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Cognition as a dynamic system: Principles from embodiment

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Abstract

Traditional approaches to cognitive development concentrate on the stability of cognition and explain that stability via concepts segregated from perceiving acting. A dynamic systems approach in contrast focuses on the self-organization of behavior in tasks. This article uses recent results concerning the embodiment of cognition to argue for a dynamic systems approach. The embodiment hypothesis is the idea that intelligence emerges in the interaction of an organism with an environment and as a result of sensory-motor activity. The continual coupling of cognition to the world through the body both adapts cognition to the idiosyncrasies of the here and now, makes it relevant, and provides the mechanism for developmental change.

Keywords: Dynamic systems; Cognition; Concepts; Development

The idea of emergence—the temporary but coherent coming into existence of new forms through ongoing intrinsic processes—is fundamental to the idea of dynamic systems. Complex systems composed of very many individual elements embedded within, and open to, a complex environment can exhibit coherent behavior: the parts are coordinated without an executive agent, plan, or program. Coherence is generated solely in the relationships between the components and the constraints and opportunities offered by the environment. This self-organization means that no single element has causal priority. When such complex systems self-organize, they are characterized by the relative stability

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or instability of their states. These ideas have been used to explain a variety of phenomena in the physical and biological world, and increasingly they have been used—as this volume attests—in the study of developmental process.

These foundational tenets of a dynamic systems approach have particularly radical implications for how we think about cognition. In particular, they imply each that thought is an in-the-moment unique event, open to a continually changing world, and the product of the intrinsic dynamics of a nonstationary system. Yet concepts, nonchanging symbolic or propositional representations, are the core theoretical construct in contemporary research on cognitive development, and are seen as essential to explaining the stability of human cognition. As Keil (1994, p. 169) wrote

> Shared mental structures are assumed to be constant across repeated categorizations of the same set of instances and different from other categorizations. When I think about the category of dogs, a specific mental representation is assumed to be responsible for that category and roughly the same representation for a later categorization of dogs by myself or by another.

This traditional cognitivist approach segregates constant concepts from the real time and inherently variable processes of perceiving and acting, the province of dynamic systems. These ideas of concepts and representations—ideas that have done considerable work in they study and explanation of cognitive development—seem completely at odds with dynamic systems notions. If we pursue a dynamic systems approach, do we then discard concepts?

The present paper reviews evidence pertinent to three principles concerning how knowing is bound to the world through body. The evidence and the principles all concern what has become to be known as the embodiment hypothesis. The embodiment hypothesis is the idea that intelligence emerges in the interaction of an organism with an environment and as a result of sensory-motor activity. The findings about embodiment derive from computational (e.g., Beer, 2000), behavioral (Bahrick & Lickliter, 2000; Zwaan, Stanfield, & Yaxley, 2002), and neuroscience (Kan, Barsalou, Solomon, Minor, & Thompsonschill, 2003; Knudsen, 2003; Stein & Meredith, 1993) perspectives on cognition to cognition suggest instead that all knowledge may be emergent from, embedded in, distributed across, and inseparable from real time processes of perceiving, remembering, attending, and acting (Samuelson & Smith, 2000; see also, Barsalou, Simmons, Barbey, & Wilson, 2003; O'Regan & Noë, 2001). Not all the proponents of this new view explicitly use the vocabulary and formalisms of dynamic systems. Nonetheless, they share the idea that cognition just is a complex set of internal processes bound to each other and to the world through perception and action in real time with no fixed and segregated representation of anything, that is, that cognition just is a complex dynamic system. This paper selectively reviews the evidence and the implications of embodiment for a dynamic systems theory of cognitive development. The evidence and theoretical concepts promise a deep new understanding of both cognition and developmental change, and it is the positive contribution of this approach that is the main thesis of this paper. However, lurking in the background throughout is the problem of concepts. Taking a dynamic systems approach to cognition requires thinking about cognition in entirely new ways.

Thought is an in-the-moment event tied to the here and now

The rationale for concepts is that constants in the head are required to explain stability in behavior. But just how stable is behavior really? Contrary to Keil's example, we do not think exactly the same thing each time we think of dog—in the context of frisbies, we think of playful puppies, in the context of race tracks, we think of streamlined (and not a bit playful) greyhounds, and in the context of muzzles, the main thought is fear. Thoughts are relevant and adaptive only if they fit the relevant idiosyncrasies of the here and now. This is the main thesis of this section and the case will be made with respect to the object concept as proposed by Piaget (1963). But first, I begin with an example from motor development that presents the essence of the argument in barebones form in a domain in which concepts are not in question. Instead, the issue concerns another hypothetical construct, the central pattern generator that like concepts is proposed to explain stability.

The stable behavior is the alternating limb pattern that characterizes the walking pattern of four-legged mammals such as cats. Classic theories in motor behavior explained the stable patter by a central pattern generator (CPG). There seemed too much support for the idea. For example, investigators (e.g., Delcomyn, 1980) found that cats would walk with alternating limbs on a treadmill even when their spinal cords were surgically separated from their brains. The conclusion from this was that the CPG was in the spinal cord. The validity of the a CPG has been questioned on many grounds (see Thelen & Smith, 1994) but the central point here is that even if a CPG did exist, it could not be the cause of the stability apparent in the alternating limb action of real cats walking across real terrains. Real cats walk backward, forward, on grass, on hills, on rubble. They side step objects; they walk when one limb is in a cast. The alternating limb pattern in apparent in all these cases but the variability to make this same pattern is remarkable. Alternating limb movement in these different contexts requires fundamentally different patterns of muscles firing to maintain the same global stability of alternation. Yet the CPG is a supposed constant. If such a CPG exists, then processes outside of this structural constant must make walking happen in globally similar but appropriately different ways in all these contexts. This is the central failure of explaining stability in behavior across contexts with a constant stability in the head. If what is in the head is constant, then the real work of behaving and knowing in the moment, of adapting to the specific demands of the here and now, must be outside of these constant constructs. If this is so, why propose such constants at all? The point: the CPG is irrelevant to explaining the stability and the variability of real time behavior and the explanation of real time behavior can only be found in the processes that bind the system to the physical world. In what follows, I argue that in the same way the hypothetical construct of a CPG is irrelevant to explaining the alternating pattern in four-legged walking, so the object concept irrelevant to explaining the stabilities and instabilities in infants search for hidden objects.

Piaget (1963) defined the object concept as the belief that objects persist in space and time independent of one's own perceptual and motor contact with them. Piaget measured infants' "object concept" in a simple object-hiding task. It works like this: the experimenter hides a tantalizing toy under a lid at location A. After a delay (typically 3–5 s), the infant is allowed to reach and most infants do reach to A and retrieve the toy. This A-location trial is repeated several times. Then, there is the crucial switch trial: the experimenter hides the object at a new location, B. Infants watch the object being hidden at the new location. But after the delay, if the infants are 8- to 10-months old, they make a characteristic "error", the so-called A not B error. They reach not to where they saw the object disappear, but back to A, where they found the object previously. Importantly, infants older than 12 months of age usually search correctly on the crucial B trials (see Wellman, 1986). Piaget suggested that this pattern indicated that older infants but not younger ones know that objects can exist independently of their own actions. There has, of course, been much debate about this conclusion and many relevant experiments pursuing a variety of alternatives (Acredolo, 1979; Baillargeon, 1993; Bremner, 1978; Diamond, 1998; Munakata, 1998; Spelke & Hespos, 2001), including that infants much younger than those that fail the traditional A not B task do—in other tasks—represent the persistence of the object beyond their own perceptual contact.

In this context of divergent views on the phenomenon, Smith, Thelen and colleagues (Smith, Thelen, Titzer, & McLin, 1999; Spencer, Smith, & Thelen, 2001; Thelen & Smith, 1994; Thelen, Schoner, Scheier, & Smith, 2001), sought to understand infants' behavior in the task. At the behavioral level the task would seem to be about reaching to the right location in visual space; hence, these researches sought to understand infants failures and successes in the task in terms of visually guided reaching. In the task, infants look at objects at particular locations, and then—repeatedly—reach to those locations. From the perspective of visually guided reaching, the key components of the task can be described analyzed as illustrated in Fig. 1. The infant watches a series of events, the toy being put into a hiding location and then covered with a lid. From this, the infant must formulate a motor plan to reach and must maintain this plan over the delay, and then execute the plan. Smith, Thelen and colleagues argue that competence that underlies success (or failure) in this task is embedded in the real time processes that create actions in the world. Their explanation—of both failure and success in the task—includes no construct anything like an object concept. One might conclude from this that the A not B task just does not happen to tap—is not relevant to—an object concept. But Smith and Thelen's idea is more radical than that: the motor plan, necessary in any account of infants' actual performance in this task, in and of itself, implements a "belief" on the part of the system that objects persist in space and time. In this way, sensory-motor processes create a

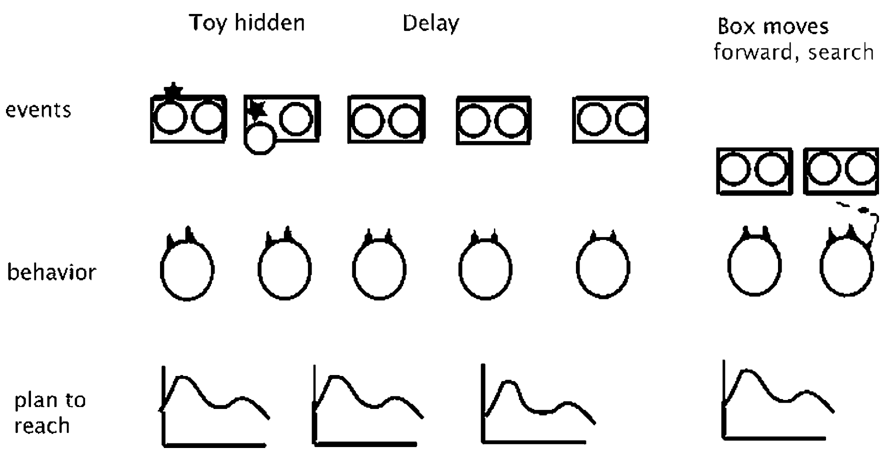

Fig. 1. A task analysis of the A not B error, depicting a typical A-side hiding event. The box and hiding wells constitute the continually present visual input. The specific or transient input consists of the hiding of the toy in the A well. A delay is imposed between hiding and allowing the infant to search. During these events, the infant looks at the objects in view, remembers the cued location, and undertakes a planning process leading to the activation of reach parameters, followed by reaching itself.

stability in the system that from the outside might look like a belief about objects but that is instead embedded in—not mediating between—processes of perceiving and acting.

These ideas lie at the core of Thelen et al.'s (2001) formal dynamic systems account of the A not B error. The theory specifies the sensory events and their dynamic integration in the formation (and maintenance over the delay) of a reaching plan. The theory is illustrated in schematic form in Fig. 2. The center figure illustrates the activation that is a plan to move the hand and arm in a certain direction. Three dimensions define this motor planning field. The *x*-axis indicates the spatial direction of the reach, to the right or left. The *y*-axis indicates the activation strength; presumably this must pass some threshold in order for a reach to be actually executed. The *z*-axis is time. All mental events occur in real time, with rise times, durations, and decay times. In brief, the activation in the field that is the plan to reach evolves in time as a function of the sensory events, memory, and the field's own internal dynamics.

According to theory, activation in this field is driven by three inputs to the field. The first is the continually present sensory activation due to the two covers on the table. These drive activation (perhaps below a reaching threshold) to those two locations because there is something to reach to at those locations. The second input is the hiding event that instigates a rise in activation at the time and location of the hiding of the object. It is this activation from this specific input that must be maintained over the delay if the infant is to reach correctly on B trials. The third input is the longer-term memory of the previous reaches which can perturbs the evolving activation in the field, pulling it in the direction of previous reaches.

Fig. 3 shows results from simulations of the model. Fig. 3A illustrates the evolution of activation in the hypothesized motor planning field on the very first A trial. Before the

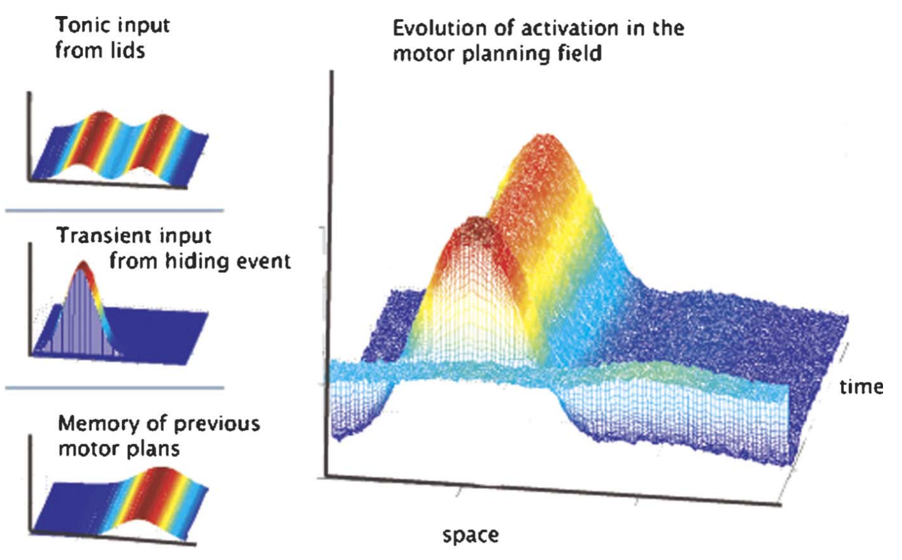

Fig. 2. An overview of the dynamic field model of the A not B error. Activation in the motor planning field is driven by the tonic input of the hiding locations, the transient hiding event, and the memories of prior reaches. This figure shows a sustained activation to a hiding event on the left side despite recent memories of reaching to the right, that is a nonperseverative response.

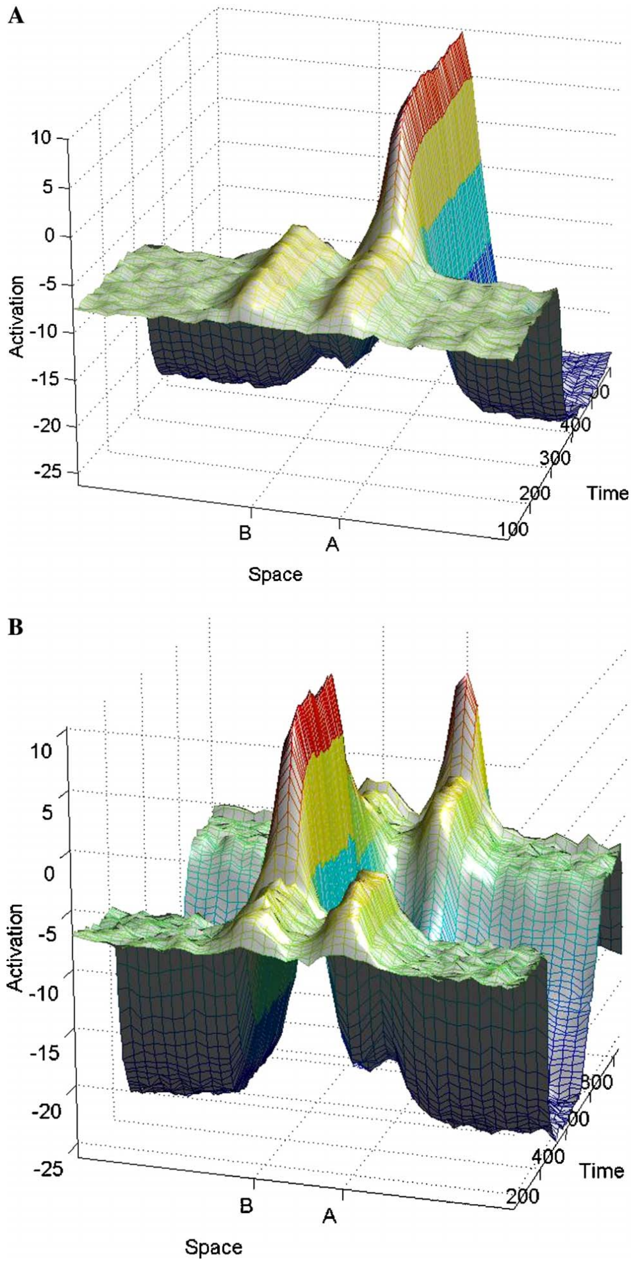

Fig. 3. (A) The time evolution of activation in the planning field on the first A trial. The activation rises as the object is hidden and due to self-organizing properties in the field is sustained during the delay. (B) The time evolution of activation in the planning field on the first B trial. There is heightened activation at A prior to the hiding event due to memory for prior reaches. As the object is hidden at B, activation rises at B, but as this transient event ends, due the memory properties of the field, activation.

infant has seen any object hidden, there is low activation in the field at both the A and B locations that is generated from the perceptual input of the two hiding covers. As the experimenter directs attention to the A location by hiding the toy; that perceived event produces high transient activation at A. The field evolves and maintains a planned reaching direction to A. This evolution of a sustained activation peak that can drive a reach even after a delay, even when the object is hidden, is a consequence of the self-sustaining properties of the dynamic field. Briefly, the points within a field provide input to one another such that a highly activated point will exert a strong inhibitory influence over the points around it, allowing an activation to be maintained in the absence of external input.

One crucial aspect of this dynamic field account is that once infants reach, a memory of that reach becomes another input to the next trial. Thus, at the second A trial, there is increased activation at site A because of the previous activity there. This combines with the hiding cue to produce a second reach to A. Over many trials to A, a strong memory of previous actions builds up. Each trial embeds the history of previous trials. Fig. 3B illustrates the consequence of this on the critical B trial. The experimenter provides a strong cue to B. by hiding the object there. But as that cue decays, the lingering memory of the actions at A begin to dominate the field, and indeed, over the course of the delay through the self-organizing properties of the field itself activation shifts back to the habitual, A side. The model predicts that the error is time dependent: there is a brief period immediately after the hiding event when infants should search correctly, and past research shows that without a delay, they do (Wellman, 1986).

The model makes a number of unexpected predictions that have been tested in a variety of experiments (see Thelen et al., 2001). Indeed, simulations from the model an be used to design experimental manipulations that cause 8- to 10-months olds to search correctly on B trials and that cause 2- to 3-years old to make the error (Spencer et al., 2001) utility of this model is confirmed by the fact that it can be used to design experimental manipulations that cause babies to make and not make the error. These effects are achieved by changing the delay, by heightening or lessening the attention-grabbing properties of the covers or the hiding event, and by increasing and decreasing the number of prior reaches to A (Diedrich, Highlands, Spahr, Thelen, & Smith, 2001; Smith et al., 1999). What do these effects mean about the object concept? Does such a concept have any role to play in explaining behavior—or like the construct of a CPG is the object concept irrelevant to explaining how infants actually do or do not search at B on B trials? What is knowing? Do 10-months old infants know something different when they make the error compared with when they do not? In the moment, they clearly do, and this is what the model seeks to explain: A decision to reach to find the toy emerges in the moment from multiple components in relation to the task and to the immediately preceding activity of the system. From this perspective of the in-the-moment behavior, there may be no single cause, no single mechanism and no one "concept" that distinguishes 10-months old from 12-months old or 2-years old in this task. Instead, there may be many contributing processes that make knowing in the moment and thus that make the error appear and disappear. Ten-months old, 12-months old, and 2-years old, can be regarded as complex systems that self-organize in specific tasks through processes of perceiving, acting, and remembering. The object concept as it is usually conceived seems to have nothing to do with it.

In the dynamic field model, the processes that underlie the behavior—the activations in the dynamic field—are conceptualized as motor plans. Indeed, by this account, it is the maintenance of a motor plan to reach to the most recently seen hiding location that differentiates between infants who make the error and those who do not. We have strong evidence for this claim that the relevant processes are embedded in the sensory-motor system, in processes of reaching to locations in space. One result derives from experiments in which the infants' posture was shifted between A and B trials (Smith, Clearfield, Diedrich, & Thelen, in preparation; see also, Smith et al., 1999). Specifically, an infant who sat during the A trials was made to stand up to watch the hiding event at B and the infant remained standing during the delay and during the search on the B trial. Why should a shift in posture matter? Because just as cat walking must be tied to the specific terrain, the reaching plan must be specific to the current body position. To be effective, the plan must task the hand from its current location to the search location. Reaching plans must be bound to the current body position.

This idea is a critical part of the dynamic field model and crucial to the origins of perseveration in the task. Recall that the motor plan field, as illustrated in Fig. 3, has three inputs—the tonic input from the lids on the table, the transient hiding event, and the memories for previous reaching plans. Those memories for previous reaching plans must be tied to specific body positions as they specify how to move the arm from a particular starting position to a location in space. If those memories are in the coordinates of the body's position, they may not be active, might not be input to the motor planning field, when the body's position is shifted. If this is so, a posture shift should effectively wipe out the perseverative reach to A and this is what we found. A posture shift between A and B trials (but not other kinds of distractions) caused even 8- and 10-months old infants to search correctly. The processes that lead to success or failure are necessarily—just like walking over grass versus walking on rubble—tied to the specifics of the body in the moment. Consequently, just like real time walking, the A not B error cannot be explained by a constant (or its lack) in the head, but be explained by the processes that bound cognition through the body to the here and now world. Again, some fixed belief, an object concept, seems to have little to do with it.

In a second experiment (Smith et al., in preparation), we replicated this in-the-moment bodily nature of the processes that give rise to the A not B error by altering the weight of arm between A and B trials. We altered the weight of the arms by putting wrist weights on. Heavy arms require a different movement plan that light ones. This experiment thus again alters the bodily information relevant to a reaching plan between the A and B trials but does so in a different way. And again, when the needed reaching plan was so altered, infants did not make the error but reached correctly. Infants who reached with "heavy" arms on A trials but "light" ones on B trials (and vice versa) did not make the error, again performing as if they were 2- to 3-months older. These results again indicate that the relevant memories are in the language of the body and close to the sensory surface. They underscore the embeddedness of knowing in processes of perceiving and acting. If knowing is to matter in the world, in real time performance, it must be melded to the specifics of the here and now.

Some might see these results as indicating that there is an object concept but that the A not B task is not a good measure of that underlying concept as it does not draw upon that knowledge. This line of argument is supported by the many studies (e.g., Spelke & Hespos, 2001) that show that babies are less likely to make the error in tasks that do not involve active reaching (see especially, Munakata & McClelland, 2003). Perhaps reaching somehow disrupts infants' ability to demonstrate their competence, the underlying reality of an object concept. This form of explanation—competence hidden by the processes of real time performance—is quite common in contemporary cognitivist developmental psychology and it is not easily dismissed (see, e.g., Durand & Lécuyer, 2002; Hood, Cole-Davies, & Dias, 2003). There are no possible results that can disprove the existence of an object concept (or CPG) that need not show itself in actual behavior.

However, this competence-divorced—from performance explanation also obscures two potentially important insights from the dynamic field model of the A not B error. The first insight is that whether or not there is an object concept that is or is not measured by the A not B task, knowing in the moment, emerges in processes that include perception and action. The second insight is that a "belief" in the persistence of objects beyond immediate perceptual contact, also resides in and is distributed across sensory-motor processes, in the persistent activation of a motor plan.

Cognition is embedded in a physical world

Cognition is neither observable nor effective unless it is linked to the body and to the physical world beyond the body. Importantly, the physical world has its own independent dynamics; it changes whether we want it too or not. The fact that effective cognition must be coupled to the here and now is one argument against the idea of a CPG and an object concept and concepts in general. The system's continuous coupling to the they physical world is also a source of intelligence. In particular, all intelligence needs not be distributed within a single cognitive system, it may be distributed across the brain, the body and the world. That is, the embeddedness of cognition in a physical body in a physical world also means that not all knowledge needs to be put into the head, into dedicated mechanisms, into representations; rather, it can reside in the interface between body and world. This is dramatically illustrated by passive walkers. Knowledge of the alternating limb movement of bipedal locomotion—knowledge traditionally attributed to a central pattern generator—appears to reside in the dynamics of two coupled pendulums, gravity, an inclined plane (McGeer, 1990). The intelligence that makes alternating leg movements is not strictly in the brain, not the body, nor the world but in the interaction of a particularly structured body in a particularly structured world.

There is a growing literature suggesting that much human intelligence resides in the interface between the body and the world. The phenomenon of change blindness is often conceptualized in this way. People do not remember the details of what is right before their eyes because they do not need to remember what they can merely look at and see (O'Regan & Noë, 2001). Similarly, Ballard, Hayhoe, Pook, and Rao (1997) have shown that in tasks in which people are asked to re-arrange arrays of squares, they off-load their short-term memory to the world (when they can). This off-loading in the interface between body and world appears a pervasive aspect of human cognition and may be critical to the development of higher-level cognitive functions or in the binding of mental contents that are separated in time.

This idea is also supported by a new series of experiments on children's learning of object names (Smith, 2005a, 2005b; see also Smith & Gasser, 2005; for a preliminary presentation of the results), a phenomenon that is surprisingly but deeply related to the A not B error. The experimental procedure derives from a task first used by Baldwin (1993) and illustrated in Fig. 4. The participating subjects are very young children $1\frac{1}{2}$- to 2-years of age. The experimenter sits before a child at a table, and (A) presents the child with first

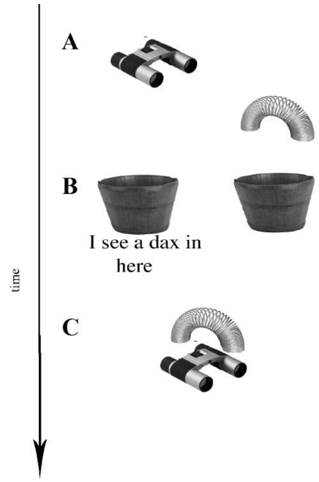

Fig. 4. Events in the Baldwin task. See text for further clarification.

one object to play with and then with a second. Out of sight of the child, the two objects are then put into containers and the two containers, (B) are placed on the table. The experimenter looks into one container and says, "I see a dax in here." The experimenter does not show the child the object in the container. Later the objects are retrieved from the containers, and (C) and the child is asked which one is "a dax". Notice that the name and the object were never jointly experienced. How then can the child join the object name to the right object? Baldwin showed that children as young as 24 months could do this, taking the name to refer to the unseen object that had been in the bucket at the same time the name was offered. How did children do this? How, if one were building an artificial device, would you construct a device that could do this, that could know the name applied to an object not physically present when the name was offered?

There are a number of solutions that one might try, including reasoning and remembering about which objects came out of which containers and about the likely intentions of speakers when they offer names. The evidence, however, indicates that young children solve this problem in a much simpler way, exploiting the link between objects and locations and space. What children do in this task is make use of a deep and foundationally important regularity in the world: a real object is perceptually distinguished from others based on its unique location; it must be a different place from any other object. The key factor in the Baldwin task is that in the first part of the experimental procedure, one object is presented on the right, the other on the left. The containers are also presented one on the right, one on the left, and the name is presented with attention directed (by the experimenter's looking into the bucket) to one location, for example, on the right. The child solves this task by linking the name to the object associated with that location. We know this is the case because we can modify the experiment in several crucial ways. For example, one does not need containers or hidden objects to get the result at all. One can merely present the target object on the right and have children attend to an play it with it there, then present the distracter object on the left and have children attend to and play with it there. Then, with all objects removed, with only an empty and uniform table surface in view, one can direct children's attention to the right and offer the name (dax) or to the left and offer the name. Children consistently and reliably link the name to the object that had been at this location.

Young children's solution to this task is simple, a trick in a sense, that makes very young children look smarter than they perhaps really are. But it is a trick that will work in many tasks. Linking objects to locations and then using attention to that location to link related events to that object provides an easy way to bind objects and predicates (Ballard et al., 1997). People routinely and apparently unconsciously gesture with one hand when speaking of one protagonist in a story and gesture with the other hand when speaking of a different protagonist. In this way, by hand gestures and direction of attention, they link separate events in a story to the same individual. American Sign Language formally uses space in this way in its system of pronouns. People also use space as a mnemonic, looking in the direction of a past event to help remember that event. One experimental task that shows this is the "Hollywood Squares" experiments of Richardson and Spivey (2000). People were presented at different times with four different videos, each from a distinct spatial location. Later, with no videos present, the subjects were asked about the content of those videos. Eye tracking cameras recorded where people looked when answering these questions and the results showed that they systematically looked in the direction where the relevant information had been previously presented.

This is all related to the idea of "deictic pointers" (Ballard et al., 1997) and is one strong example of how sensory-motor behaviors—where one looks, what one sees, where one acts—create coherence in our cognition system, binding together related cognitive contents and keeping them separate from other distinct contents. In sum, one does not necessarily need lots of content-relevant knowledge or inferential systems to connect one idea to another. Instead, there is a cheaper way; by using the world and the body's pointers to that world.

These young word learners' performances in the Baldwin task are also deeply related to younger babies' performances in the A not B error. Fig. 5 (top) illustrates the structure of the A not B task and (bottom) the structure of the Baldwin task. In the A not B task, children reach and look to locations to interact with objects and objects, through a motor plan to reach, are bound to those actions and locations. In the Baldwin task, children reach and look to locations to interact with objects as they learn their names. Children bind objects to locations of action—reaching, looking, and then use location to map a name to a nonpresent object. Ongoing research suggests that these processes—the processes that enable children to competently link names to intended referents—may be fundamentally the same the as those that create A not B error in that children's linking of names to objects through space in this task are—like the A not B error—disrupted by shifts in posture and body position.

The surface similarity of the Baldwin task—as task where embodiment and spatial orientation create competence—to the A not B task suggests that the usual interpretation of the A not B error as diagnostic of cognitive immaturity may be fundamentally wrong. The A not B error may not be so important for what it tells us about infantile incompetence as for what it tells us about cognition is fundamentally bound to the real time bodily processes through which we act in a physical world.

Cognition is a nonstationary system

Even the most casual observation tells us that there are dramatic differences in the cognitions of 1-year old, a 3-year old, a 6-year old, and adults? The cognitive system is non-

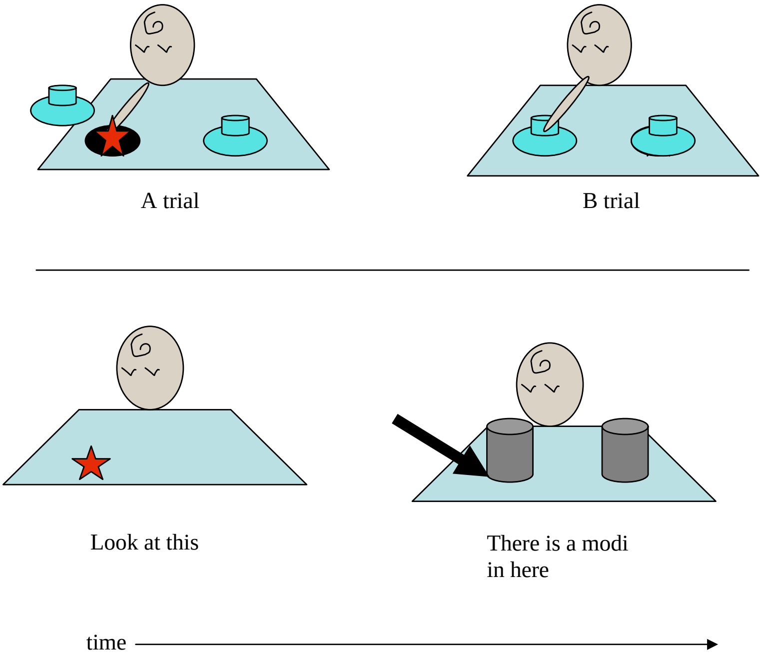

Fig. 5. An illustration of two time steps in the A not B task and the Baldwin task. In the A not B task, children repeatedly reach and look to locations to interact with objects at location A causing motor planning memory biased to location, and in this way binding the object to location A. In the Baldwin task, children repeatedly reach and look to locations to interact with objects. This causes objects—through remembered motor plans and attentional plans—to be bound to locations; children can then use this binding of objects to locations to link a name to a nonpresent object.

stationary, in its behavior and in its own internal processes. The system responds differently in different contexts and changes as a consequence of its own activity in the world. Understanding cognitive development requires understanding how the processes that binding the cognitive system to the physical world change themselves through their own activity (Samuelson & Smith, 2000). The nonstationarity of the cognitive system is often underplayed in the cognitivist tradition, which has favored the view of a mind armed with stable concepts that force stability on our experiences of a variable world.

The fact of continuous change in the system is clearly evident at much a finer grain than the broad sweep of development. Each individual experience, each moment of wakeful living, changes us, at least a little. We know this must be true at some level or we would have no memories of the individual events of our lives and no connectedness with our past. The power of individual one-time experiences to alter cognition has been experimentally documented many times (e.g., Brooks, 1987; Jacoby, 1983; Rovee-Collier & Hayne, 1987; Salasoo, Shiffrin, & Feustel, 1985). One particularly powerful result of this kind was reported by Perris, Myers, and Clifton (1990). In one study of visual cues to control reaching, Perris et al. taught 6-months old children to reach in the dark for different sized objects. The different sizes were signaled by different sounds (e.g., bells for big objects and squeaks for little ones). The innovation was to bring these children back to the laboratory one to two years later. The children who had participated in the reaching experiment as babies were brought back to the laboratory along with a control group of children who had not participated in the reaching in the dark experiments. The lights were turned off, and a sound was played. Children who had been in the experiment as babies reached for the sounding objects; control children did not. The one-time experience at six months permanently changed these children, altering the likelihood of behaviors one and two years later. Each moment in time, each act of perceiving, remembering, attending, acting, changes us. This is important because development can only be the long-time accrual of changes incurred in milliseconds to milliseconds and second to second events.

But the changes we see in the cognitive system over development are not simply additions (more of the same thing). Nor is cognitive development simply a case of external forces being internalized (though that does happen). Most critically, the nonstationarity of the system derives from: (1) the systems continuous coupling to a physical world with its own dynamics and that never quite repeats itself and (2) to changes in the systems own internal dynamics, changes driven by the system's own history. It is this second kind of change that can lead to noticeable discontinuities that is most commonly considered development. The remainder of this section expands on three embodied mechanisms of change that may change the internal organization of the cognitive system: (1) the multi-modal sensory-motor system, (2) exploration, and (3) dynamic coupling to social entities with similar internal and external processes.

Multi-modality

Emergence within complex systems—the shift from one dynamically stable state to another—derives from a system of interactions among heterogeneous subsystems. Within the complex system that is human cognition, one set of heterogeneous subsystems crucial to driving change is the multi-modal sensory-motor system. We are bound to the physical world in real time through multiple modalities, through vision, audition, touch, smell, proprioception, and balance. Each of these subsystems provides—in real time—a different take on the same external world. These different takes are all bound to the same reality in real time; this multi-modal nature of experience is a major driver of change in the system itself (Barsalou et al., 2003; Knudsen, 2003; Stein & Meredith, 1993; Turkewitz & Kenny, 1985). In this way, the present view is highly consistent with Piaget's (1963) understanding of sensory-motor development.

Multi-modality is also a crucial driver of change in Edelman's (1987) Neural Darwinism, as exemplified in his discussion of degeneracy. The notion of degeneracy in neural structure means that any single function can be carried out by more than one configuration of neural signals and that different neural clusters also participate in a number of different functions. Degeneracy creates redundancy such that the system functions even with the loss of one component. For example, because we encounter space through sight, sound, movement, touch, and even smell, we can know space even if we lack one modality. Being blind, for example, does not wipe out spatial concepts; instead, as studies of blind children show (e.g., Landau & Gleitman, 1985) comparable spatial concepts can be developed through different clusters of modalities.

Degeneracy also means that sensory systems can educate each other, without an external teacher. Careful observers of infants have long noted that they spend literally hours watching their own actions (e.g., Cohn & Tronick, 1988; Piaget, 1963) holding their hands in front of their faces, watching as they turn them back and forth, and some months later, intently watching as they squeeze and release a cloth. This second characteristic of multimodality is what Edelman calls re-entry, the explicit inter-relating of multiple simultaneous representations across modalities. For example, when a person experiences an apple—and immediately characterizes it as such—the experience is visual, but also invokes the smell of the apple, its taste, its feel, its heft, and a constellation of sensations and movements associated with various actions on the apple. Importantly, these multi-modal experiences are time-locked and correlated.

Changes in the way the hand feels when it moves the apple are time-locked with the changes one sees as the apple is moved. The time-locked correlations create a powerful learning mechanism, as illustrated in Fig. 6, which shows four related mappings. One map is between the physical properties of the apple and the neuronal activity in the visual system. Another map is between the physical properties of the apple and neuronal activity in the haptic system. The third and fourth maps are what Edelman calls the re-entrant maps: activity in the visual system is mapped to the haptic system, and activity in the haptic system is mapped to the visual system. Thus the two independent mappings of the stimulus—the sight and the feel—provide qualitatively different glosses on the world, and by being correlated in real time, they educate each other. At the same time, the visual system is activated by time-varying changes in shading and texture and collinear movement of points on the apple, the haptic system is activated by time-locked changes in pressures and textures. At every step in real time, the activities in each of these heterogeneous processes are mapped to each other, enabling the system in its own activity to discover higher-order regularities that transcend particular modalities.

One demonstration of the power of this idea comes from a study of how babies come to understand transparency. Transparency is a problematic concept; think of birds who harm themselves by trying to fly through windows. Transparency is a problem because correlations between visual cues and the haptic cues that characterize most of our encounters with the world do not work in this case. So babies, like birds, are confused by transparency. In one study, Diamond (1990a, 1990b) presented infants with toys hidden under boxes such that there was an opening on one side—as illustrated in Fig. 7. These boxes were either

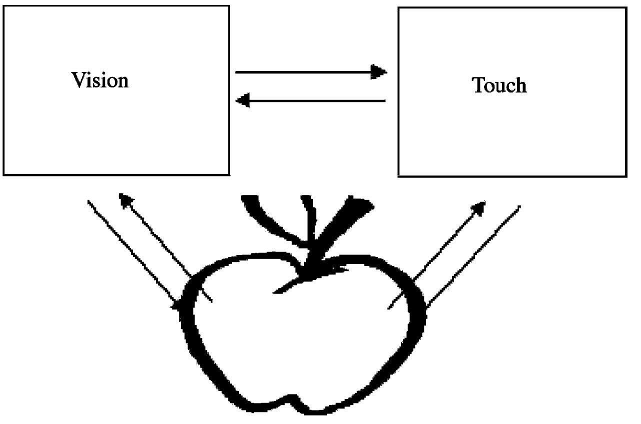

Fig. 6. Illustration of the time-locked mappings of two sensory systems to the events in the world and to each other. Because visual and haptic systems actively collect information—by moving hands, by moving eyes, the arrows connecting these systems to each other.

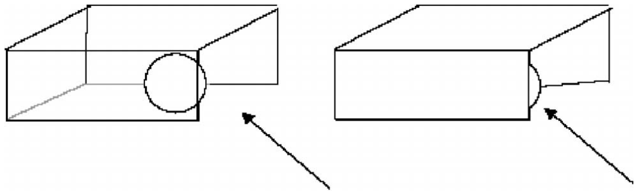

Fig. 7. A toy (ball) hidden under a transparent box and an opaque box in the Diamond's task. The opening is indicated by the arrow.

opaque—hiding the toy—or transparent so that the infants could see the toy under the box. The key result is that 9-months old infants are better able to retrieve the toy from the opaque than from the transparent container. The problem with the transparent container is that infants attempt to reach for the toy directly, through the transparent surface, rather than searching for and finding the opening.

Infants readily solve this problem, however, if they are given experience with transparent containers. Titzer, Thelen, and Smith (2003) gave 8-months old babies either a set of opaque or transparent buckets to play with at home. Parents were given no instructions other than to put these containers in the toy box, making them available to the infants during play. The infants were then tested in Diamond's task when they were 9-months old. The babies who had been given opaque containers failed to retrieve objects from transparent ones just as in the original Diamond study. However, infants who played with the transparent containers sought out and rapidly found the openings and retrieved the object from the transparent boxes.

Why? These babies in their play with the containers—in the inter-relation of seeing and touching—had learned to recognize the subtle visual cues that distinguish solid transparent surfaces from no surface whatsoever and had learned that surfaces with the visual properties of transparency are solid. The haptic cues from touching the transparent surfaces educated vision, and vision educated reaching and touching, and enabling infants to find the openings in transparent containers. These results show how infants' multi-modal experiences in the world create knowledge—about openings, object retrieval, and transparent surfaces.

Recent experimental studies of human cognition suggest that many concepts and processes may be inherently multi-modal in ways that fit well with Edelman's idea of re-entrance (Barsalou, 2005; Ellis & Tucker, 2000). One line of evidence for this conclusion is that even in tasks meant to be explicitly unimodal, multiple modalities contribute to performance. For example, visual object recognition appears to automatically activate the actions associated with the object (Ellis & Tucker, 2000). In one study, adults were shown a picture of a water pitcher such as that illustrated in Fig. 8. The task was simple, to indicate by pressing a button whether the object was a pitcher ("yes") or it was not ("no"). Response time was the dependent measure. This is a purely visual object recognition task. Yet the participants were much faster at recognizing the object if the button pressed to indicate the "yes" response was on the same side as the pitcher's handle, as if seeing the handle primed (and readied) the motor response of reaching to that side. Similar results have been reported with a wide variety of objects and in tasks using several different methods (see Kan et al., 2003; Smith, 2005a, 2005b). Experience is inherently multi-modal—actions time-locked to sights, sights time-locked to sounds. Each unique modality with its

Fig. 8. Illustration of the Tucker and Ellis task. On each trial the task is the same, to answer as rapidly as possible the question: "Is this a pitcher?" Half the participants answer "yes" by pressing a button on the right and half by pressing a button on the left. Participants are faster when the handle is on the same side as the "yes" response.

individual take on the world is bound to other modalities and educates and alters them, and in so doing permanently changes us.

Exploration

Thelen (1994) once asked: How can a learner who does not know what there is to learn manage to learn anyway? Action and the time-locked multi-sensory correlations that action yields provide an answer. The world does not have to present babies with pre-specified learning tasks and goals. Babies can discover both the tasks to be learned and the solution to those tasks through exploration. Spontaneous movement creates both tasks and opportunities for learning. One elegant demonstration concerns the study of reaching. Thelen and colleagues (Thelen, 1993) tracked the week-by-week development of four babies over a 3-months period as they transitioned from not reaching to reaching. Four very different patterns of development were observed. Some babies in the nonreaching period hardly lifted their arms at all, but sat placidly watching the world. Other babies were more high-strung and active, flailing and flapping, and always moving. These different babies had to learn to solve very different problems in order to learn to reach out and grasp an object. The flailer would have to learn to become less active, to lower his hands, to bring them into midline. The placid baby would have to learn to be more active, to raise her hands, to lift them up from their usual positions on her side. Each baby did learn, finding a solution that began with exploration of the movement space.

Thelen (1994) used a second experimental task "infant conjugate reinforcement" to make the same point. In these studies, infants (as young as three months) are placed on their backs and their ankles are attached by a ribbon to a mobile which is suspended overhead. Infants, through their own actions, discover this link. As the infants kick their feet, at first spontaneously, they activate the mobile. Within a few minutes they learn the contingency between their foot kicks and the jiggling of the mobile, which presents interesting sights and sounds. Young mammals—including children—spend a lot of time in behavior with no apparent goal. They move, they jiggle, they run around, they bounce things and throw them, and generally abuse them in ways that seem, to mature minds, to have no good use. All these activities create time-locked correlations across modalities in self-organizing change in the system itself.

Socially like others

The physical world also contains social entities. Cognition is coupled through the body to physical world and to the social partners in that world, who in tasks like the A not B task and the Baldwin task direct and reflect infants' attention. Let us re-imagine the infant conjugate reinforcement paradigm. However, in this case instead of coupling the infant's leg by ribbon to a mobile, we couple the infants face by mutual gaze to another face, to the face of a mature partner. Many developmental researchers have observed mother–infant face-to-face interactions and they report a pattern of activity and learning that looks very much like conjugate reinforcement, but with an added twist (e.g., Cohn & Tronick, 1988; Rogoff, 1990; Schaffer, 1996; Trevarthen, 1988).

Mothers' facial gestures and the sounds they make are tightly coupled to the babies' behavior. When babies look into their mother's eyes, mothers look back and smile and offer a sound with rising pitch. When babies smile, mothers smile. When babies coo, mothers coo. Babies' facial actions create interesting sights and sounds from mothers, just like their kicks create interest sights and sounds from attached mobiles. And just as in the case of the ribbon-tethered mobiles, these contingencies create a context for arousal and exploration. In the initial moments as infants and mothers interact, infants' vocalizations, and facial expressions become more active, broader, and diverse. This exploration sets up the opportunity for learning time-locked correspondences between infants' facial actions and vocalizations and those of the mother, such that the infants' actions become transformed by the patterns they produce in others. But crucially, the social partner in these adventures offers much more than a mobile, and this changes everything. Mature social partners do not just react conjugately to the infants' behavior; they build on it and provide scaffolding to support it and to transform it into conventionally shared patterns. For example, very early infant behavior shows a natural rhythmic pattern of intense excitement alternating with patterns of relative calm (e.g., Cohn & Tronick, 1988; Rogoff, 1990; Schaffer, 1996; Trevarthen, 1988). Caregivers are thus able to create a conversation-like exchange by weaving their own behavior around the child's natural activity patterns. Initially, it appears as if the caregiver alone is responsible for the structure of interaction. But babies' behaviors are both entrained by the mother's pattern and educated by the multi-modal correspondences those interactions create. Incrementally and progressively the babies become active contributors, affecting their mothers by their own reactions to her behavior, and keeping up their own end of the conversation. Imitation provides another example of the scaffolding mature partners provide to the developmental process. Although there is controversial evidence that babies reflexively imitate parental facial gestures at birth, other research strongly suggests that infants learn to imitate parent vocalizations. Parents provide the structure for this learning by imitating their babies! That is, parents do not just respond to their infants' smiles and vocalizations; they imitate them. This sets up a circular pattern: vocalization by the infant, imitation by the parent, repeated vocalization by the infant, imitation by the parent, and so on. This creates opportunities for learning and fine-tuning the infant's facial and vocal gestures to match the adult model. In brief, the cycle works to strengthen and highlight certain patterns of production as parents naturally select those that they take to be meaningful (see Masur & Rodemaker, 1999; also Breazeal, Buchsbaum, Gray, Gatenby, & Blumberg, 2005). Mature social partners also provide multi-modal supports to help ground early language learning. When a parent introduces an object to a toddler and names it, the parent musters a whole of array of sensory-motor

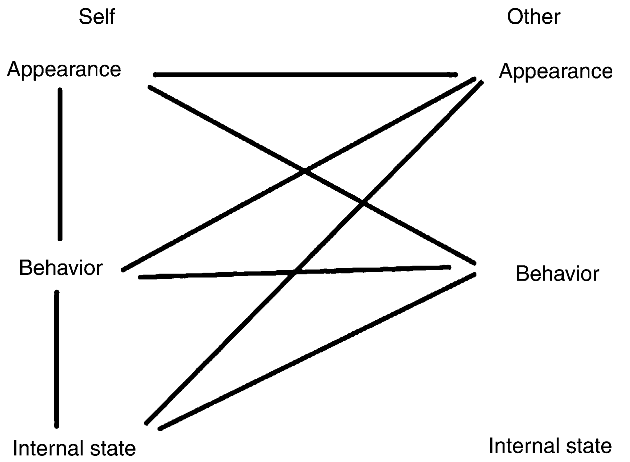

Fig. 9. The higher-level correlations available to the self from the coupling of behavior with a social other. (The internal correlations of the other are not shown because these are not directly observable to the self but must be inferred.)

supports to bring the child's attention to the object and to bind that object to the word (Gogate & Bahrick, 2001; Gogate & Walker-Andrews, 2001; Gogate, Walker-Andrews, & Bahrick, 2001). Parents look at the object they are naming, they wave it so that the child will look at it, and they match the intonation patterns in which they present the name to their very actions in gesturing at or waving the object. Our multi-modal nature drives self-organizing developmental change and undergirds the social scaffolding of cognitive development.

Developing in a social world does not just mean that development is guided by a mature partner. It also provides an additional level of higher-order multi-modal correlations crucial to concepts of self, other, intention, and what is commonly known in the literature as theory of mind (e.g., Leslie, Friedman, & German, 2004). Being a body with a cognitive system in a world with like bodies and like cognitive systems yields time-locked multi-modal correlations that arise from the coupling of one's own behavior with a social other. These are illustrated in Fig. 9. These new correlations are between: the appearance of the self and the appearance of others (e.g., hands to hands and feet to feet), the behavior of the self and the behavior of others, and the internal states of self and the outward manifestations of the internal states of others. Just as coupled multi-modal systems time-locked to the physical world are computationally powerful, these dynamic socially embedded coupling of two intelligent systems—to each other and to the jointly experienced physical world—are even more computationally power, an enormous driving force of change and re-organization.

Conclusion

This paper began with the question of concepts. What is the role of concepts in a understanding of cognition as a dynamic system? Concepts are merely hypothetical constructs. They are theoretical entities that have been proposed to explain stabilities in behavior. Although the field of cognitive development has been defined as the enterprise of studying concepts, concepts are themselves somewhat mythological entities. As theoretical constructs, they have reality only if they are necessary to explain phenomenon. It is not at all clear that concepts are necessary. From a dynamic systems point of view, dynamic stabilities and instabilities (the potential for change) emerge as a consequence of how complex systems composed of many heterogeneous components self-organize in context and in time. The unitary, context-free, and timeless theoretical entity of a concept has no role to play in this endeavor.

So should we abandon concepts for dynamic systems? The construct of a concept has led to real insights into cognition and into development. Dynamic systems has not yet been systematically applied to the study of cognitive development except by a very few investigators and laboratories, and is not yet a proven theoretical framework. This seems on the cusp of change. This review suggests that cognition just is an event in time, the emergent product of many heterogeneous systems bound to each other and to the world in real time. Developmental change must reside in the real time changes—in the accrual of changes that happen in the system or the order of milliseconds and seconds—that emerge in this real time activity. These are the core ideas of dynamic systems theory: emergence of new forms in time as a consequence of many decentralized and local interactions. We may have to abandon some old constructs if we are fully to understand the temporal coupling of cognition to the body, to the world, and to other social entities.

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