CHAPTER 13

Are Dynamic Systems and Connectionist Approaches an Alternative to Good Old-Fashioned Cognitive Development?

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The goal of this book, and the conference that motivated it, is to determine whether connectionism and dynamic systems are two distinctly different theories of cognitive development or whether together they represent a paradigm shift in the field of cognitive development toward a single new unified theory. The three authors of this chapter represent relative outsiders to this discussion. We each have studied cognitive development from a blend of traditional theoretical approaches, influenced by the theories of Piaget, Gibson, and Vygotsky, as well as by the broad range of theories that fall under the umbrella of information-processing approaches to cognitive development. We each represent a different blend of these theoretical frameworks, and we are all sympathetic to the general aims of and ideas behind connectionism and dynamic systems. We therefore have taken on the task of critically evaluating these new approaches from the perspective of good old fashioned cognitive development (GOFCD), with an eye toward understanding what connectionism and dynamic systems bring to the field as well as understanding the extent to which they differ from more traditional approaches to cognitive development.

We have organized this chapter into four sections. In the first section, we discuss what connectionism and dynamic systems bring to the study of cognitive development. Because many of the chapters in the book deal directly with this issue, this section is relatively brief. In the second section, we examine how connectionist and dynamic systems theories relate to other GOFCD theories of developmental change. In some sense, this section traces the historical roots of key ideas in connectionist and dynamic systems theories. In addition, we show through examples of systematic programs of work examining developmental change in cognitive processes how the ideas inherent in connectionism and dynamic systems are not unique, although, importantly, connectionist and dynamic systems approaches may make some of these ideas more explicit and central, in part because developing formal analytical methods for modeling change provides a new set of sharper tools to drive progress. Next, we evaluate the contribution of connectionism and dynamic systems in more depth by examining explanations of two historically important issues in cognitive development: infants' behavior in the A-not-B task and children's solutions to the balance scale problem. Here we evaluate how these new theories compare to more traditional explanations of children's developing behavior in these tasks. Finally, we consider how well connectionist and dynamic systems approaches address criticisms often leveled at other theories of cognitive development.

Dynamic Systems and Connectionist Approaches to the Study of Change

The field of cognitive development is broadly concerned with how children's thinking

evolves from the preverbal representations of an infant to the high-level conceptual abilities of a 16-year-old. The challenge, of course, is how to characterize and study such change and the causes of change. Dynamic systems and connectionist approaches to cognitive development explicitly focus on understanding change over time. Each is concerned with demonstrating through mathematical models and careful empirical studies *how* change occurs, not simply documenting *that* change occurs. As a result, they bring a focus on mechanism to the forefront. Proponents of the two viewpoints are concerned with how systems self-organize, with organization arising from a less organized (or sometimes unorganized) state through real-time processes and the dynamic activity of the system. The two approaches conceive of this self-organization differently. For dynamic systems theories, developmental change is an emergent product of interactions among multiple components, occurring on many different timescales (Smith & Thelen, 2003). Theories adopting this framework emphasize multicausality and self-organization emerging out of the real-time dynamics of the child's own activity in a structured environment (Smith & Thelen, 2003). For connectionist theories of development, reorganization emerges out of nonlinearities in learning (Marchman, 1997; Thelen & Bates, 2003), and new structures only emerge from the interaction of the existing structure and environmental input (Bates & Elman, 2002; Elman, 2005). From an outsider's perspective, it is very difficult to distinguish between these two ways of thinking about change; for both, self-organization and emergent structure are a key feature of change. Structural change emerges from activity that occurs in real time, and developing systems exhibit high levels of variability during the process of change. Central to both connectionist and dynamic systems theories of development, therefore, is the explicit idea that new structures and behaviors are emergent products of multiple, interacting components. Moreover, in both styles of theorizing, change at longer timescales necessarily emerges from change at shorter timescales because all behavior is linked together through time. Perhaps most important, both approaches involve developing formal mathematical models of developmental change that provide a detailed level of specificity about those interactions (although it is important to point out that the two most influential volumes on connectionist and dynamic systems approaches to development did not include formal models; Elman et al., 1996; Thelen & Smith, 1994).

One consequence of these core ideas is that studies conducted within connectionist and dynamic systems frameworks often involve repeated observations of behavior over time, although the timescale is often relatively short (e.g., within a single session or across sessions separated by a few days or weeks). Because real-time change (i.e., the changes that happen from moment-to-moment) is intimately tied to change at longer timescales, development can be understood by observing change over many trials or epochs within a single experimental session or over several sessions across several days or weeks (for examples, see Samuelson, 2002; Spencer, Vereijken, Diedrich, & Thelen, 2000; Thelen, Corbetta, & Spencer, 1996). Because the work from a GOFCD perspective often does not have an explicit goal of uncovering the mechanisms of change, studies involving repeated observations over time are relatively rare (for a notable exception, see Siegler, 1996). Instead, GOFCD theorists generally use cross-sectional studies to document cognitive changes that occur over relatively long timescales (e.g., months, years). As others have noted, it is very difficult to examine mechanisms of change with cross-sectional studies. Thus, one contribution of the connectionist and dynamic system movements in cognitive development is to put the focus back on repeated observations over time. It must be pointed out that this approach is not new to cognitive development—Heinz Werner (Werner & Garside, 1957) called it microgenesis and Bob Siegler (1996) has strongly advocated and practiced this style of research over the past decade or more (for empirical examples of this approach, see also Oakes & Plumert, 2002; Plumert & Nichols-Whitehead, 1996). It should also be noted that despite their interest in the connections between changes on different timescales, most studies from a dynamic systems perspective examine change over relatively short timescales (such as trials or minutes). Thus, one weakness of many studies adopting a connectionist or dynamic systems framework is that they do not often examine changes over long timescales (Thelen's work on reaching would be an exception, e.g., Spencer et al., 2000; Thelen et al., 1996).

Another key contribution of dynamic systems and connectionist approaches to cognitive development are the tools they provide for studying the emergence of new structures or behaviors (Bates et al., 1998; Thelen, Schöner, Scheier, & Smith, 2001). As is evident from several of the chapters in this book (e.g., Chapters 4, 6, 7, 8, 10, and 11), not only do connectionist and dynamic systems theorists value repeated observations over time, but they also call for studies that seek to understand the processes that give rise to emergent behaviors. Such studies typically include perturbations or supports that change the organism–environment interaction. Usually, this entails manipulations of environmental structure (e.g., changing the salience of location B and noting the effect on infants' reaching for the location A in the A-not-B task; Diedrich, Highlands, Spahr, Thelen, & Smith, 2001), but sometimes it entails manipulation of organism characteristics (e.g., teaching children shape-based categories in the laboratory, presumably changing how they approach the word-learning context in general, and noting the influence of this change on their rate of vocabulary acquisition outside the laboratory; Samuelson, 2000). Observing how manipulations of either the task or the organism changes the resulting behavior leads to a better understanding of the processes that give rise to behavior. Again, this type of approach is not unique to dynamic systems and connectionism. There are many examples from GOFCD and other approaches (for example, see Johnston & Lickliter, Chapter 14) that explicitly engineer changes to either the organism or the environment to gain insight into developmental process (e.g., Oakes & Plumert, 2002; Plumert & Hund, 2001; Robinson, 2005).

As the chapters in this volume also make clear, these two theoretical paradigms have provided new mathematical and computational tools that make it easier to examine organism–environment interactions (see Chapters 1 and 2; Bates et al., 1998). For example, the dynamic field theory allows researchers to directly test how hypothesized processes within the organism (e.g., memory, attention) and inputs from the environment (e.g., salience of perceptual information) interact to produce predictable patterns of behavior (e.g., Schutte, Spencer, & Schöner, 2003). Likewise, connectionist models of learning allow researchers to directly test how patterns of behavior emerge out of the interaction of simple processing units (e.g., Mareschal, Quinn, & French, 2002). Together, the conceptual and computational focus on how behavior emerges from interacting components offers a significant step forward in our understanding of developmental process.

In summary, a major contribution of these two approaches to the field of cognitive development is a focus on the mechanisms of change that lead to the emergence of new behaviors. Hence, any new theory from either a dynamic systems or a connectionist perspective would seek to outline general principles that govern how new ways of thinking or behaving arise from multiple, interacting components. Importantly, this new theory would make explicit this focus on the emergence of new behaviors through such interactions and have as a central goal understanding those interactions rather than describing age changes in cognitive skills. In the next section we evaluate whether this would indeed be a new theory and show how many GOFCD theories have also had this as a goal.

Is This a New Way of Thinking about Developmental Change?

GOFCD has long been interested in change, and much of the research and theorizing in the field of cognitive development is ultimately motivated by understanding developmental change. For example, information-processing theories, which have been criticized for focusing on *what* develops rather than on mechanisms of developmental change (Thelen & Smith, 1994), have described change in terms of an increase in processing speed (Kail, 1986), the number of relations a child can keep in mind (Halford, Wilson, & Phillips, 1998), the capacity and duration of memory stores (Case, 1985), and the availability of strategies for solving problems (Siegler, 1996). Importantly, in each of these examples, mechanisms of changes are provided through increasingly thorough and detailed descriptions of what is developing.

Why then does the emphasis on change in dynamic systems and connectionist approaches seem to be so unique and novel? In the 1980s and 1990s, nativist theories dominated the study of cognitive development. Such theories focused on identifying early emerging capabilities and not on how change occurs. This focus reflects, in part, the influence of Chomsky's (1968) notions that environmental events simply trigger preexisting behaviors (i.e., those specified in biology). The highly publicized and influential work of investigators such as Elizabeth Spelke (Spelke, Breinlinger, Macomber, & Jacobson, 1992; Spelke & Newport, 1998), Karen Wynn (1998), and Rochel Gelman (Gelman & Gallistel, 1978) was aimed at showing high-level cognitive competence at an early age rather than documenting the mechanisms that produce changes in cognitive abilities. This led to the impression that the field of cognitive development had collectively lost an interest in understanding how change occurs.[1]

However, understanding the mechanisms that lead to the emergence of new behaviors has a long history in the study of cognitive development and was central to the theories of Piaget, Gibson, and Vygotsky (a fact that is acknowledged by theorists from both connectionist and dynamic systems perspectives [see Bates & Elman, 2002; Thelen & Bates, 2003]). Piaget, for example, proposed that new mental structures emerge through the dynamic interplay between the child's developing cognitive structures and input from the environment. Similarly, for Gibson, changes in the organism lead to increased sensitivity to environmental structure, which in turn leads to changes in the organism at both neural and behavioral levels. Hence, change emerges out of cyclical organism–environment interactions over both shorter and longer timescales (Gibson, 1988; Gibson & Pick, 2000). For Vygotsky, new skills emerge at times when children are sensitive to social experiences that allow them to try out new ways of thinking and acting, sometimes referred to as the *zone of proximal development* (Wertsch, 1985). The notion that adult guidance must be developmentally appropriate necessarily implies that cognitive change emerges out of the interaction of the child and the social environment. Thus, the idea that behaviors emerge through interactions between the organism and the environment has been central to our understanding of development for quite some time. These historical views on emergence have played an important role in the application of dynamic systems and connectionist frameworks to understanding development.

Importantly, however, ideas about emergence in the theories of Piaget, Gibson, and Vygotsky have largely been lost or ignored over time, even by theorists who came from these traditions. Modern theorists whose work originated in a Piagetian tradition shifted focus from understanding how cognitive structures emerge out of the interaction of the child and the world to an almost exclusive focus on the cognitive structures or concepts themselves (Flavell, 1970). Gibsonian theorists have shifted away from viewing affordances as an emergent property of the interaction between the organism and environment to viewing affordances as objective properties of the environment—"information available about surfaces, places, obstacles, and

[1] It should be pointed out that although Rochel Gelman's views have historically been nativist in flavor, her recent chapter with Lucariello on learning in the third edition of *Stevens' Handbook of Experimental Psychology* (Gelman & Lucariello, 2002) is remarkably non-nativist. Thus, the reference here is to the work in the 1980s and 1990s that contributed to the nativist movement in the field of cognitive development, rather than the most recent writings by Gelman or any of the cited authors.

things as well as about oneself" (Gibson, 2003, p. 293). Likewise, sociocultural approaches to cognitive development have almost exclusively focused on the social environment and have had very little to say about how organism characteristics interact with social structure to produce changes in thinking. We believe these shifts in theoretical perspectives over time have occurred because the notions of *interaction* and *emergence* are very difficult concepts. It is difficult to think about *behavior* or *thinking* as being simultaneously determined by organism characteristics and environmental structure. It is much easier to assign causal priority to one or the other, rather than to both at the same time.

An additional issue is that arguments about the emergence of new ways of thinking and behaving from a GOFCD perspective have been made primarily at a conceptual level. Although this theorizing has led to advances in our understanding of the mechanisms of development, the hypothesized mechanisms have often been difficult to test. One significant contribution of connectionist and dynamic systems theories of cognitive development is to illustrate how interaction and emergence can be simulated with sophisticated formal models. Indeed, one of the most exciting products from this movement is the collection of mathematical models that simulate the emergence of qualitatively different stages of behavior from multiple, interacting components. Although computational models can oversimplify the complexity of cognitive processes, they offer important steps forward in formalizing and testing ideas about cognitive change.

Because interaction and emergence are difficult to conceptualize, many studies of cognitive development from a GOFCD perspective may appear to be merely descriptive at first blush, rather than revealing processes of cognitive change. However, the rich descriptions of cognitive development amassed over the last several decades have actually provided considerable understanding of the mechanisms of change, although the explicit goals of these investigations may not have always been to uncover such mechanisms. Thus, we have made more progress in our understanding of mechanisms of change than we often credit ourselves for, and we have even advanced our understanding of how behavior and structure emerge from organism–environment interactions. This progress has not occurred *despite* a focus on description, but rather is intimately tied to the descriptive success. In part, the two enterprises are linked because the rich description of change strongly constrains the search for explanation. But even more than that, rich description focuses attention on plausible mechanisms and explanatory principles. These mechanisms can then be tested in studies that may themselves seem (on the surface) descriptive. That is, investigators often test explanatory ideas by evaluating predictions regarding descriptive questions, such as how manipulations of task characteristics or environmental input will affect children's behavior or cognitive abilities.

Consider an example of a cognitive change: the emergence of configural, as opposed to featural, processing of visual stimuli. We may simply ask: At what age do people process upright and inverted faces differently (an effect that has been interpreted as a hallmark of configural rather than merely featural processing)? This may seem a supremely descriptive question (although an improvement over a global question such as when can children process faces). Yet, the answer revealed by research asking this descriptive question turned out to be quite complex. On the basis of classic work by Carey and Diamond (1977), we would conclude that a change in processing faces occurs around 10 years of age, and what propels this change to configural processing are prolonged developmental changes—maturational and experiential factors that occur over many years. Evidence that configural processing is in place by 4 to 5 months of age (Bhatt, Bertin, Hayden, & Reed, 2005; Turati, Sangrigoli, Ruel, & De Schonen, 2004), in contrast, led to a very different account of what factors influence a change from featural to configural processing. If configural face processing emerges early, then infants' experience with faces during the period in which the visual system is organized becomes a potentially important factor contributing to that change. Indeed, early restriction of visual experience,

occurring when infants are born with congenital cataracts, has an enduring influence on face processing (Le Grand, Mondloch, Maurer, & Brent, 2004)—an observation that might appear to be merely a descriptive fact but that is also a test of a mechanism.

Even further specificity turns out to be possible. It turns out that there are three types of configural processing, which mature at different rates (Maurer, Le Grand, & Mondloch, 2002). Although some aspects of configural face processing may be present in infancy, others may not reach adult levels until 14 years of age. In addition, effects of early visual deprivation can co-occur with surprising levels of adult plasticity (Maurer, Lewis, & Mondloch, 2005), as may arguably be seen in the advent of configural sensitivity to non-face stimuli (Gauthier & Tarr, 2002). Taken individually, each of these investigations could be characterized as descriptive—they illustrate how the behavior unfolds over time. Taken together, however, the data (at a minimum) strongly constrain the family of possible accounts of developmental mechanisms. This body of work captures an important feature of rich description: Determining the timing of environmental effects and residual plasticity allows us to move beyond minimal explanations of developmental change (i.e., when and how adult competence is acquired) to formulating sophisticated (and explanatory) accounts of how environmental inputs and neural substrates interact to induce developmental change.

In our view, the (more or less explicit) goal of work conducted from a variety of GOFCD perspectives has been to understand how such interactions contribute to the emergence of new behavior. Examples from our own work will serve as illustrations of this approach. Ours are not the only programs of research that exemplify this trend, but they illustrate how studies that do not have the same explicit goals of dynamic systems and connectionism can reveal a great deal about emergence and interactions. Importantly, the focus of many of these studies was revealing the mechanisms of developmental change—or testing hypotheses about how such mechanisms constrain children's emerging behaviors. Moreover, these programs of research, although not explicitly adopting a dynamic systems framework or a connectionist framework, are aimed at uncovering how child–environment interactions operate to allow new behaviors to emerge.

For example, Oakes and her colleagues have studied infants' categorization from an information-processing perspective. This approach focuses on how basic cognitive processes such as attention and memory operate to produce categorization behavior. Their work, which was also influenced by Vygotskian notions of the context dependency of cognitive abilities, has shown that infants' categories are highly flexible and dependent on interactions between the developmental state of the infant (i.e., age) and the task (see Oakes, Horst, Kovack-Lesh, & Perone, 2008). At 10 months of age, infants respond to a category of *people* that excludes other land mammals (such as horses) in an object-examining task but not in a less structured sequential-touching task (Oakes, Plumert, Lansink, & Merryman, 1996). By 13 months of age, infants attend to this distinction even in the less structured task (Oakes et al., 1996). Thus, whether infants recognize the significance of the distinction between people and animals is determined both by infant age and how the items within and across categories are encountered. Oakes and Ribar (2005) observed a similar effect for 4- to 6-month-old infants' attention to the category of dogs versus cats in visual familiarization tasks. At 4 months of age, infants responded to this distinction only when the task minimized memory and other cognitive demands, whereas at 6 months of age, infants responded to the distinction even in a more cognitively demanding familiarization task. The point is that, in each of these investigations, infants' ability to respond to a particular category is a function of the interaction between their cognitive abilities (such as their ability to encode and recall individual items) and the structure of the task. In demanding tasks, infants have difficulty recognizing subtle distinctions (such as that between dogs and cats). In tasks that place fewer demands on infants' cognitive abilities, or as those abilities develop, infants can more easily recognize subtle distinctions between categories. Infants' recognition of the category, therefore, is emergent: it resides in the interaction between their abilities and the task context. They may have knowledge and past experience relevant to recognizing the category in the moment, but their behavior in the experimental task reflects more than this existing knowledge and past experience. Similarly, infants clearly have the ability to form narrowly defined categories even at 4 months of age, but whether they actually form such categories at any given moment is complexly determined by the interaction of their existing knowledge, the cognitive abilities they use to form such categories, and the context in which they are forming those categories. Although not motivated by connectionist or dynamic systems theories of categorization, these findings are consistent with these approaches, and future work may represent a blending of GOFCD (e.g., information-processing approaches) and these new approaches to development.

In a very different domain, Plumert and her colleagues have studied categorical bias in memory for location by combining ecological and information-processing perspectives. The aim of this work was to discover how categorical bias emerges out of the interaction of the cognitive system and the available environmental structure (for a review, see Plumert, Hund, & Recker, 2007). Categorical bias refers to the tendency to remember locations in the same spatial group (e.g., same quadrant of a room) as closer together than they really are. The work by Plumert and her colleagues reveals the same general pattern as observed by Oakes and her colleagues: categorical bias is a function of developmental level (i.e., age) and environmental structure. When asked to learn the locations of 20 miniature objects in a large open box, memory for those locations is determined not only by age (e.g., 7-year-olds have less accurate memories than do adults) but also by task structure, such as the cues available for organizing the locations into groups during learning (Hund & Plumert, 2003; Hund, Plumert, & Benney, 2002; Plumert & Hund, 2001), by how long participants are required to maintain memory of locations over time (see Hund & Plumert, 2002, 2005), and by the cues available at test (Plumert & Hund, 2001). Importantly, this work demonstrates that we cannot explain patterns of categorical bias by referring only to task structure (e.g., presence or absence of boundaries) or by referring only to developmental differences in the cognitive system (e.g., strategic encoding of spatial groups). These studies have consistently shown that all age groups exhibit categorical bias under some task conditions but not under others. For example, adults always show significant categorical bias when at least one cue is available during learning, but they do not show bias when no cues are available during learning. Thus, it is impossible to predict categorical bias by referring to age alone. Likewise, these studies have consistently shown that children and adults differ in how they respond to cues for organizing the locations into groups, such as visible boundaries, spatiotemporal experience, or object relations. Clearly, children and adults extract different things from their experience with these tasks even though the task structure is identical for all participants. These variations in how the same age group responds to different task structure and how different age groups respond to the same task structure support the idea that categorical bias emerges out of the interaction of the cognitive system and the task structure.

A final example from work by Newcombe and her colleagues also illustrates how spatial thinking emerges out of the interaction of the child and the task. In a task in which children are required to find a hidden object after being disoriented (i.e., they are turned around with closed eyes), Newcombe and her colleagues have found that children's use of geometric properties (e.g., relative length of walls defining enclosures) and featural information (e.g., colors or markings on surfaces) to reorient is not solely a function of the child's underlying competence or developmental level. Rather, the exact mix of features children use to reorient depends on a confluence of factors such as the reliability, variability, and usefulness of the sources of information and the certainty with which the sources of information have been encoded, which contrasts

with the nativist modular view of the origins of spatial knowledge. According to this view, various sources of spatial information are processed independently in separable cognitive processing units (e.g., Wang & Spelke, 2002). On the basis of the facts that (1) a wide variety of animal species can use geometric properties of enclosing spaces (e.g., relative length of walls defining enclosures) to reestablish spatial orientation after being disoriented (Cheng, 1986; Hermer & Spelke, 1996; for a review, see Cheng & Newcombe, 2005) and (2) both rats and human children fail to use disambiguating, nongeometric (i.e., featural) information (e.g., colors and markings on surfaces), some investigators have suggested that geometric processing constitutes a specialized cognitive module that is impenetrable to nongeometric information, even when that information has been processed (Gallistel, 1990). Moreover, some researchers have argued that this module is innately available (Hermer & Spelke, 1996).

Newcombe and Ratliff (2007) proposed, in contrast, that the existing data on integration of featural and geometric information can be best explained by an adaptive combination approach in which the likelihood of using the two kinds of information varies depending on factors such as uncertainty, cue validity, and cue salience (e.g., Ernst & Banks, 2002; Huttenlocher, Hedges, & Duncan, 1991). Newcombe and her colleagues have documented the conditions under which children use the colors of walls to find hidden objects, thereby showing that use of geometric versus featural information is not an all-or-none phenomenon at a given age. For example, younger children are more likely to use featural information in large rooms and under conditions in which they can move about the space (Newcombe & Ratliff, 2007). These differences in performance of children of the same age under different task conditions are difficult to explain from a modularity perspective. Hence, this program of research has provided the kind of data needed to differentiate between opposing theoretical views of the origins of fundamental spatial skills.

In summary, these three programs of research—by Oakes and her colleagues, Plumert and her colleagues, and Newcombe and her colleagues—were not motivated by a connectionist or dynamic systems theory of development and yet, nevertheless, examined the emergence of behavior as a function of multiple, interacting components. The research described here is compatible with connectionism and dynamic systems views, but has its roots in information-processing, Piagetian, Gibsonian, and Vygotskian perspectives. Some of this work may provide evidence for the kinds of mechanisms of change proposed by connectionist and dynamic systems theories of development—and could indeed be the foundation for future modeling and theorizing from these perspectives. The important point here is that ideas central to connectionist and dynamic systems approaches to development are compatible with (at least some) GOFCD approaches Although connectionism and dynamic systems approaches may provide new tools for examining these types of interactions in development, as may other modeling approaches, it is important to remember that these tools would all be used to support and further specify conclusions drawn from studies conducted from within GOFCD approaches.

A Closer Look at Explanations of Change: How Do Dynamic Systems and Connectionist Theorists Explain Change on the A-not-B and the Balance Scale Tasks?

In this section we will further discuss the general approaches of dynamic systems theory and connectionism by examining specific examples of how these approaches have been used to explain developmental change in two domains: the A-not-B error and the balance scale (or balance beam) task. These two domains provide particularly good contexts for understanding the contributions of these approaches because they are classic problems that have been studied from the perspectives of GOFCD, connectionism, and dynamic systems theory. (Note that a formal dynamic systems model of the balance scale problem has not yet been proposed; van der Maas and colleagues have developed a cusp model of the balance beam task [see Chapter 15] that derives from dynamical principles but is not a pure dynamic systems model.) Thus, these domains allow us to consider dynamic systems and connectionist explanations of well-understood cognitive problems, as well as to consider how these approaches are (or are not) an advance over previous, more traditional cognitive development approaches.

The Case of the A-not-B Error

In his classic work on the development of the understanding of object permanence during the sensorimotor period, Piaget noted that toward the end of the first year of life infants exhibit somewhat odd behavior toward hidden objects. Although infants can retrieve a hidden object by 8 or 9 months of age (when they enter stage IV of Piaget's sensorimotor period), they make the A-not-B error. In the prototypical error, infants observe an attractive object hidden underneath a cloth, and they successfully retrieve the object. After several such hidings (repeatedly in the same location, location A), the experimenter hides the object (while the infant watches) under a different cloth (or location B). Infants in Piaget's stage IV of sensorimotor development (from approximately 8 to 12 months of age) search not where they have just observed the object hidden, but rather where they have successfully uncovered it on previous trials. In other words, after seeing the object hidden at location B, infants search for the object in location A.

This puzzling behavior has long been the focus of study in infant cognitive development. A large number of studies have been conducted to replicate the conditions under which infants make this error and to understand why infants fail to search in the location they have just seen the object hidden. Piaget's classic interpretation is that this behavior indicates an incomplete understanding of object permanence. According to Piaget, the infant "seems to reason as if the place where the object was found the first time remains where he will find it when he wants to do so" (Piaget, 1954, pp. 46–47) even though the infant directly observes the object hidden in the new location! The infant has developed awareness that the object can be retrieved even when it is out of sight, but the infant does not fully understand the relation between the hiding place and where the object can be retrieved. Rather, according to Piaget, the infant conceives of the object *only* in the first place that he or she saw the object hidden and successfully retrieved it.

There have been many explanations for the A-not-B error, ranging from an appeal to innate or early emerging conceptual abilities (Baillargeon, 2004) to a discussion of the development of neuroanatomical structures responsible for inhibiting prepotent responses (Diamond, 1991). The dynamic systems and connectionist explanations of this behavior grew out of these previous theories (and indeed rely on the large corpus of data that has been collected examining the conditions under which the A-not-B error is obtained). The dynamic systems and connectionist explanations differ from those that came before them in that they focus directly on the error as an emergent product of the development of infants' underlying cognitive structures and the task demands. Previous explanations focused on what the error reveals about the development of the type of underlying representations. For example, context effects in infants' performance were viewed as masking infants' underlying competence, and as a result, it was proposed that the A-not-B error could be overcome by using tasks that more effectively tapped this competence (Baillargeon & Graber, 1988).

In contrast, dynamic systems and connectionist theories of the A-not-B error provide explanations of how the error emerges and changes in real time (i.e., in the context of a particular trial or experimental session) and how that emergence is a product of the task factors (e.g., salience of a particular hiding event) interacting with developmental changes in memory abilities, motor abilities, and other factors. For example, the dynamic systems account is that the error is actually an error in reaching, determined by the competition between the transient memory of the hiding event and the longer-term motor memory for past reaches (Smith, Chapter 4; Smith & Thelen, 2003; Thelen et al.,

2001). In clever and systematic studies, Smith, Thelen, and their colleagues have shown that the incidence of the error can be increased by increasing the strength of the motor memory for reaches at location A (e.g., increasing the number of reaches at location A) and decreasing the salience of the transient memory for the hiding event at location B (e.g., making location B more similar to location A). Furthermore, the incidence of the error can be decreased by reducing the strength of the motor memory (e.g., changing the infant's posture or arm weights before reaching on B-trials) or increasing the salience of the hiding event at location B (e.g., making location B very different from location A; see Smith, Chapter 4; Smith & Thelen, 2003). These types of manipulations are explicitly designed to perturb the components hypothesized to play a role in infants' behavior in the A-not-B task. In so doing, they reveal how organism–environment interactions give rise to the A-not-B error.

For Munakata and Morton's connectionist model of the A-not-B error, the strength of the underlying representation for the hiding event at location A competes with the underlying representation for the hiding event at location B. The system creates an *active representation* for the more recent hiding event (the working memory–like component) and a *latent representation* for previous hiding events (the long-term memory–like component; see Morton & Munakata, Chapter 7; Munakata, 1998; Munakata, Morton, & Stedron, 2003). Infants' representation of the location of the object is graded due to competition between latent and active memory for the hiding event. As was true for Smith and Thelen's dynamic systems model of the A-not-B error, early in development the transient memory for the hiding event at location B cannot compete with the stronger memory for the hiding event at location A that was built up over time. With development, the active memory for the hiding event at location B becomes more effective at competing, and as a result, the error is reduced. Moreover, Munakata and Morton can evaluate how this process works in real time by examining how connection weights change as the simulated child reaches several times to location A and then sees the object hidden at location B.

In both cases, online dynamics in context are the cause of the behavior. Both theories have received significant support, with empirical tests confirming predictions made by each model. Clearly, therefore, the two approaches are similar in many ways. They both describe the behavior in terms of the competition between longer term, more established memories and shorter term, more transient memories. This raises the central question of this volume: Are these actually separate theories, or are they two variations of the same unified theory? There are important differences in the details of the theories: a key component of Munakata and Morton's model (Chapter 7; Munakata, 1998; Munakata et al., 2003) is the internal representation (in terms of connection weights and recurrence) of the hiding events, whereas the hiding event and object are not represented in any obvious way in the dynamic systems theory of Smith and Thelen (Smith, Chapter 4; Smith & Thelen, 2003; Thelen et al., 2001). Similarly, the dynamic systems account is embodied, with the infant's memory for his or her own action playing an important role in behavior. The connectionist model does not have an obvious component for memories for actions carried out by a real body in actual space.

Are these approaches simply relabeling the same components? Perhaps the accounts of the A-not-B error are more similar than they are different. Moreover, these accounts have commonalities with more traditional ways of discussing the issues, such as in the discussion of errors relative to competing spatial frameworks that may each be used to code the locations of objects (Newcombe, 2001; Newcombe & Huttenlocher, 2000). Thus, this comparison may not be the best one for understanding the differences between the two approaches. But, considering these two approaches to the A-not-B task may be a good means of understanding what connectionism and dynamic systems have to offer beyond GOFCD. Although these two approaches to this task have similarities to some GOFCD theories of the error (Newcombe, 2001), clearly none of the approaches appeal to the qualitative changes in mental representation characteristic of a Piagetian approach or to innate competencies advocated by nativists. Thus, although the two explanations clearly derive from different theoretical stances—and as a result they have incorporated different components into their models and have argued for roles of different aspects of development in this error—they may have more in common than not. It may be that the truth is a blending of these two approaches, involving embodied cognition in which objects and locations are represented in long-term memory and actions are carried out by physical bodies in real space. Indeed, as is clear from several chapters in this book, in several domains, theorists are blending connectionism and dynamic systems to create new models of development (see Chapters 10 and 11). What is important for the present discussion is that both of these models of the A-not-B error have attempted to understand the error in terms of the real-time dynamics of the task combined with changes over a longer timescale.

The Case of the Balance Scale Task

In a very different series of observations, Inhelder and Piaget (1958) documented children's responses to the *balance scale task*. In this task, children are presented with a balance scale and are asked to predict whether the scale will balance or tip when different configurations of weights are placed on each side of the fulcrum. To correctly solve this problem, children must consider not only the amount of the weight placed on each side, but the distance of the weights from the fulcrum as well. Based on the children's performance on this task, Inhelder and Piaget argued for qualitative changes in children's thought. Children with concrete, operational approaches were unsuccessful at solving this problem; they typically believe that weight is the only relevant factor. Children who had attained formal operations (and therefore were capable of propositional thought and hypothetical-deductive reasoning), in contrast, could successfully combine the two relevant variables in an accurate way, implicitly or explicitly computing torque.

As with the A-not-B task, there have been subsequent explorations of children's performance on the balance scale task from perspectives other than Piaget's. A well-known series of studies by Siegler (1976, 1981), adopting an information-processing approach to cognitive development, used rule-assessment methodology to delineate a succession of four modes of reasoning on balance scale problems, beginning with children 5–6 years of age. Importantly, Siegler's work clearly addressed questions about mechanisms of development; for instance, he showed that it was possible to diagnose which children would respond to environmental input regarding how the balance scale worked.

Subsequent work on the balance scale problem has, for the most part, fit within the GOFCD tradition. There has been discussion of issues such as whether rule-assessment methodology should be supplanted or supplemented by other techniques, such as latent class analysis (Jansen & van der Maas, 2002), and whether children younger than 5 years can also exhibit systematic (albeit one-dimensional) reasoning about these problems (Halford, Andrews, Dalton, Boag, & Zielinski, 2002). From these studies, a rich portrait of developmental change on this task has emerged, including an interesting suggestion that some aspects of change are abrupt and stage-like, whereas, at other periods, various rules or strategies coexist as children experiment with solutions (Jansen & van der Maas, 2002).

There have also been efforts to model children's behavior in this task. Some researchers have used connectionist approaches (e.g., McClelland, 1989, 1995; Shultz, Mareschal, & Schmidt, 1994), while others have not. Dynamic systems theorists have not dealt with the balance scale problem, arguably because thinking about the problem is a more symbolic and logical task than the A-not-B task and is also less intimately involved with motor experience. However, van der Maas and his colleagues have developed a cusp model of children's performance on the

balance scale task that is derived from catastrophe theory and has some overarching points of contact with dynamic systems thinking (Jansen & van der Maas, 2001). These models have been less successful in making novel predictions and stimulating new research than connectionist or dynamic systems models of A-not-B, and, as argued at length by van der Maas and Raijmakers (Chapter 15), these models do not even do a complete job of accounting for known empirical phenomena. However, as in the case of models of the A-not-B error, such models represent a hybrid or mix of concepts from different traditions. Interestingly, van der Maas recently offered an ACT–R model of children's performance on the balance scale task (see van der Maas & Raijmakers, Chapter 15; van Rijn, van Someren, & van der Maas, 2003), which involves the postulation of explicit rules. This model seems to do the best job so far of capturing how children really behave. Although van der Maas and Raijmakers remain optimistic regarding the potential of neural networks with nonlinear properties, they suggest that more symbolic approaches seem to work better in the short run.

Overall, the history of dynamic systems and connectionist approaches to the balance scale problem suggests caution about how easy it will be to apply the techniques used so far in these traditions to higher cognitive functioning (van Geert [1998] provided a conceptual dynamic systems model of higher level cognitive processing, but there are no pure formal dynamic systems models of higher level cognitive processes). GOFCD has made good progress in delineating the progression of children's behavior in this realm and in suggesting reasons for developmental change that may differ at with age, including change in the encoding of relevant information, working memory, experimentation with strategies, and responses to direct instruction. It remains to be seen how successful nonlinear, dynamic models will be in explaining development in such domains and how these models will combine symbolic models with ideas from connectionism and dynamic systems approaches.

Can Dynamic Systems and Connectionism Evade Classic Issues Facing the Study of Cognitive Development?

In this chapter, we have examined the contributions of dynamic systems and connectionist viewpoints and have argued that many of these contributions are not completely new ideas in the study of cognitive development. Rather, dynamic systems theory and connectionism bring ideas such as interaction and emergence to the forefront in our explanations of developmental change and provide formal models of these conceptions of development, therefore playing an important role in shaping how we think and talk about development. An important issue is whether these new frameworks avoid the problems of many previous theories of cognitive development; that is, how do these frameworks address the criticisms that have been leveled against many different theories of cognitive development? If dynamic systems and connectionism frameworks are in a position to replace traditional GOFCD frameworks, they must overcome those criticisms. We have identified at least four problems characteristic of many theories of cognitive development—some of these problems are solved by dynamic systems and connectionist approaches to cognitive development, while others are problematic for these approaches just as they are for GOFCD approaches.

First, all models of development must grapple with the difficult problem of characterizing the environment and the actual nature of the input and feedback that children receive. This is a central problem that was most clearly articulated and studied from an ecological perspective but was later minimized by the information-processing approach. The computational models developed from connectionist and dynamic systems approaches help bring the environment back into clear focus because they must describe the input and feedback the models receive. However, as was discussed in the section on the A-not-B error, it is not always transparent why a particular input to the model represents real, physical input in the environment. For instance, in Munakata's (1998) connectionist model of the A-not-B error, there are three input nodes, A, B, and C, corresponding to three potential hiding locations. However, it is not clear whether those nodes must refer to location (e.g., is the spatial relation between locations represented, and does it matter?) or whether they could equally well represent other features that differentiate the locations (e.g., colors of lids). When comparing models of the A-not-B error, we made the argument that these two models may be simply using different labels for essentially the same input. This is not characteristic of all connectionist and dynamic systems models, however. For instance, Mareschal and his colleagues (Mareschal, French, & Quinn, 2000) found that variability in the head and face regions of dog and cat stimuli predicted both how connectionist models and 3- to 4-month-old infants learned the categorical distinction between dog and cat. French et al. (2002) found that by blurring the visual input in a way that mimicked the visual acuity of young infants, a connectionist model would respond to the same kinds of categorical distinctions as infants do. Similarly, Smith and her colleagues (Yoshida & Smith, 2001) examined the structure of nouns to which children from different language environments are exposed and how those different kinds of inputs help create biases in children's assumptions about the referents of new words. Clearly, characterizing the nature of the input is extremely difficult. However, as recently pointed out by Saffran (2008; Saffran, Reek, Niebuhr, & Wilson, 2005), we cannot really understand the learning mechanism without understanding *what* is being learned.

A second problem that faces models of development is how to characterize the start and end states (and indeed, determining whether or not there is an end state) of the cognitive system with respect to a given ability. At minimum, a model must accurately characterize the cognitive system at the entry point of the period of development under study. Formal models from dynamic systems and connectionist perspectives accomplish this on one level because they must be very explicit about the starting state of the system (e.g., determining the weight or value of some parameter that refers to strength of memory trace). But, such determinations often seem arbitrary (e.g., how does a parameter value relate to a child's actual working memory capacity), and it is not often clear how they map onto actual developmental starting states in the child. In particular, often it is not clear where those start states came from (i.e., what developmental events occurred beforehand to create the starting state of the system), or whether and when development of a system ends. Some might argue that this is not the goal of these models, but the initial state of the system (e.g., the limited motoric and perceptual abilities of the newborn infant) places important constraints on how the system operates and, thus, what kinds of organism–environment interactions are possible.

Third, theories that focus on emergence must attempt to explain the nature of organism–environment interactions. Clearly, one advantage to connectionist and dynamic systems approaches is that they have brought the discussion of change to the forefront—in some sense, connectionist and dynamic systems theories are defined by their approach to emerging structure and their focus on understanding that emergence. In this way, these frameworks appear to address the criticism of GOFCD theories of development that such theories are merely descriptive. Although we believe that many cognitive developmentalists have indeed been interested in mechanisms of change (and have collected data relevant to understanding those mechanisms), we applaud the dynamic systems and connectionist frameworks for making this discussion explicit and for adding tools to our battery of methods for understanding change.

Finally, development is characterized by variability, and theories of cognitive development must come to terms with the high levels of variability that emerge with developmental change and task variation. For many, such variability is a nuisance; the goal is to develop sensitive tasks that eliminate sources of extraneous variability and reveal children's true competence. Dynamic systems and connectionist models embrace variability in behavior and use variability over time or with task variations as ways of explaining developmental changes in organism–environment interactions (see also Siegler, 1996). In fact, for the dynamic systems perspective, variability is a necessary precursor of change; systems must go through some sort of instability in order to change. Importantly, dynamic systems theory and connectionism provide an overall framework for thinking about the role of the environment or task, but understanding how specific tasks operate at specific points in development is a problem that can only be addressed by continued empirical and theoretical work in the field.

Conclusion

Is this a new unified theory of development that represents a radical departure from good old-fashioned cognitive development? We don't think so. We think that, simply, but not at all trivially, this unified theory of development has helped to refine the explanations of development that have emerged in the field and has helped to enhance our search for the principles of emergence. Perhaps most importantly, these new approaches have provided us with new tools that will allow us to explore more deeply interactions and emergence in development. These new tools, in turn, have shifted the focus in our thinking about development to those processes. Thus, these new approaches have been and will continue to be important in shaping how we collectively think about developmental change. But, it is important to remember that the core notions underlying hypothesized mechanisms of developmental change have played important roles in our conceptualization and study of cognitive development for a long time and that dynamic systems theory and connectionism are not immune to the criticisms that have been raised about GOFCD theories.

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