Reassessing Piaget's Theory of Sensorimotor Intelligence: A View from Cognitive Science*

Julie C. Rutkowska
Cognitive & Computing Sciences,
University of Sussex, Brighton, BN1 9QH, UK.

email: julier@cogs.susx.ac.uk

Abstract

This paper assesses the current status of Piaget's theory of sensorimotor intelligence in relation to three persistent issues about the abilities of human infants: the nature of initial mechanisms; the traditional view that re-presentational functioning is the outcome of infant development; and the place of general-purpose developmental processes. Varela's view of three successive paradigms for cognitive science — cognitivism, emergence and enaction — is introduced as a means for locating Piaget's ideas on action and epigenesis in relation to approaches of particular relevance to understanding infancy. The contribution of work that aims to understand how situated systems can be organized to function as autonomous agents exhibiting adaptive behaviour is considered through examples of computational work in behaviour-based robotics. This supports Piaget's stress on action, but challenges his assumptions about the outcome of infant development. Finally, the relevance to infancy, and to Piaget's theory, of Karmiloff-Smith's proposals for cognitive development through a process of representational redescription is considered.

1 Persistent issues

Whether endorsed or (more likely, nowadays) disputed, Piaget's (1953, 1955) theory of the role that sensorimotor intelligence plays in the development of the mind has been the most significant single influence on the way infancy researchers pose questions and interpret data. This chapter offers a contemporary evaluation of Piaget's ideas by locating infancy research within the broader context of theoretical advances in cognitive science. Two questions provide the background to this analysis: What is

*To appear in: J.G. Bremner (ed.) *Infant Development: Recent Advances.* Lawrence Erlbaum

the current status of sensorimotor functioning in explanations of ability? And what, then, might be its significance for our understanding of development? The picture that emerges has implications for the three main components of Piaget's perspective on infant development.

First is the issue of the infant's initial state. We need to characterize early mechanisms so that they are 'open to development' in an appropriate way (Piaget, 1953). How does Piaget's approach to action-based mechanisms fare, and his commitment to progressive coordination of sensory and motor schemes as the key to development? Currently influential interpretations of infancy data generally attribute something more by way of preadaptation to the infant. However, they lack consensus as to what this 'more' is — from ecological psychology's preattuned realist infant, directly perceiving environmental affordances, to the nativist cognitivist infant, operating *ab initio* with concepts and representations.

Next is Piaget's characterization of the outcome of development in terms of conceptual and representational mechanisms that support superior understanding of the world by overcoming (what he considers) the limitations of perception and action within it. Piaget makes very traditional assumptions about the nature of intentionality, identifying the infant's transformation from a biological subject to a conscious psychological one with evidence for conceptual-representational functioning, such as anticipatory 'cognizance' (Piaget, 1976, 1978) of a goal of action as evidenced by means-end coordinations towards the end of the first year. So deeply rooted are such traditional views that it is difficult to entertain alternatives to Piaget's core assumption that pragmatic knowledge is qualitatively different from, and inferior to, the kinds of conceptual and representational abilities that he believes develop through a radical reconstruction of sensorimotor mechanisms during the course of infancy. Nevertheless, it is important for our appreciation of Piaget's theory, and of infancy in general, to take account of other options, over and above alternatives that merely attribute precocious concepts and representations to ever younger infants.

Finally the general form of development remains an issue. Several related aspects of Piaget's constructivism are at stake. In view of current evidence for infant preadaptations, many find it increasingly hard to concur with Piaget's claim that our knowledge of the world is not in large measure predetermined. The apparent domain specificity of such preadaptations also seems to question the need for, or at least the power of, any general-purpose developmental process along the lines of Piaget's notorious equilibration. What, then, of his commitment to epigenesis, wherein the structure of knowledge is a mutual product of the environment and the subject's activity within it, prefigured in neither the world nor the centralized mind (Piaget, 1971)? If the subject's activities are a necessary component of coming to know the world, how might they affect the nature of that knowledge?

2 Three paradigms for cognition

A useful starting place from which to assess the current status of the sensorimotor is Varela's cartography of ideas in cognitive science, which aims to integrate European and American traditions of cognitive inquiry (Varela, 1988, 1993; cf. Varela, Rosch & Thompson, 1991). Cognitive science's attempt to understand intelligence is undergoing a number of significant changes, and Varela identifies three major paradigms, marking shifts that follow a historical progression as far as mainstream cognitive science, with its allegiance to computational explanation, is concerned. In Figure 1, these developments in cognitive science are schematized in terms of cumulative, concentric circles of activity, that are used to locate contributors' names that appear in this chapter and/or that are likely to be familiar to readers.

Figure 1: Contributors to three paradigms for cognition

For infancy purposes, it is important to note that it is the most recent cognitive interpretations of infant abilities that mesh closely with assumptions of the longest standing inner circle of 'cognitivism'. By way of contrast, Varela locates Piaget's seminal sensorimotor perspective at the forefront of the newly emerging outer circle of 'enaction'.

2.1 Traditional cognitivism

Approaches committed to the most traditional *cognitivism* are dominated by a 'between the ears', centralized and disembodied focus on the mind. They locate the abilities of intelligent systems primarily with internal representations, which model things in the world. In the computational discipline of artificial intelligence (hereafter AI), this worldview sees representations as internal symbol structures that make explicit information about objects, their properties and their location with regard to one another and to the subject (Newell & Simon, 1976). The more exhaustive and explicit the representation, the greater should the subject's knowledge be. Rule-governed manipulation of such structures (i.e. computation) underlies the reasoning processes that use them to formulate goals and plan behaviour.

Traditional AI systems built along these lines are notoriously brittle — a system may be good at a game like chess, but will be stopped in its tracks by encountering even another game environment. It seems virtually impossible to get into a single system all the knowledge and program rules for deploying it that seem necessary for flexible, adaptive behaviour (cf. Dreyfus, 1981). This kind of *domain specificity* of knowledge may be a drawback for AI implementations, but some cognitivist positions consider it is actually an important property of the mind's structure. For example, Chomsky's (1980) view of language as a human-specific, circumscribed 'mental organ' falls within the inner circle of traditional cognitivism. So too does Fodor's (1980, 1983) view of mental processes as formal computations, with its influential distinction between input systems (e.g. low-level vision and speech perception) and central systems (e.g. thought and problem solving). The former are assumed to be modular, hard-wired, data-driven, informationally encapsulated computational reflexes; the latter to be voluntary and flexible, with unrestricted access to the subject's beliefs and knowledge.

Some of the most notable current ideas about the infant mind fit closely with this perspective. A similar perception–cognition distinction is at the heart of Spelke's (1988, 1990, 1991) interpretation of a range of impressive data on young infants' understanding of the physical world. This proposes that a visual input system delivers an unsegmented array of surface points, which is then carved up into 'unitary objects' by a central conceptual system that employs unchanging principles such as cohesion, boundedness and rigidity. Related views include Baillargeon's (1986) ideas of conceptually based belief in object permanence. Such proposals for preadapted, domain-specific knowledge of the physical world are matched by attribution to young infants of conceptually rather than perceptually grounded social understanding of persons (e.g. Legerstee, 1992).

This style of 'conceptual' explanation is compatible with some aspects of Piaget's traditional, centralized view of higher mental functioning. It differs from it in considering such mechanisms as the starting point not the outcome of infancy. And its domain-specific assumptions are incompatible with Piaget's more general-purpose notion of intelligence, in which the infant's developing physical and social understanding are served by the same mechanisms, and language acquisition is firmly rooted in broader cognitive-symbolic developments. Detailed evaluation is available elsewhere (e.g. Rutkowska, 1991, 1993; Willatts, this volume), but two points about this new nativism are relevant here. One is that it downplays the nature and possible import of output systems, hence having nothing significant to say about action. The function of central processes is simply rationalistic: producing beliefs about the world that can be expressed in terms of propositions that are true or false. The behavioural aspect of action is treated as at best an index of such central beliefs and knowledge; and any environmental contribution to adaptive functioning is minimised. This turns out to make it hard to say anything substantive about epigenetic development, a point that will be taken up in section 4. Notably, related cognitivist positions set little store by the idea of 'development', constructivist or otherwise. For Fodor (1975), the language of thought in which innate concepts are represented renders implausible the possibility of acquiring truly novel concepts. For Chomsky (1980), natural development is considered more like growth than like development or even learning, as in 'the growth of rich and highly articulated structures along an intrinsically determined course under the triggering and partially shaping effect of experience, which fixes parameters in a an intricate system of predetermined form (1980, p.1)'.

2.2 Emergence

Varela sees the first major advance in computational ideas about cognition in the notion of *emergence* that is central to recent work in parallel distributed processing or connectionism. This purports to characterize cognition at a subsymbolic level, in terms of multiple, interconnected simple units operating in parallel (cf. neurons, though how appropriately is debatable). Rather than relying on fixed, sequential programmed rules, computation generally involves statistical inference; the whole network settles into a stable pattern of activation by trying simultaneously to satisfy many soft or weak constraints that are only meaningful if considered collectively.

Rule-like behaviour that traditionalists attributed to an explicit program is assumed to emerge from patterns of activity recurring within the network (e.g. Rumelhart & McClelland, 1986). Furthermore, individual units are unlike molar classical symbols, which too often tended to be equivalent to linguistically meaningful whole concepts. Ideally they operate as subsymbols or microfeatures that support dimension-shifted representation (Clark & Lutz, 1992). For example, no single unit would correspond to something like 'dog' or a 'cat'. Instead, units might code properties such as legs, fur, barking, tail, purring and so forth. The overall pattern of activation of these units would determine discrimination and recognition of an input as a dog, cat or neither. Varela's notion of emergence is compatible with viewing symbolic processes of a classical variety as an emergent global property of the local functioning of such networks, that is as a rough approximation to the operation of a connectionist system (Smolensky, 1988).

Compared with traditional computational systems, on some tasks connectionist networks can achieve relative flexibility under noisy or variable circumstances, by settling into the most likely of a range of related solutions. Pattern discrimination or categorization has been one of the great implementational successes of self-organizing connectionist systems (though explanatory theories of how they work remain contentious). This illustrates a continuing link with infancy concerns through Hebb's (1949) 'old connectionism', which was a significant influence on 60's and 70's attempts to explore Piagetian issues by developing notions of model/schema formation in infant cognition (Rutkowska, 1990). More recently, psychologists suggest that such systems may bridge the gap between cognitivist accounts of perception and the theory of direct perception's notion of unmediated pickup of invariants from the optic array (e.g. Humphreys & Riddoch, 1986; Marr, 1982). In particular, connectionist systems often claim to provide roles for both environmental information and the subject's information processing; operate without the extra-perceptual concepts, memory or knowledge of mysterious origin that are anathema to the direct perception theorist; and imply their (purported) biological plausibility makes them a strong contender for evolutionarily determined preadapted organization.

This might make emergence seem a promising paradigm for infancy, and one concurring with positions that take direct perception to offer a more plausible account of early infant perception than is possible for Piaget's strongly constructivist style of cognitivism (e.g. Butterworth, 1989, 1993; Gibson, 1987). Motor/output processes might be encompassed too, since this style of parallel computation can be fitted to ecological psychologists' ideas of how groups of muscles may be organized to operate collectively in 'coordinative structures' (Kugler, Kelso & Turvey, 1982).

Ecological psychology, which aims to extend the theory of direct perception to a theory of direct action, offers a radical alternative to psychologies that take conceptual-representational abilities as the starting point for infant development (Gibson, 1979). In relation to perceiving, making sense of the world is seen as a question of pragmatic knowledge — acting in the environment, not formulating more or less accurate central beliefs about it (Shaw & Turvey, 1980). This appears to endorse Piaget's preoccupation with action, but the perspectives diverge considerably on assumptions about action-based abilities. *Contra* Piaget, ecological psychology considers that genetic preattunement enables infants, from the outset, to see at least some of what things are 'for' — their 'affordances' for activity; and to generate potential purposive acts or 'effectivities' that complement those environmental affordances (Gibson, 1979; Jones, Spelke & Alley, 1985). For example, anything that exhibits an invariant combination of properties including solidity, boundedness and being about infant hand size affords grasping for an infant. This goes against the grain of Piaget's insistence on reciprocal assimilation, whereby all 'looking in order to act' is a developmental outcome of the infant's initially unconnected sensory and motor exchanges with the environment, and better fits contemporary evidence for pre-experience functional links between sensory and motor processes.

Piaget and ecological psychology diverge also in their characterization of mechanisms for action, yet converge in presenting pictures of limited power for tackling developmental issues. Piaget's notion that sensorimotor schemes underlie the subject's voluntary activity is opaque, not least because he speaks of these underlying mechanisms almost exclusively in terms of behavioural processes. For example, discussion of the initial organization and development of vision primarily features movements involved in 'looking' or 'directing the glance' (Piaget, 1953). How sensory processes might work and what they might be doing, key topics of contemporary inquiry, remain unexplored. Piaget regularly emphasises abstract structures into which he assumes schemes become coordinated, a precursor of the structure of operational schemes underlying environment-independent thought, at the expense of clarifying what mechanisms the infant requires to coordinate sensory *and* motor components of purposive activity.

Ecological psychology's treatment of action is likewise problematic, undercutting its challenge to Piaget. At its psychological grain of analysis, seemingly familiar notions like 'intention' and 'attention' are introduced as alternatives to Piaget's mysterious schemes in order to account for the subject's contribution to control of action. These appear too molar to work as psychological primitives. For example, 'intention to grasp' is said to be part of the effectivty of grasping (Michaels & Carello, 1981). But, is it useful to assume that the neonate's reaching and grasping reveals an underlying intention equivalent to that of the nine-month-old? A finer-grained way of discussing infants' psychological mechanisms seems necessary in view of the kinds of developmental restructuring that are typical even of everyday activities like prehension; for example, infants' progressive ability to adjust grasping to the weight of an object prior to contact (of which more in Section 4.2, below). Certainly, neither Piaget's schemes nor his version of re-presentational development offer much help here.

Ecological psychology's insistence on subject–environment mutuality, which is illustrated in 'effectivity–affordance' and 'intention–goal object' relations, marks an important theoretical advance. But just how mutual *is* this perspective's style of explanation, given its (over)commitment to direct realism? Insistence on locating information, including affordances, objectively in the environment (e.g. Gibson, 1979; Turvey, Shaw, Reed & Mace, 1981) appears at odds with Gibson's (1979) argument that, strictly speaking, affordances are *neither* objective nor subjective. It seems more straightforward to see them as *both*: the functionality of things in the environment emerging in their use for action by a perceiving and behaving subject.

In the past, direct perception and Piagetian frameworks have been used to support unprofitable debates about whether early infant abilities offer more support for perception *or* for behaviour (often inappropriately equated with action) as the basis of early knowledge. However, recent theorizing is marked by spreading acknowledgement that there is no real dichotomy here; perception and behaviour are of equal significance to adaptive action, and both Piaget and Gibson, despite apparently different emphases, held action to be central to development (e.g. Bertenthall & Pinto, 1993; Costall, 1994; Rutkowska, 1993).

2.3 Enaction

Action and subject–environment mutuality are central to Varela's advocacy of a constructivist final paradigm: *enaction*. Connectionist systems associated with emergence do not go far enough in this direction. Despite pleas to biological plausibility, they remain far from modelling real-life development and deployment of mental processes. Their sensory interfaces with environmental inputs rarely consist of intensity arrays, tending to involve experimenter selection and hand-coding to a degree that questions the label 'self-organizing'; and networks generally model or simulate only isolated subsystems, rather than being part of a whole system that is embedded in a real environment. Furthermore, they persist with 'recovery' or 'discovery' metaphors for the subject's relationship to information.

Varela describes information as the phlogiston of cognitive science, insofar as the notion is constantly overexploited to explain regularities in the way we know the world. From a biological perspective, he contends, there is no pre-given order outside the subject's activities. At many levels of biological structure, from the cell upwards, significance and information emerge from processes that establish domains of interaction between a 'self' and its environment. The central nervous system's sensorimotor neurons and interneurons are but one specialist adaptation for achieving closure, a reflexive interlinking of subject and environment processes that supports construction of a coherent unity, in this case neurocognitive identity. For this epigenetic perspective, evolutionary, cultural and developmental history determine the world that is 'enacted' or 'brought forth' in perceiving and behaving, hence Piaget's allocation to the nascent enaction paradigm:

> The basic notion then is that cognitive capacities are inextricably linked to a history that is lived, much like a path that does not exist but is laid down in walking. Consequently the view of cognition is not that of solving problems through representations, but as a creative bringing forth of a world where *the only required condition is that it is effective action:* it permits the continued integrity of the system involved. (Varela, 1988, pp. 59-60; italics added)

The in-principle aims of Piaget's 'neither nativist nor empiricist' constructivism clearly justify this placement. However, some differences between the perspectives prove relevant to comparing their developmental implications. In particular, Piaget's ideas appear to end up more realist at heart than Varela's commitment to a fully co-relative perspective on subject and known world. Certainly, Piaget's idea of knowledge is one involving acting on the world, not simply copying it. Yet it remains consistent with action giving rise to representations that *model* selected aspects of an objective reality, with the relation between knowledge structures and reality being one of 'isomorphic models among which experience can enable us to choose' (Piaget, 1970, p.15).

Recent computational directions that Varela considers relevant to elaborating the notion of enaction focus on attempting to build and understand *autonomous systems*, a new route to phrasing questions about the flexible, general knowledge that eluded traditional AI systems. Two lines of research converge on this aim. *Artificial life* (or 'A-Life') concerns itself with how complex-seeming self organization in many types of system, from chemical through to social, may emerge from the interplay of fundamentally simple processes (for a popular introduction see Levy, 1992; and Varela & Bourgine, 1992, for examples of more technical papers). *Animat* research labels an interdisciplinary attempt to use insights about how animals work to build simulated animals or real robots that can exhibit adaptive behaviour in order to survive in a constantly changing, often unpredictable environment (for reviews see Meyer & Guillot, 1991, 1994). Contributing to both of these directions is computational work in behaviour-based robotics (for an important collection of papers see Maes, 1990a).

In keeping with Piaget, this work takes sensorimotor intelligence seriously. Perceptual and motor skills are viewed as the hard problems solved by intelligent systems, and solutions to them as imposing important constraints on remaining components of natural intelligence. Trying to understand intelligence by working incrementally from the (evolutionary) bottom up is a favoured strategy, reflected in slogans like 'insects first, people later' (cf. Cliff, 1991). *Contra* Piaget's thinking, there is little enthusiasm for the explanatory power of concepts or of representations that model the world. Ecological psychology's commitment to direct perception and action is often cited as a source of inspiration, illustrated by the assumption that the best model of the world is the world itself. This should not, however, be taken to mean that researchers in this vein do or must agree to advocate the type of methodological realism that is central to ecological psychology. Bersini (1992) argues, rightly in my view, that some animat researchers' attempts to distance themselves from over-centralized models of the mind have resulted in them promoting too exclusively the environment's role in accounts of their systems' activities. This is not necessitated by either of the animat movements key concerns: 'behaviour rather than excessive rationality' and 'autonomy rather than programmer dependence'. Bersini proposes the term *syntactic subjectivism* to label approaches, including Varela's enaction, which more appropriately highlight mutual constraints between subject and environment, taking on board the experiential and the ecological.

A prominent feature of much of this new work is commitment to grounding intelligence in *situated action*, viewed as a mechanism alternative to more traditional abstract cognitivist models (e.g. see Cognitive Science, 1993). This contrasts with Piaget's treatment of sensorimotor intelligence in some important respects, founded on the assumption that the irrevocably subjective situatedness that arises from an embodied system's physical embedding in an environment can support rather than hinder intelligent functioning.

3 Situated action in behaviour-based robotics

Piaget treats action predominantly as a stepping-stone to purportedly more valid and objective knowledge that is freed from environmental constraints. This leads him to offer a deficit account of infant action, working backwards from abilities he believes the young infant lacks until the end of the Sensorimotor Period, rather than forwards from a focus on the early mechanisms that are possessed. 'Forwards' is the direction favoured by 'bottom up' behaviour-based robotics, and its ideas about action prove more compatible with Varela's positive perspective on the effective action that emerges from an ongoing co-relative subject–environment relationship. Looking at typical models, and at their implications for notions of representation, helps to clarify this contrast.

3.1 Emergent functionality

Recent computational work that endorses a situated approach to the mind adopts *emergent functionality* as a key organizational principle (Rutkowska, 1994a & c). This assumes that the complex abilities of situated systems can emerge indirectly from the operation of independent, seemingly simple components, without the hierarchical control and planning that is typical of traditional AI systems. Central to the functionality of these components is their interplay with the environment (e.g. Maes, 1990b; Steels, 1991).

How a system organized along these lines can work is illustrated by the architecture of Brooks's (1986, 1990, 1991) artificial Creatures. This decomposes a situated system into a number of simple task-achieving behaviors, each of which links specific sensory and motor capacities so that it can (ideally) interact independently and reactively with properties of the environment in which it is embedded. The robot's contribution to interaction between individual task-achieving behaviors bypasses traditional selection and ordering controlled by explicit goal-directed planning. Instead, layered control is achieved by building first the lowest level task-achieving behaviour, debugging its operation, then building another on this foundation and so on. For example, a robot for real-world exploration can be built by starting with Level 0: 'do not come into contact with other objects'. Adding Level 1: 'wander aimlessly' will produce moving around without hitting things. With the addition of Level 2: 'visit interesting places' (e.g. corridors of free space detected by sensors), the robot's behaviour comes to look like exploring, without any goal or plan directed at that function.

Brooks sees such systems' organization as carving up vertically rather than horizontally, with no traditional decomposition into a sequence of processing components between sensors and actuators, devoted to perception, then modelling, then planning, and finally task execution and motor control. Nor is there a central place where an exhaustive, general-purpose description of *the* world is delivered as a preliminary to planning what behavior(s) to execute. Brooks's (1990) classic title, 'Elephants don't play chess', clearly marks disaffection for the rationalistic notions of explicit central representations, goals and plans that characterized the explanations of traditional cognitivism — and towards which the Piagetian infant's development can be seen to be heading.

Such systems have important implications for our understanding of sensorimotor intelligence and of Piaget's position on it. By demonstrating the sufficiency of novel architectures for behavioural control, they begin to suggest alternatives to traditional notions that have been exploited by Piaget and in subsequent theorizing about infancy. For example, Bruner's (e.g. 1968, 1973) explanations of infants' early competence on a range of activities drew on then prevailing ideas that featured goals and feedback in the control of 'skilled action'. Disputing Piaget's chronology for the infant's developmental path, he concluded that the serial ordering of component behaviours must be governed by a controlling intention from the outset. In early prehension, for example, behaviours such as bringing hands together at the midline and mouth opening were interpreted as revealing precocious anticipation of the behavioural goal towards which as yet unsuccessful selection and sequencing of preadapted components was aiming (fine motor manipulation in the first case, oral exploration in the second). There are, however, a range of problems with clarifying the functional significance of infant hands' 'proximal midline activity'; and systematic longitudinal observations of infants before they attain top-level reaching suggest that mouth opening regularly follows rather than proceeds the infant making contact with an object (Rutkowska, 1992, 1994a & b). It is possible that early prehension may be controlled along the lines of exploration in Brooks's Creature. Preadapted sensory-motor pairings, say between vision and reaching or between manual contact and retrieval to the mouth, may be interacting independently with the infant's experience of the environment to generate an *illusion* of hierarchically controlled sequencing and goal-directedness.

Just what kind of explanation best captures this kind of control is a hotly disputed issue. Psychology in general has difficulty in formulating 'spanning concepts' to discuss structures and processes that emerge from mutual interplay of subject and environment, and this may be one reason for the rising appeal of dynamic systems theory as an anti-cognitive contender (e.g. Beer & Gallagher, 1992; for infancy applications see Butterworth & Hopkins, this volume, Thelen & Smith, 1994). Brooks often discusses mechanisms in purely physical and engineering terms, provocatively laying emphasis on special-purpose wires and denying the relevance to his work of computational notions, whether of classical or connectionist varieties (e.g. Brooks, 1991). However, the workings of the *subsumption architecture* that supports layered control appear compatible with classical computational concepts involving programs and symbol manipulation, provided these are used to define architectures that have a high degree of (inter)dependence with the environment. Thus, there are many parallels with a computational model of the infant that rejects conceptual central processes in favour of multiple 'action programs', whose coordination of sensory and motor processes drive and are driven by ongoing transactions with the environment rather than by an internal model of it. (Rutkowska, 1993, 1994a & c; Cf. Vera & Simon's, 1993, argument that situated action is 'thoroughly symbolic').

3.2 Implications for representation

These new approaches to action diverge from Piaget's perspective on the developmental import of sensorimotor intelligence as far as *representation* and the reasoning that it supports are concerned. Work in behaviour-based robotics often claims that it has no need for representations. It is, however, quite compatible with viewing representation in terms of mechanisms that establish *selective correspondence* with the environment, rather than as internal models that substitute for things in the world in the overplayed traditional sense of re-presentation that is favoured by Piaget. Such action-based mechanisms need not be considered trivially representational as Piaget might contend. They map clearly onto Dretske's (1988) analysis of (unconventional) natural systems of representation, whose expressive elements neither mean anything in isolation nor have their meanings assigned to them by any external source. The meanings of their elements are intrinsic to the system and arise from the way they evolve, develop or are designed to play a role in its perceiving and behaving in its environment.

In infants, for example, low-level directionally selective visual elements can be considered to have acquired the function of indicating an approaching object on a hit course from the way they are used by an action program to invoke effective (avoidance) behaviours in our environment of evolutionary adaptedness. Animat design simulates this kind of evolutionary adaptedness. Thus, a sonar pattern associated with free space does not indicate or mean anything in isolation to one of Brooks's Creatures, but it acquires the function of indicating a place to visit from the way it is wired into a task-achieving behavior that effectively embeds the animat in the environment for which it is designed.

Such ideas are also compatible with Israel's (1988) behaviour-based notion of the need for 'information and control states' to explain a system's attunement to constraints in its world. Coming from the linguistic situation semantics framework, this illustrates how such views of representation may encompass human activities that are uncontroversially seen as re-presentational. In general, the quest for an increasingly objective model of the world, which drives Piaget's view of the direction of development, may be supplanted by a notion of representation as a vehicle for controlling our subjective interventions, movements and actions in the environment (Clark, 1994).

Contemporary work on situated systems also changes the focus on Piaget's assumption that sensorimotor schemes are the developmental precursors of thought operations. For Piaget, the logic inherent in coordinations of action is said to be reconstructed at the level of internal thought, ultimately enabling objective logico-mathematical knowledge. This view equates the development of reasoning with proficiency in formal inference. However, an alternative to this pervasive traditional view is offered by the notion of *situated inference*. The validity of formal inference depends on a central system applying the right abstract rules, irrespective of what they are applied to, as in Fodor's version of a computational theory of mind or Piaget's vision of mature thought. Piaget sees the infant as moving in this direction by the end of the Sensorimotor Period, with overt actions giving way to internal actions on 'an image of absent objects and their displacements' (Piaget, 1955, p.4).

By way of contrast, situated inference depends on the subject's embedding circumstances (Barwise, 1987). A basic kind of situated inference exploits constant environmental features. If those conditions break down, such inference will cease to be valid, even if identical computational steps have been followed. Along these lines, infants can be seen as employing situated inference when 'deciding' that it is appropriate to generate avoidance behaviour. The soundness of such processing depends upon the reliability of the infant's action-based representation, which in turn depends on the continuation of natural environmental conditions. In the face of unnatural conditions such as a laboratory shadow-caster, the infant may inappropriately attempt to avoid an expanding shadow, revealing that their action-based understanding is capable of a key property of conventional systems of representation: misrepresentation (Dretske, 1988). From this perspective, development may not involve increasingly abstract thought so much as a widening appreciation of constraints on action. The infant's increasingly insightful behaviour may not require 'mental combination' based on images, as Piaget contends, so much as action-based representation of preconditions for successful behaviour (Rutkowska, 1993; Willatts, 1989).

These examples illustrate how Piaget's ideas about the relation between sensorimotor mechanisms and representation are interestingly different from those that are coming to characterize work on situated robotic systems. However, a potentially significant area of *rapprochement* merits attention. This comes from recent computational work that is informed by the role that visual behaviours play in the adaptive functioning of real-life creatures: the *animate vision* paradigm.

Earlier, it was suggested that Piaget's ideas about the psychological mechanisms underlying action are too motor-fixated to be of much use for clarifying how sensorimotor processes contribute to intelligent functioning. Taken in conjunction with the numerous recent findings that point to preadapted perceptual organization in infancy, it is difficult to take seriously Piaget's (e.g. 1953) claims that behavioural exchanges with the environment are central to the development of such organization. It seems superfluous to propose a process of motor construction, involving a looking scheme that develops from looking for its own sake (functional or reproductive assimilation) to differentiate into more specific schemes that deal, say, with stationary versus moving objects, (generalizing and recognitory assimilation). Looking behaviour may affect what sensory processing outcomes are sought and when, but not processing itself, even if the information value and meaning of the patterns that it generates are ultimately determined by their usefulness for action.

Ballard's (1989, 1993) work suggests that this conclusion will prove to be wrong: perceptual and behavioural aspects of action are inextricably intertwined in ways that are just starting to become clear. The way that eye movements, especially gaze control, work for embodied animals is enabling the design of robots whose information processing and real-time action control are more successful than those that rely more exclusively on traditional central processing.

Piaget's idea of behavioural-motor involvement in visual processing is supported by Ballard's (1989, p.1639) argument that 'the visuo-motor system is best thought of as a very large amount of distinct special-purpose algorithms where the results of a computation can only be interpreted if the behavioral state is known.' Taking the behavioural state of the system into account can constrain the interpretation of input data in ways that are unavailable to a static imaging device, often simplifying the processing problem. For example, when a stationary point is being fixated, it is possible to interpret optical flow as a depth map; when a moving target is being pursued, this interpretation ceases to be valid. To the extent that humans exploit such mechanisms, it must be noted that these ideas of a motor-constructive contribution to information processing do not necessarily entail the kind of developmental construction that Piaget proposes. They might be prewired through evolution. It would, however, be premature to reject the possibility of a role for individual experience.

The developmental potential of this research direction becomes clearer if we look at proposals for the role of visual behaviours in the control of action, though these turn out to be less compatible with Piaget's theory. Contemporary infancy research continues Piaget's interest in relationships between infants' understanding of objects, space and their own activities (for reviews see Bremner, 1989; Harris, 1989). This work makes an important distinction between egocentric and allocentric strategies for coding object position. Subjective egocentric codes are centred on the subject's body (e.g. 'it's on my right'), whereas objective allocentric codes relate position to the surrounding spatial framework (e.g. 'it's at a specific landmark'), and a developmental shift between them has been considered a significant advance in infants' spatial and object understanding. An interesting alternative to either of these familiar ideas is suggested by animate vision, in the form of a frame of reference centred on the subject's fixation point.

This superficially simple idea illustrates the kind of *deictic representation* that is being formulated in studies of situated action — instead of representing things by trying to match them to a comprehensive general-purpose internal world model, they are actively represented in terms of their relation to the subject and their function in the subject's changing engagement with a task (e.g. Agre & Chapman, 1990). In the case of eye-hand coordination, for example, adopting position coordinates relative to a fixation point frame of reference supports a 'do-it-where-I'm-looking' hand movement strategy that does not require precise information about the three-dimensional layout and relative position of objects in the environment.

An egocentric code, as infancy researchers are well aware, is of limited value even for activities as straightforward as reaching for an object, let alone for remembering its position; it can effectively support ballistic (open loop) control of behaviour in a stable world, but any change in position of subject or of object will render it out of date and invalid. A deictic position code based on a fixation point frame of reference, such as 'the-block-I'm-fixating', does not suffer from this limitation. Because its referent constantly alters with the subject's activity, it is automatically updated and offers a form of invariant position code that can support feedback-governed (closed loop) control strategies, achieved by directing the hand to the centre of the retinal coordinate system while simultaneously moving it in depth relative to the plane of fixation. Thus, this kind of active position code is viewer-oriented without being viewer-centred in the limiting way that static egocentric codes are, and it is object-centred without requiring an objective description of the features or location of the object involved.

Ballard makes suggestions for extending these basic ideas about visual behaviours to search and identification tasks; learning eye-hand coordination problems such as block manipulation; and spatial position memory. In search, for example, neither uniform image sampling nor a comprehensive model of what is being looked for are biologically plausible, but strategies such as looking for a characteristic property like colour are (e.g. to locate a box of film, redirect gaze until Kodak yellow is encountered). Further details of the range of mechanisms proposed are beyond the scope of this chapter. However, what all the examples share is commitment to the view that gaze control and fixation are not just a way of getting high-resolution images for visual processing: they are task-dependent strategies for problem-solving. The subjective viewpoint inherent in vision is not a problem to be overcome, in evolution or in development, but an adaptive way for a real-world system to deploy its resources.

As far as the infant's appreciation of objects and of space goes, details of animate vision mechanisms may prove relevant to clarifying the outcome of development. They appear compatible, for example, with Bremner's (1989) view that the egocentric–allocentric dichotomy may not capture how infants are changing. Increasing use of landmarks to guide search for objects does not appear to involve abandonment of self-referent coding in place of a supposedly more objective spatial code. Instead, landmarks may support updating of what remains a self-referential code, by aiding fixation during the infant's movements. What animate vision work already makes clear is just how complex are the workings of a seemingly basic behaviour like fixation. What is also clear is how little these ideas match up with Piaget's assumption that action-based coding of objects is superseded by an appreciation of space as a container in which the self and other objects are located, ultimately yielding an objective representation of the world in which the self and its activity have no priviledged place.

4 Equilibration revisited

So far, some advances in cognitive science have been outlined that suggest new ways of looking at the mechanisms infants (and adults) may exploit in interacting with the world, and their implications for the Piagetian view of sensorimotor functioning and the direction of development have been considered. But do these new ideas have a distinctive story to tell about *developmental processes*? At an explicit level, the answer is 'not yet'. The robotics work of the preceding section involved only systems whose processes exhibit stable organization, not changing organization over time. Most consistency in ideas about changing mechanisms is to be found in research on genetic algorithms. Though there are many genetic algorithms, all are informed by evolutionary principles of change. Essentially, they explore phylogenetic acquisition of the genetic basis for solutions to problems such as locomotion, by simulating mutation and crossing-over in populations of chromosomes, fitness–reproduction relations and so forth. Some animat constructors suggest that the hand-design approach favoured by Brooks and others is simply too difficult to be feasible at any but a toy scale. Instead, they propose using genetic algorithms to guide robots' acquisition of their own control architectures through interaction of initially random 'neural' networks and an environment (e.g. Cliff, Husbands & Harvey, 1992). As far as individual learning is concerned, very diverse methods and questions are being investigated, and general principles are not yet forthcoming. Of clear import for developmental psychology, however, is this area's avowed aim of ultimately providing generalizations about adaptive behaviour in terms of a principled typology of environments, problems tackled and proposed solutions (Meyer & Guillot, 1990). This prompts the question of what might be said about the general form of infant development. Reservations have been expressed about Piaget's assumption of a general shift from reliance on action mechanisms to model-like internal representations. So what might development with the focus on situated action begin to look like?

4.1 Emergent functionality in development

In the preceding section, some parallels were drawn between the notion of emergent functionality and the possible organization of early infant action. Of special relevance to understanding sensorimotor processes in development, emergent functionality is said to serve a system well 'when there is a lot of dependence on the environment and it is difficult to foresee all possible circumstances in advance' (Steels, 1991, p. 459), a condition that applies *par excellence* to the young infant.

Organization of infants' early sensorimotor coordinations along the lines of an emergent functionality architecture would confer a clear developmental advantage: preadaptation without rigid predetermination (Rutkowska, 1994a & b). An apparent paradox of everyday infant activities is that their development often appears predetermined, yet permits considerable flexibility. Whatever mechanisms underwrite 'normal' development are also capable of generating more unusual or exotic variants (e.g. locomotion by scooting in place of walking, Dennis, 1960). They would be severely (over)restricted if based on predetermined 'goal-seeking'. Emergent functionality would allow sensorimotor coordinations that had proven useful in the course of evolution, or sequences of such coordinations, to be 'tuned in' if their viability is confirmed through interaction with the particular environment encountered. In the face of altered environmental conditions and/or properties of the infant (e.g. physical-motor disabilities) novel coordinations could be established.

This view of emergent functionality connects in interesting ways with developmentalists' interest in social *scaffolding* of infants' construction of activity (e.g. Rogoff, Malkin & Gilbride, 1984; Valsiner, 1987). In contrast with the Piagetian infant, who is essentially a monadic creature, concern here is with social constraints on the developmental space within which infants' learning can operate. Scaffolding can usefully be thought of as temporarily engineered emergence of function that has the potential to become permanent adaptive change. One of its key characteristics involves adults manipulating the relationship between infants' sensory and motor capacities and the environment so that the infant repeatedly experiences an outcome that they would neither spontaneously attempt, nor be able to attain, without support. The infant experiences reaching a 'goal' that is in the adult's mind, not his/her own, through activity that is controlled more by the adult than by the infant. As far as infant mechanisms are concerned, the alignment of the sensory and motor processes involved, and their operation's outcome, are purely serendipitous — accidental and unplanned but fortunate; nothing at the level of an action program or a task-achieving behaviour coordinates them. Such scaffolded functionality has the potential, however, to become stable adaptive change. For this to work, development needs a process that will fix viable patterns of activity as permanent adaptive changes to processing potential.

4.2 Representational redescription in infancy

Karmiloff-Smith's (1992) computationally informed theory of *representational redescription* currently presents the widest-ranging evidence for a general-purpose endogenous process in cognitive development. It promises to clarify Piaget's (1976, 1978) important questions of how practical success relates to theoretical understanding of how and why things work, without resorting to his less satisfactory solution in terms of equilibration. Comparing Piaget's cognitivism with more contemporary varieties, Karmiloff-Smith notes the significance of early preadaptations, unforeseen by Piaget, which give the infant a step up on the developmental path. However, she questions cognitivist positions such as Fodor's that see early abilities as evidence for modular, domain-specific knowledge. The integration of knowledge that characterizes domain-specific systems is better considered an outcome of interactive experience. Evidence of recurrent qualitative change over many domains, ages and forms of representation show that the new nativism proposed by Chomsky, Spelke and others does not tell the whole story. As suggested earlier, in section 2, understanding the general form of change entails including output systems in any account of cognitive development, so as to incorporate Piaget's apposite focus on action.

What is shared by the many developmental data that support representational redescription is evidence that local reactions, in which every problem is represented and handled independently, are transformed to general anticipation, with connections between tasks being explicitly acknowledged. Thus, children may master the ability to use a word correctly for two purposes, but only subsequently come to represent it as a single word with two functions. Domains of integrated knowledge are being constructed through an internal process that operates in conjunction with the subject's activities. Karmiloff-Smith characterizes the general form of this process as *knowledge explicitation*, a form of abstraction whereby knowledge that is implicit *in* the system's functioning (level I representations) becomes explicit knowledge *for* the system (Level E representations). In the current context, we need to ask whether representational redescription operates within infancy. If early abilities are assumed to involve conceptual mechanisms, as Spelke and others propose, this mapping proves difficult to make (Rutkowska, 1994d).

Relating levels of representational explicitation to the kind of abstraction that characterizes concepts is far from straightforward. Philosophers generally suppose concepts to support inter-related and flexible knowledge through the way they explicitly represent invariances as properties of things (e.g. concepts allow you to represent that a range of things share a property, and to entertain the notion that other, arbitrary things might possess that property too). In the representational redescription model, Level I representations are assumed to mediate rigid and context bound input–output relations that characterize the first phase of behavioral mastery. So, if infant abilities are conceptual in nature, they might be expected to require at least Level E1 representations, whose flexibility is attributed to them having extracted components of representations for use outside their original input–output context. However, Karmiloff-Smith doubts this is the case for infancy. She suggests, for example, that Spelke's unchanging principles are most likely at Level I, embedded in response to environmental stimuli. Rather than the notion of representational redescription in infancy being awry, this may mean that young infants operate without concepts as philosophers characterize them (cf. Hobson 1991).

Developmentally, if infants' early object understanding is grounded in a Fodorean central system, it is hard to see how the underlying representations could be redescribed at a qualitatively new knowledge level. Only change such as enrichment of core principles, as suggested by Spelke (1991), would be straightforward. In fact, many of the habituation phenomena that support attribution of central concepts to infants may be amenable to explanation in terms of 'input' computations of low-level vision (Rutkowska, 1991, 1993); their significance may be quite different from studies that investigate infants' use of sensory inputs in activity (cf. Costall, 1994; Willatts, this volume).

Representational redescription's place in infancy becomes clearer if we assume that infant abilities lie in action mechanisms, and see the infant as a developing situated agent. Then, central processing is concerned with coordinating action, not with building propositional beliefs, and redescription can operate to alter this level's selective use of sensory and motor processes, hence the infant's contribution to control of action. This offers a good fit between phases of representational redescription and empirical data on infants' changing levels of control in domains such as prehension. Thus, three distinct levels are found in infants' appreciation of object size-weight covariation as indexed by grasping and lifting a series of objects (Mounoud & Hauert 1982). At 6- to 8-months, infants presented with an inappropriately light trick object will treat it like a normal object with proportional size and weight, persisting with a local, one-off adjustment to the current task. Around 9- to 10-months, lifting will be disrupted, for example by rapid upward arm movement, and affective responses suggest that an anomaly has been detected. By 14- to 16-months, the two preceding responses are integrated, with quick compensation following initial disruption.

Such examples of anticipatory development in the second half of the first year converge with the representational redescription framework in a number of important ways. Notably, there is reorganization of what appears to be already successful functioning (cf. the centrality in scaffolding of fostering 'success'). In keeping with a focus on situated action, information in recurring patterns of sensory and motor activity becomes explicit in the infant's action-based representation, supporting anticipatory rather than reactive functioning. At the computational level of action program control, this can be viewed as abstraction of novel perceptual and motor variables from a range of local problem solutions; and more generally as a process of making explicit, or becoming attuned to, novel constraints on action (cf. Clark's, 1994, view that concepts may turn out to be abstractions of control-related features). Like representational redescription, this process is conservative; initial mechanisms are supplemented but not replaced by the development of anticipatory mechanisms, as the final level infant's ability to integrate them shows.

The success-based nature of this form of change is in clear disagreement with Piaget's (1953, 1976, 1978) long-standing assumption that disadaptation ('disturbance') is the fundamental trigger for the equilibration-governed development that results in cognizance of how and why action works. There are, however, important agreements too. Notably, the process is endogenous and general-purpose across ages and domains of activity — it is not so much constrained by domains of knowledge as serving to construct them. The notion of construction is significant here, for this kind of change is genuinely *epigenetic* in both process and product. Inputs to the process by which novel representations are abstracted are determined equally by the subject's activities and by the environment in which they occur. And those novel representations are not internal models of an outside world, but distributed representations that govern the operation of future perceptual and behavioural processes in novel action.

5 Conclusions

The past 25 years of infancy research have seen an ascendance of cognitive theories that often proposed their central mental processes as redressing the balance of Piagetian action's apparent preoccupation with 'peripheral' sensorimotor aspects of infant ability. The main conclusion of looking at recent theoretical advances in cognitive science is that behaviour is back, with a vengeance, but embedded in ideas about action that often diverge significantly from those of Piaget.

As far as infants' initial mechanisms are concerned, the 'something more' than

Piaget's proposals that needs attributing to the infant by way of preadaptation can increasingly be viewed in terms of more innovational accounts of action than were available to Piaget. It may be appropriate to talk from the outset of infants' perceptual-behavioural action, rather than purely sensorimotor activity. While this conclusion appears to favour ecological psychology over cognitivist accounts of the mind, recent views of action prove compatible with work from computational cognitivist directions. A clear focus on perceiving and behaving playing equal roles *within* action supersedes conflicting interpretations of the theories of Gibson (meaning is in perception) and Piaget (perception is misleading until supplemented by behaviour).

Early representation remains a key issue, but focussing on action-based representation should lead to greater concern with how adaptive functioning and meaning depend on the subject's situatedness in the environment, not on disembodied internal models of it. These directions should enrich our understanding of non-conceptual action as the core of infant intelligence (Hobson, 1991; Rutkowska, 1993; Trevarthen et al., this volume).

Ideas about representation and reasoning that emerge from exploring situated action question Piaget's assumptions of the inferiority of subjective, action-based understanding, and his traditional view that things are improved through shifting to purportedly objective conceptual mechanisms. This is not to say that there are no qualitative shifts in the way that infants' knowledge is organized, but anticipatory developments may owe more to changing control of action than to acquisition of concepts and re-presentational ability. While this view of where infant development goes to questions Piaget, ideas about how it gets there continue to support some of his general ideas. In particular, preadaptations need not imply predetermination of domain-specific knowledge; and proposals for epigenetic change through a general-purpose endogenous process need taking seriously. The overall conclusion, however, is subtly but significantly different from Piaget: both the developmental process and its outcome are grounded in *effective action.*

References

[1] Agre, P.E. & Chapman, D. (1990). What are plans for? In: P. Maes (Ed.), *Designing Autonomous Agents.* Cambridge, MA: MIT Press/Bradford Books.

[2] Ballard, D.H. (1989). Reference frames for animate vision. In N.S. Sridharan (Ed.), *Proceedings of the Eleventh International Joint Conference on Artificial Intelligence.* San Mateo, CA: Morgan Kaufmann.

[3] Ballard, D.H. (1993). Sub-symbolic modelling of hand-eye coordination. In D.E. Broadbent (Ed.), *The Simulation of Human Intelligence.* Oxford: Blackwell.

[4] Barwise, J. (1987). Unburdening the language of thought. *Mind and Language, 2,* 82-96.

[5] Beer, R. & Gallagher, J.C. (1992). Evolving dynamical adaptive networks for adaptive behavior. *Adaptive Behavior, 1,* 91-122.

[6] Bersini, H. (1992). Animat's I. In F.J. Varela & P. Bourgine (Eds.), *Towards a Practice of Autonomous Systems: Proceedings of the First European Conference on Artificial Life.* Cambridge, MA: MIT Press/Bradford Books.

[7] Bertenthal, B.I. & Pinto, J. (1993). Complementary processes in the perception and production of human movements. In L.B. Smith & E. Thelen (Eds.), *A Dynamic Systems Approach to Development: Applications.* Cambridge, MA: MIT Press/Bradford Books.

[8] Bremner, J.G. (1989). Development of spatial awareness in infancy. In A. Slater & J.G. Bremner (Eds.), *Infant Development.* Hove and London: Lawrence Erlbaum.

[9] Brooks, R. (1986). A robust layered control system for a mobile robot. *IEEE Journal of Robotics and Automation, RA 2,* 14-23.

[10] Brooks, R. (1990). Elephants don't play chess. In P. Maes (Ed.), *Designing Autonomous Agents.* Cambridge, MA: MIT Press/Bradford Books.

[11] Brooks, R. (1991). Intelligence without representation. *Artificial Intelligence, 47,* 139-160.

[12] Butterworth, G.E. (1989). Events and encounters in infant perception. In A. Slater & J.G. Bremner (Eds.), *Infant Development.* Hove and London: Lawrence Erlbaum.

[13] Bruner, J.S. (1968). *Processes in Cognitive Growth: Infancy.* Barre, MA: Clark University Press.

[14] Bruner, J.S. (1973). Organization of early skilled action. *Child Development, 44,* 1-11. Chomsky, N. (1980). Rules and representations. *Behavioral and Brain Sciences, 3,* 1-61.

[15] Clark, A. (1994). Representationalism refreshed? Talk presented at the University of Sussex, Brighton, 14 June. Paper under review.

[16] Clark, A. & Lutz, R. (Eds.). (1992). *Connectionism in Context.* London: Springer-Verlag.

[17] Cliff, D. (1991). The computational hoverfly. In J.-A. Meyer & S.W. Wilson (Eds.), *From Animals to Animats: Proceedings of the first international conference on the simulation of adaptive behavior.* Cambridge, MA: MIT Press/Bradford Books.

[18] Cliff, D., Husbands, P. & Harvey, I. (1992). Issues in evolutionary robotics. In J.-A. Meyer, H.L. Roitblatt & S.W. Wilson (Eds.) *From Animals to Animats 2: Proceedings of the Second International Conference on Simulation of Adaptive Behavior.* Cambridge, MA: MIT Press/Bradford Books.

[19] Cognitive Science. (1993). Special Issue:*Situated Action. 17(1).*

[20] Costall, A. (1994). On neonatal competence: Sleepless nights for representational theorists? In P. van Geert & L.P. Mos (Eds.), *Annals of Theoretical psychology.* Vol. 7. New York: Plenum.

[21] Dretske F.I. (1988). *Explaining Behaviour: Reasons in a World of Causes.* Cambridge, MA: MIT Press/Bradford Books.

[22] Fodor, J.A. (1975). *The Language of Thought.* New York: Cromwell.

[23] Fodor, J.A. (1980). Methodological solipsism considered as a research strategy in cognitive science. *Behavioral and Brain Sciences, 3,* 63-110.

[24] Fodor, J.A. (1983). *The Modularity of Mind.* Cambridge, MA: MIT Press/Bradford Books.

[25] Gibson, E.J. (1987). Introductory essay: What does infant perception tell us about theories of perception? *Journal of Experimental Psychology: Human Perception and Performance, 13,* 512-523.

[26] Gibson, J.J. (1979). *The Ecological Approach to Visual Perception.* Boston, MA: Houghton-Mifflin.

[27] Harris, P.L. (1989). Object permanence in infancy. In A. Slater & J.G. Bremner (Eds.), *Infant Development.* Hove and London: Lawrence Erlbaum.

[28] Hebb, D.O. (1949). *The Organization of Behaviour.* New York: Wiley.

[29] Hobson, P. (1991). Against the theory of 'Theory of Mind'. *British Journal of Developmental Psychology, 9,* 33-53.

[30] Humphreys, G.W. & Riddoch, J. (1986). Information processing systems which embody computational rules: The connectionist approach. *Mind and Language, 1,* 201-212.

[31] Israel, D. (1988). Bogdan on information. *Mind and Language,* 3, 123-140.

[32] Karmiloff-Smith, A. (1992). *Beyond Modularity: A Developmental Perspective on Cognitive Science.* Cambridge, MA: MIT Press/Bradford Books.

[33] Kugler, P.N., Kelso, J.A.S. & Turvey, M.T. (1982). On the control and coordination of naturally developing systems. In J.A.S. Kelos & J.E. Clark (Eds.) *The Development of Movement Control and Coordination.* Chichester: Wiley.

[34] Legerstee, M. (1992). A review of the animate–inanimate distinction in infancy: Implications for models of social and cognitive knowing. *Early Development and Parenting, 1,* 59-67.

[35] Levy, S. (1992). *Artificial Life: The Quest for a New Creation.* London: Jonathan Cape.

[36] Maes, P. (1990a). (Ed.), *Designing Autonomous Agents.* Cambridge, MA: MIT Press/Bradford Books.

[37] Maes, P. (1990b). Situated agents can have goals. In P. Maes (Ed.), *Designing Autonomous Agents.* Cambridge, MA: MIT Press/Bradford Books.

[38] Marr, D. (1982). *Vision.* San Francisco: Freeman.

[39] Meyer, J.-A. & Guillot, A. (1991). Simulation of adaptive behaviour in animats: Review and prospect. In J.-A. Meyer & S.W. Wilson (Eds.), *From Animals to Animats: Proceedings of the First International Conference on the Simulation of Adaptive Behavior.* Cambridge, MA: MIT Press/Bradford Books.

[40] Meyer, J.-A. & Guillot, A. (1994). From SAB90 to SAB94: Four years of animat research. In D. Cliff, P. Husbands, J.-A. Meyer & S.W. Wilson (Eds.), *Animals to Animats 3: Proceedings of the Third International Conference on Simulation of Adaptive Behavior.* Cambridge, MA: MIT Press/Bradford Books.

[41] Michaels, C.F. & Carello, C. (1981). *Direct Perception.* New York: Prentice Hall.

[42] Mounoud, P. & Hauert, C.A. (1982). Development of sensorimotor organization in young children: Grasping and lifting objects. In G.E. Forman (Ed.), *Action and Thought: From Sensorimotor Schemes to Thought Operations.* New York: Academic Press.

[43] Newell, A. & Simon, H.A. (1976). Computer science as empirical inquiry: symbols and search. *Communications of the ACM, 19,* 113-126.

[44] Piaget, J. (1953). *The Origin of Intelligence in the Child.* London: Routledge and Kegan Paul.

[45] Piaget, J. (1955). *The Child's Construction of Reality.* London: Routledge and Kegan Paul.

[46] Piaget, J. (1970). *Genetic Epistemology.* New York and London: Columbia University Press.

[47] Piaget, J. (1971). *Biology and Knowledge.* Edinburgh: Edinburgh University Press.

[48] Piaget, J. (1976). *The Grasp of Consciousness.* London: Routledge and Kegan Paul.

[49] Piaget, J. (1978). *Success and Understanding.* London: Routledge and Kegan Paul.

[50] Rogoff, B., Malkin, C. & Gilbride, K. (1984). Interaction with babies as guidance in development. In B. Rogoff & J.V. Wertsh (Eds.) *Children's Learning in the Zone of Proximal Development.* San Francisco: Jossey-Bass.

[51] Rumelhart, D.E. & McClelland, J.L. (1986). PDP models and general issues in cognitive science. In D.E. Rumelhart & J.L. McClelland (Eds.), *Parallel Distributed Processing.* Vol. 1. Cambridge, MA: MIT Press/Bradford Books.

[52] Rutkowska, J.C. (1990). Action, connectionism and enaction: a developmental perspective. *AI & Society,* 4, 96-114.

[53] Rutkowska, J.C. (1991). Looking for 'constraints' in infants' perceptual-cognitive development. *Mind and Language, 6,* 215-238.

[54] Rutkowska, J.C. (1992). Early prehension intention. Paper presented at the BPS Developmental Section Annual Conference. Edinburgh, 5-8 September.

[55] Rutkowska, J.C. (1993). *The Computational Infant: Looking for Developmental Cognitive Science.* Hemel Hempstead: Harvester Wheatsheaf.

[56] Rutkowska, J.C. (1994a). Emergent functionality in human infants. In D. Cliff, P. Husbands, J.-A. Meyer & S.W. Wilson (Eds.), *Animals to Animats 3: Proceedings of the Third International Conference on Simulation of Adaptive Behavior.* Cambridge, MA: MIT Press/Bradford Books.

[57] Rutkowska, J.C. (1994b). Prehension intention from 12 to 22 weeks. Poster presented at the IXth International Conference on Infant Studies. Paris, 2-5 June.

[58] Rutkowska, J.C. (1994c). Scaling up sensorimotor systems: Constraints from human infancy. *Adaptive Behavior, 2,* 349-373.

[59] Rutkowska, J.C. (1994d). Situating representational redescription in infants' pragmatic knowledge. *Behavioral and Brain Sciences.* (In press).

[60] Spelke, E.S. (1988). Where perceiving ends and thinking begins: the apprehension of objects in infancy. In A. Yonas (Ed.), *Perceptual Development in Infancy: The Minnesota Symposium on Child Psychology.* Vol. 20. Hillsdale, NJ: Lawrence Erlbaum.

[61] Spelke, E.S. (1990). Principles of object perception. *Cognitive Science,* 14, 29-56.

[62] Spelke, E.S. (1991). Physical knowledge in infancy: Reflections on Piaget's theory. In S. Carey & R. Gelman (Eds.), *The Epigenesis of Mind: Essays on Biology and Cognition.* Hillsdale, N.J.: Lawrence Erlbaum.

[63] Steels, L. (1991). Towards a theory of emergent functionality. In J.-A. Meyer & S.W. Wilson (Eds.), *From Animals to Animats: Proceedings of the first international conference on the simulation of adaptive behavior.* Cambridge, MA: MIT Press/Bradford Books. Turvey, M.T., Shaw, R.S., Reed, E.S. & Mace, W.M. (1981). Ecological laws of perceiving and acting. *Cognition, 9,* 237-304.

[64] Thelen, E. & Smith, L.B. (1994). *A Dynamic Systems Approach to the Development of Cognition and Action.* Cambridge, MA: MIT Press/Bradford Books.

[65] Valsiner, J. (1987). *Culture and the Development of Children's Action.* Chichester: Wiley.

[66] Varela, F.J. (1988). *Cognitive Science: A Cartography of Current Ideas.* Author's unpublished translation of F.J. Varela (1989). *Connaitre – Les Sciences Cognitives: Tendances et Perspectives.* Paris: Editions du Seuil.

[67] Varela, F.J. (1993). Organism: A meshwork of selfless selves. Keynote address delivered at the Second European Conference on Artificial Life. Brussels, 24-26 May.

[68] Varela, F.J., Rosch, E. & Thompson, E. (1991). *The Embodied Mind: Cognitive Science and Human Experience.* Cambridge, MA: MIT Press/Bradford Books.

[69] Vera, A.H. & Simon, H.A. (1993). Situated action: A symbolic interpretation. *Cognitive Science, 17,* 7-48.

[70] Willatts, P. (1989). Development of problem-solving in infancy. In A. Slater & J.G. Bremner (Eds.), *Infant Development.* Hove & London: Lawrence Erlbaum.

[71] Wood, D., Bruner, J.S. & Ross, G. (1976). The role of tutoring in problem-solving. *Journal of Child Psychology and Psychiatry, 17,* 89-100.