squishing, banging, bouncing, cruising) could give the developing artificial creature a large amount of multimodal correlated sensory information, which could be used to bootstrap cognitive processes, such as category formation, deferred imitation, or even a primitive sense of self. In a plausible (but oversimplified) 'developmental scenario', the human designer could endow the robot with simple biases, i.e. simple low-level 'valences' for movement, or for sound in the range of human voices. A critical issue will be to have the robot develop new higher-level valences so as to bias exploration and learning for longer periods of time that transcend the time frame of usual sensorimotor co-ordination tasks. Another possible route could be grounded in recent neurophysiological findings, which seem to suggest that cognition evolved on top of pre-existing layers of motor control. In this case, manipulation (a sensorimotor act) could play a fundamental role by allowing 'baby robots' (or infants) to acquire the concept of 'object' in the first place, and to evolve it into language (Rizzolatti and Arbib 1998). This aspect, although partially neglected so far, might prove to be an important next step *en route* to the construction of human-like robots.

In conclusion, the generation of robots populating the years to come will be characterized by many human-like features, not thought to be part of intelligence in the past but considered to be crucial aspects of human intelligence nowadays. The success of the infant field developmental robotics and of the research methodology it advocates will ultimately depend on whether truly autonomous 'baby robots' will be constructed. It will also depend on whether by instantiating models of cognition in developmental robots, predictions will be made that will find empirical validation.

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Notes

1. Ontogenetic development designates a process during which an organism develops from a single cell into its adult form.
2. Also known as the law of uphill analysis and downhill invention. This law suggests that the synthesis (construction) of something new is easier than the analysis of something that already exists. We contend, however, that the definition of a comprehensive set of quantitative design principles or— even better—of a theory of synthesis for behaving system is a much harder problem.
3. This point was also very strongly made by Dewey (1896) over 100 years ago.
4. The space of possible motor activations is very large: ‘consider the 600 or so muscles in the human body as being, for extreme simplicity, either contracted or relaxed. This leads to 2^{600} possible motor activation patterns, more than the number of atoms in the known universe’ (Wolpert *et al.* 2003).
5. Soft-assembly refers to a self-organizing ability of biological systems to recruit *freely* the components (such as neurons, groups of neurons and mechanical degrees of freedom) that are part of the system, yielding flexibility, variability and robustness against external perturbations (Thelen and Smith 1994, Goldfield 1995, Clark 1997).
6. General movements represent one of the most important type of spontaneous movements that have been identified. They last from a few seconds to a several minutes, are caused endogenously by the nervous system and in normal infants involve the whole body.
7. Theory of mind defines a set of socially-mediated skills relating the individual’s behaviour in a social context, e.g. detection of eye contact.
8. The hypothesis suggests that infants try to match visual information against appropriately transformed proprioceptive information.
9. Thanks to an anonymous reviewer for pointing this out.
10. Neuromodulatory systems are instantiations of value systems that find justification in neurobiology. Examples include the dopaminergic and the noradrenergic systems.
11. Remote-presence robots may indeed be one of the killer applications of robotics in the near future (Brooks 2003: 135).
12. Imitation that takes place a certain amount of time after the demonstration by the teacher.
13. Taga (1991: 148): ‘Since the entrainment has a global characteristic of being spontaneously established through interaction with the environment, we call it global entrainment’.

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