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

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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 (195 , 1955) theory of 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, 195). 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

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, 199 ; 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 raditional 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 persons (e.g. Legerstee, 1992).

This style of 'conceptual' explanation is compatible with some aspects of Piaget's traditional, centralized view of unitswould

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 sub-

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 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

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, 199 ; 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 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.16 9) 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

to use a word correctly for two purposes, but only subsequently come to variation 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

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, 199 ; 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.*

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