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Is Cognition Enough to Explain Cognitive Development?

Linda B. Smith, Adam Sheya

Department of Psychological and Brain Sciences, Indiana University, Bloomington

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Abstract

Traditional views separate cognitive processes from sensory–motor processes, seeing cognition as amodal, propositional, and compositional, and thus fundamentally different from the processes that underlie perceiving and acting. These were the ideas on which cognitive science was founded 30 years ago. However, advancing discoveries in neuroscience, cognitive neuroscience, and psychology suggests that cognition may be inseparable from processes of perceiving and acting. From this perspective, this study considers the future of cognitive science with respect to the study of cognitive development.

Keywords: Cognitive development; Dynamic systems; Perception–action

1. Introduction

Thirty years ago, the consensus view divided mental life into three mutually exclusive parts: sense, think, and act (e.g., Chomsky, 1975; Fodor, 1975, 1981; Keil, 1981; Pylyshyn, 1980). Cognition was strictly about the ''think'' part (Keil, 1994) and was understood to be amodal, propositional, and compositional, and thus to be fundamentally different from the processes responsible for perceiving and acting (Pylyshyn, 1980). Contemporary research in neuroscience, cognitive neuroscience, psychology, and robotics suggests that these traditional ideas are wrong. Instead, this newer research indicates that knowledge is embedded in, distributed across, and thus inseparable from noncognitive processes of perceiving and acting. Indeed, cognition *may simply be* the operation of a complex system of noncognitive processes (e.g., Anderson, 2003; Ballard, Hayhoe, Pook, & Rao, 1997; Barsalou, Breazeal, & Smith, 2007; Beer, 1995; Brooks, 1991; Ghazanfar & Schroeder, 2006; O'Regan & Noe, 2001; Pfeifer & Scheier, 1999; Port & van Gelder, 1995; Samuelson & Smith, 2000; Spivey,

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Correspondence should be sent to Linda B. Smith, Department of Psychological and Brain Sciences, Indiana University, Bloomington, IN 47405. E-mail: smith4@indiana.edu

2007; Sporns, 2000; Thelen & Smith, 1994; Wilson, 2002). If this is so, cognitive science must move its boundaries beyond concepts, representations, and computations, and embrace the noncognitive.

Traditional ideas about cognition as separate from perception and action had a particularly profound impact on the study of cognitive development. The emphasis was on competence and concepts and not on process or performance; as a consequence, programmatic research on perceptual development, learning, attention, memory, action, and performance took the backseat. There have now been many evaluations and reviews of both the empirical advances and the critical limitations of competence-based developmental research (e.g., Blumberg, 2005; Elman, Bates, Johnson, & Karmiloff-Smith, 1996; Smith & Katz, 1996; Spencer et al., 2009; Thelen & Smith, 1994). All these critiques see the critical failing as the lack of a theory of change of, for example, how babies who could not walk or talk became toddlers who could do both, of how tool use emerged and became inventive, of the obvious growth in causal and relational reasoning that characterizes the preschool period, and so forth. The separation of cognition from perceiving and acting seems a likely culprit in these failings. Learning and development, after all, are the accrued product of the real-time internal events that are themselves the consequence of perceiving and acting in a physical world.

2. Integration

If one reaches further back in time, before the cognitive revolution that defined the start of the Cognitive Science Society, Piaget (1952) offered a much more integrative view of how cognition was *made* out of noncognitive processes. Consider his description of a secondary circular reaction: A rattle is placed in a young infant's hands. The infant moves the rattle and so it comes into and out of sight and makes a noise. Piaget noted that this aroused and agitated the infant, causing more body motions, and thus causing the rattle to move more rapidly into and out of sight and to make more noise. Young infants have little organized control over hand and eye; yet over just minutes of interacting with the rattle, their activity becomes highly organized and clearly goal-directed. Piaget believed this pattern of activity, involving multimodal perception–actions loops, held the key to understanding the origins of human intelligence.

Contemporary theorizing in computational neuroscience agrees and also sees multimodal perception–action loops as driving neural change and connectivity (Lungarella, Pegors, Bulwinkle, & Sporns, 2005; Lungarella & Sporns, 2006; McIntosh, Fitzpatrick, & Friston, 2001; Metta & Fitzpatrick, 2003; Tononi, 2004). These analyses show that coupled *heterogeneous* systems—systems with fundamentally different properties and sensitivities—when coupled in a task to each other and to the physical world create a dynamic complex system that learns on its own, discovers higher-order regularities, and changes the internal properties of the subsystems as well as their connections to each other.

Fig. 1 illustrates these ideas from computational theory using Piaget's circular reaction. The figure shows three systems—motor, vision, and audition—receiving qualitatively different physical inputs from the very same event, a moving rattling rattle. The qualitatively

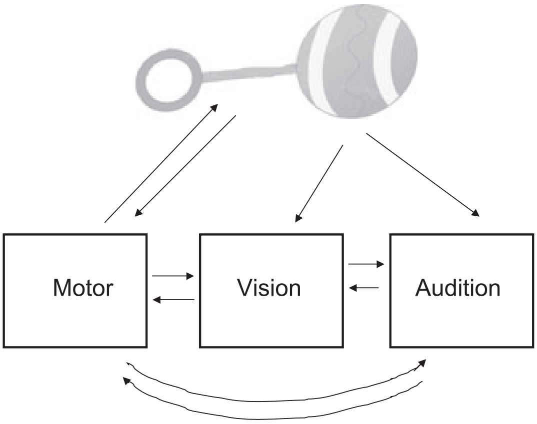

Fig. 1. A schematic of illustration of the complex dynamic system underlying a circular reaction. Events in the physical world—the sight, sound, and feel of a shaking rattle—drive activations in the motor, visual, and auditory systems. The recurrent connection for the each of these systems represents the system's dependence not only on input but also on its own history. The component systems are also functionally connected to each other. Finally, the motor system affects events in the world.

different patterns of activation in each system have their own dynamics but these internal dynamics are also correlated with the activation patterns in other systems, as each is driven by the same external event. Moreover, each system is connected to the others and thus the pattern of activation at any moment in one system, for example, vision, depends on the immediate input, its own just previous state, *and* the just previous state of the auditory and motor systems. These mutual dependencies among components in this complex system enable (though mechanisms such as Hebbian learning) the discovery of higher order patterns that transcend individual modalities.

These ideas fit the classic (and precognitive revolution) demonstrations of Held and Hein (1963; see also Hein & Diamond, 1972; Landrigan & Forsyth, 1974) who showed that active exploration but not passive viewing created change in the visual system of kittens. The same point has also been made in studies of perceptual learning in humans as well as animals (González, Bach-y-Rita, & Haase, 2005; Harman, Humphrey, & Goodale, 1999) and is also supported by contemporary evidence from cognitive neuroscience showing that perceptual and cognitive tasks often engage the motor areas of the brain (Barsalou, Pecher, Zeelenberg, Simmons, & Hamann, 2005; Chao & Martin, 2000; Martin & Chao, 2001; Pulvermüller, Hauk, Nikulin, & llmoniemi, 2005) and that action drives changes in the functional connectivity of cortical regions (e.g. Ghazanfar & Schroeder, 2006; Upadhyay et al., 2008).

A recent developmental study of preschool letter recognition provides direct evidence of sensory–*motor* couplings as a source of *visual* representations (James, 2009). Letter recognition in adults appears to involve specialized regions in visual association cortex that are dedicated to visual stimuli with which the perceiver has expertise (such as faces as well as letters). James examined the development of this neural specialization for letters in preliterate 4-year-olds before and after different training conditions. In the sensorimotor condition, children practiced printing letters during the learning phase and thus received coupled motor and visual input. The control group practiced only visual recognition. At the end of training, both groups of children learned and could visually recognize letters equally well. However, using pre- and posttraining functional magnetic resonance imaging to compare brain activation patterns, James found that only children trained in seeing while *writing* showed enhanced (and more adult-like) BOLD activation in the visual association cortex during a visual letter perception task. These children, but not those who learned letters through a purely visual recognition task, also showed (as do adults) activation in motor regions to the mere visual presentation of letters. The implication is clear: The functional connectivity of visual and motor areas in a task of joint seeing and doing creates more specialized and expert-like *visual* processing. The apparent change of activation in these sensory–motor neural circuits provides important evidence in humans for both Piaget's and Held and Hein's original ideas—that learning is fundamentally a consequence of ''doing'' and of coupling heterogeneous sensory–motor systems in the service of a task.

3. Overlapping integrations

The human sensory–motor system is far more complex than the model system shown in Fig. 1. Each system is, itself, composed of many interconnected subsystems, each with their own sensitivities, properties, and intrinsic dynamics. These densely connected subsystems within a single modality contrast with the longer pathways across modalities (e.g., Bullmore & Sporns, 2009; Martin & Chao, 2001; Pulvermüller et al., 2005; Rogers, Patterson, & Graham, 2007). The sensory–motor system is also complex in that components couple in different ways in different tasks (Clark, 1997, 2008; Honey, Kötter, Breakspear, & Sporns, 2007; Thelen & Smith, 1994). There are reasons to believe that these overlapping coordinations are the engine of cognitive development, creating higher order abstractions (Barsalou, Simmons, Barbey, & Wilson, 2003; Sheya & Smith, 2009; Smith & Breazeal, 2007).

The theoretical idea is illustrated in Fig. 2. Systems A and B are coordinated in Task 1, creating change in both component systems and in their connections. Systems B and C are coordinated in the service of some other, second task. The key point is that the changes in System B wrought via coordination with System A in Task 1 will influence learning and performance in Task 2, constraining solutions to the search space in that task. But, of course, children's cognitive system is not made from three systems and two tasks but from many systems and subsystems in many interlaced, variable, and repeated tasks. This presents a context in which the cognitive system *as a whole* may discover higher order and more abstract regularities within single domains and across domains. This idea has been illustrated in a several computational models showing the powerful consequences of learning multiple overlapping tasks (see Reeke & Edelman, 1984; Rougier, Noelle, Braver, Cohen, & O'Reilly, 2005; Smith, Gasser, & Sandhofer, 1997; Tani, Nishimoto, & Paine, 2008; Yamashita & Tani, 2008). These overlapping coordinations may also be responsible for the cascading interactions characteristic of human development, wherein even seemingly far

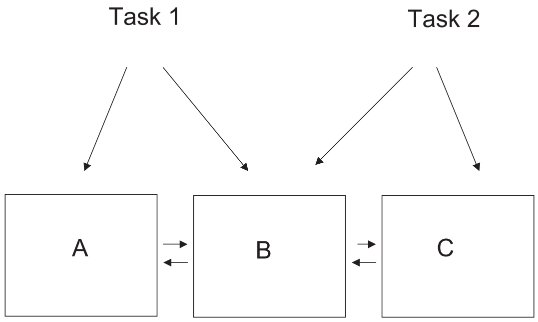

Fig. 2. A schematic illustration of overlapping integrations and how changes in component system B via coupling to A in Task 1 may influence learning and performance in Task 2 and thus changes in component system C.

achievements may be developmentally related (e.g., Smith & Pereira, 2009). These overlapping integrations may also be crucial to understanding how development builds on itself (e.g., Smith & Breazeal, 2007) and how, for example, enabling infants to grab objects early (via Velcro-covered mittens) yields advances months later in manual exploration, in coordinated hand-eye action, and even in causal reasoning (Barrett & Needham, 2008; Fitzpatrick, Needham, Natale, & Metta, 2008; Needham, Barrett, & Peterman, 2002; Sommerville, Woodward, & Needham, 2005).

Soska, Adolph, and Johnson (2010) provide a strong example in their work on early visual object recognition. They show a strong developmental link between visual completion and stable sitting. Visual completion refers to adults' strong and systematic expectations about the geometric structure of an unseen view of an object given a view of just one-side. Soska et al. showed that these expectations emerge in infants between 5 and 8 months and are specifically related to an individual infant's sitting skills. Sitting is critical because extended manual action on a single object—of the kind that can create dynamically organized views of the whole—depends on having sufficient postural control to sit without falling over.

It may not just be sitting and holding objects that matters, but the dynamic coupling of dynamic changes in seeing and doing as infants actively engage with objects. This possibility was demonstrated in a recent study of how action affects the perceived principal axis of an object (Smith, 2005; see also, Street, James, Jones, & Smith, unpublished data). The perceived principal axis—usually the axis of maximal elongation or symmetry—is an object-centered structural property that provides a means for aligning and comparing internal representations and is therefore an important property in many theories of high-level vision (Biederman, 1987; Marr & Nishihara, 1978). An object's axis of elongation in relation to the body is also important for grasping, for goal-directed actions, and for an object's likely path of motion (Sekuler & Swimmer, 2000). Smith (2005) showed that experience in actively moving objects either along a path or symmetrically around an internal point of the object (but not the experience of merely watching objects move) altered 2-year-olds' visual perception of the principal axis and thus the object shape. This is a mere demonstration experiment showing that the manner of actively moving an object *can* alter its perceived shape. But it is a potentially profound one for the development of visual object representations. Infants and toddlers spend a lot of time stacking, aligning, and inserting objects into openings. These are activities dependent on the geometrical structure of things and activities that couple vision and action.

In sum, action couples sensory–motor systems. These *functional* couplings occur everyday, over and over, *in multiple tasks*, such that the component systems may change the internal workings of each other, finding higher order regularities that transcend specific modalities and specific tasks (see Barsalou et al., 2003). These multiple integrations—the openness of the system to many different overlapping integrations and variable functional connectivity—may lead to what we think of as uniquely human abstractions (see also Honey et al., 2007; Smith, 2009).

4. Creating stabilities

Alan Kay, a pioneering computer scientist in object-oriented programming, gave a talk in 1987 titled ‘‘Doing with images makes symbols.’’ One of his ideas, much like Karmiloff-Smith’s (1996) ideas about re-representation, was that actions create perceivable stabilities. Examples of such created stabilities in a toddler’s life might be stacked blocks, a scribble, a grouping of things, and one thing under another thing; these are all created patterns that endure beyond the actions that created them. Both Kay and Karmiloff-Smith (though in somewhat different ways) noted that these stabilities—made from and thus correlated with actions—created opportunities for re-representing goals and tasks in more symbol-like ways. Here, we consider the development of spatial classification as an example.

Spatial classification is a kind of symbolic representation; we represent similarity by proximity in space. Children begin doing this at around 2 years of age (Sugarman, 1983). Indeed, around this time, they become almost compulsive spatial sorters. Confronted with an array of four identical cars and four identical dolls, they physically group them—moving all the cars spatially close to each other and spatially apart from the groups of dolls, even though there is no explicit task to do so. They are so reliable at doing this that many developmental psychologists use the task as a way to measure young children’s knowledge of categories (e.g., Mandler, Bauer, & McDonough, 1991; Nelson, 1973; Rakison & Butterworth, 1998). Their reasoning is that if a 2-year-old child knows that two objects are the same kind of thing, she should spatially group them together. A perhaps just as interesting question is why the child bothers to actively spatially group objects at all.

Sheya and Smith (2009, 2010) propose that spatial classification, like the intention to shake a rattle to make noise, is discovered through action. Their analysis begins with a consideration of the dynamics of sequential action, and specifically with the question of how a target-directed action at time 1 potentiates or influences the selection of the *next* target at time 2. The analysis uses the theoretical construct of a dynamically updated salience map. Imagine an array of eight toys, five of one kind and three of another as illustrated in Fig. 3. Sheya and Smith propose that the touching of one toy alters the salience map, by activating

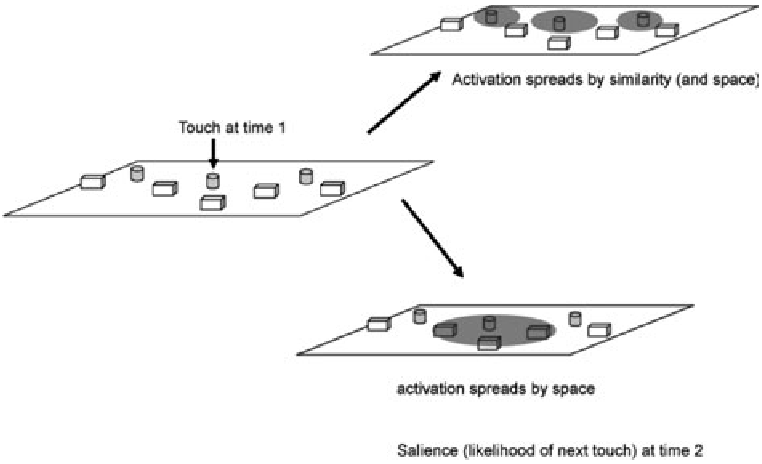

Fig. 3. An illustration of the two ways in which perceptual–motor activity at one moment in time may organize attention and behavior at the next. A touch to one object may increase the salience of objects at locations near to that touch or a touch, to one object may increase the salience of objects similar in their properties to the first object.

the spatial location of that toy. The key question is how activation from an initial action spreads and so influences the likelihood of the next action. Within this map activation can spread along two potential dimensions, by spatial proximity or by featural similarity. In their behavioral experiments, Sheya and Smith (2010) showed that activation in this salience space (as measured by the next toy touched) spreads mostly by spatial proximity for younger infants (12-month-olds) but by feature similarity as well as space for older infants (18-month-olds).

Sheya and Smith (2009) conjecture that the emergence of dynamic updating by featural properties rather than just space (a result that also implicates integration of dorsal and ventral visual information) may underlie the emergence of spatial classification. As children are drawn to nearby and similar things, they are likely—through just these processes alone—to drop similar things near each other, with the interactive effects of spatial proximity and physical similarity increasing the salience of reaching, again and again, to like and near things. A system whose activity is biased to both reach to similar locations and similar objects, will as a consequence of reaching and dropping those things, ends up with similar things near each other. It is here that Alan Kay's idea enters in. The perhaps originally unplanned consequence of similar things ending up near each other creates *an image*, a stable array of like things in proximity and apart from different things.

There is evidence consistent with this idea that *seeing* the stable end product of actions—even when that end product is unplanned—can teach the goal. Namy, Smith, and Gershkoff-Stowe (1997) conducted a microgenetic study with the goal of encouraging the development of spatial classification in toddlers who did not yet spatially group like objects. The children's ''training'' was the task of putting objects into a transparent shape sorter such that children could see the objects once they had been dropped inside. The opening on the top of the shape container was structured to allow one type of object to fit inside the hole, resulting in a kind of forced spatial classification. Critically, children could *see* the outcome, a group of like things close together in the transparent container. This experience (but not sorting into opaque containers) turned the children into spatial classifiers. This is a potentially powerful force on development. As children act in their world, they change their world, creating stabilities—like things near others, stacks, one-to-one correspondences, and so forth. These perceivable stabilities, even if originally unplanned, may capture the dynamic processes that create them, leading to a re-representation of goals and outcomes.

5. Conclusion

Thirty years ago, it seemed clear that cognition, and cognitive development, had little to do with the body. We thought this despite the obvious truth that nothing gets into or gets out of our cognitive system except *through* the sensory–motor system and the body. We thought this despite significant research (viewed as outside of cognitive science) linking action to developmental change (e.g., Bertenthal, Campos, & Barrett, 1984; Bushnell & Boudreau, 1993; Held & Hein, 1963). New advances in psychology, neuroscience, and robotics (Beer, 1995; Rabinovich, Huerta & Laurent, 2008; Spivey, 2007) make clear the relevance of noncognitive processes to the very nature of cognition. And so the next 30 years of cognitive science (and cognitive development) will embrace a broader perspective in which cognition is seen not as separate from sensory–motor processes but as arising from them.

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