Twenty Years and Going Strong: A Dynamic Systems Revolution in Motor and Cognitive Development

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ABSTRACT—*This article reviews the major contributions of dynamic systems theory (DST) in advancing thinking about development, the empirical insights the theory has generated, and the key challenges for the theory on the horizon. The first section discusses the emergence of DST in developmental science, the core concepts of the theory, and the resonance it has with other approaches that adopt a systems metatheory. The second section reviews the work of Esther Thelen and colleagues, who revolutionized how researchers think about the field of motor development. It also reviews recent extensions of this work to the domain of cognitive development. Here, the focus is on dynamic field theory, a formal, neurally grounded approach that has yielded novel insights into the embodied nature of cognition. The final section proposes that the key challenge on the horizon is to formally specify how interactions among multiple levels of analysis and across multiple time scales create developmental change.*

KEYWORDS—*motor development; cognitive development; dynamical systems theory; developmental systems theory; neural networks*

Twenty years is a long time for an individual scientist, but a relatively brief period for a scientific theory. This tension of time scales underlies our evaluation of dynamic systems theory (DST) and development in this article. In particular, we take the long view, acknowledging that DST is in its infancy. From this vantage point, the differential success of individual variants of DST is normal; most critical is the evaluation en masse. In our view, DST has been extremely successful on the whole—in some cases, "revolutionary." In the sections that follow, we explain our optimism, grounding our evaluation both in past accomplishments and in future prospects. Time will tell whether the word *revolution* reflects more than just our optimism.

WHAT ARE THE GREATEST CONTRIBUTIONS OF THE DST APPROACH TO DEVELOPMENT OVER THE PAST 20 YEARS?

Recent decades have seen a shift in thinking about development. Instead of characterizing *what* changes over development, there is a new emphasis on the *how* of developmental change (see Elman et al., 1997; Plumert & Spencer, 2007; Thelen & Smith, 1994). These explorations have revealed that simple notions of cause and effect are inadequate to explain development. Rather, change occurs within complex systems with many components that interact over multiple time scales, from the second-to-second unfolding of behavior to the longer time scales of learning, development, and evolution (see Christiansen & Kirby, 2003).

The introduction of DST into psychology has spurred this new way of thinking about change. Critically, DST did not emerge in isolation. Rather, it is one contributor to a broad shift in developmental science toward a systems metatheory (see Lerner, 2006) that encompasses a wide range of work from developmental systems theory (e.g., Gottlieb, 1991; Kuo, 1921; Lehrman, 1953), sociocultural and situated approaches (e.g., Baltes, 1987; Bronfenbrenner & Ceci, 1994; Elder, 1998), ecological psychology (e.g., Adolph, 1997; Gibson & Pick, 2000; Turvey, 1990), and connectionism (e.g., Bates & Elman, 1993; Elman, 1990; Rumelhart & McClelland, 1986).

Within this family of work, confusion can arise in the distinction between two DSTs: dynamic systems theory and developmental systems theory (see Fox-Keller, 2005). These

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perspectives share many core principles; we can distinguish them by their histories and foci. Developmental systems theory was based on early work at the intersection of behavioral development, biology, and evolution by pioneers such as Lehrman and Kuo (see Ford & Lerner, 1992; Gottlieb, 1991; Griffiths & Gray, 1994; Kuo, 1921). This approach has focused on how development unfolds through an epigenetic process with cascading interactions across multiple levels of causation, from genes to environments (Johnston & Edwards, 2002). DST, in contrast, developed from the mathematical analysis of complex physical systems (Gleick, 1998; Smith & Thelen, 2003). Consequently, this approach provides a way of mathematically specifying the concepts of systems metatheory while supporting the abstraction of these concepts into more cognitive domains (see Spencer & Schöner, 2003). Thus, the aim of many dynamic systems approaches is to formally implement developmental processes to shed light on how behavior changes over time (Spencer, Blumberg, McMurray, Robinson, Samuelson, & Tomblin, 2009; van der Maas & Dolan, 2006; van der Maas & Molenaar, 1992; van Geert, 1991, 1998; Warren, 2006). In this sense, DST and developmental systems theory share an emphasis on the step-by-step processes and multilevel interactions that shape development.

A key characteristic of systems metatheory that both approaches share is the rejection of classical dichotomies that have pervaded psychology for centuries: nature versus nurture, stability versus change, and so on (for discussion, see Spencer, Blumberg, et al., 2009). In their place, systems metatheory takes the "organism in context" as its central unit of study, an inseparable unit in which it is impossible to isolate the behavioral and developmental states of the organism from external influences. Furthermore, behavior and development are *emergent* properties of system-wide interactions that can create something new from the many interacting components in the system (see Munakata & McClelland, 2003; Spencer & Perone, 2008; Thelen, 1992).

It is often helpful to consider historical change through the lens of contrast. According to Lerner (2006), systems metatheory has supplanted other influential metatheories, but which ones? To answer this, we conducted a survey of the fourth through sixth editions of the *Handbook of Child Psychology: Theoretical Models of Human Development*. These editions span more than 20 years in developmental psychology (from 1983 to 2006). Although this book is just one indication of how the field is changing, our survey revealed that four theoretical viewpoints have disappeared from the *Handbook* over time: nativism, cognitive and information processing, symbolic approaches, and Piaget's theory. Of course, scholars still actively pursue all of these perspectives. It is notable, however, that they have something in common—an attempt to carve up behavior and development into parts (broad parts like nature vs. nurture, specific parts like cognitive modules, or temporal partitions such as stages of processing or stages of development). Systems metatheory rejects this inherent partitioning.

Within the broad class of theories that make up systems metatheory, a central challenge is to examine what each perspective contributes. DST has had a particularly strong influence, bringing several critical concepts into mainstream developmental science. The first concept is that systems are self-organizing. Complex physical systems (such as the human child) comprise many interacting elements that span multiple levels from the molecular (e.g., genes) to the neural to the behavioral to the social. Within the DS perspective, organization and structure come "for free" from the nonlinear and time-dependent interactions that emerge from this multilevel and high-dimensional mix (e.g., Prigogine & Nicolis, 1971). Thus, there is no need to build pattern into the system ahead of time because the system has an intrinsic tendency to create pattern. This gives physical systems a creative spark that we contend is central to the very notion of development—development is fundamentally about the emergence of something qualitatively new that was not there before.

Of course, the notion of qualitative change over development is not unique to DST (see, e.g., Gottlieb, 1991; Munakata & McClelland, 2003; Piaget, 1954; von Bertalanffy, 1950). But we contend that DST clarifies the distinction between quantitative and qualitative changes (see Spencer & Perone, 2008; van Geert, 1998). According to DST, qualitative change occurs when there is a change in the layout of attractors, or special "habitual" states around which behavior coheres: When a new attractor appears, there is a qualitative change in the system. Although qualitative change can be special—it can reflect the emergence of something new that was not there before—it is not in opposition to quantitative change. Rather, quantitative changes in one aspect of the system can give rise to qualitatively new behaviors. This is one example where a classic dichotomy withers away in the face of a formal, systems viewpoint.

One of the historical challenges in defining qualitative and quantitative change is that changes occur over multiple time scales. For instance, a skilled infant can go from a crawling posture to a walking posture within a matter of seconds, but how is this "on-the-fly" transition related to the more gradual shift in the likelihood of crawling versus walking that unfolds across months in development (see Adolph, 1997)? In particular, it can be difficult to specify when the infant "has" walking, why walking comes and goes in different situations, and what drives this change over time. Again, DST has a unique perspective on these challenges. There is no competence versus performance distinction in DST (see Thelen & Smith, 1994); rather, the emphasis is on how people assemble behavior in the moment in context. Critically, because DST integrates processes over multiple time scales, it can explain why behavioral attractors—which form in real time—can emerge and become more likely over learning and development (for discussion, see Spencer & Perone, 2008).

Another issue that researchers have directly examined using DST is the concept of "soft assembly." According to this concept, behavior is always assembled from multiple interacting components that can be freely combined from moment to moment on the basis of the context, task, and developmental history of the organism. Esther Thelen talked about this as a form of improvisation in which components freely interact and assemble themselves in new, inventive ways (like musicians playing jazz). This gives behavior an intrinsic sense of exploration and flexibility, issues that Goldfield, Kay, and Warren (1993) have examined formally.

This characterization of behavior and development has led to an additional insight about the embodied nature of cognition. In particular, if behavior is softly assembled from many components in the moment, then the brain is not the "controller" of behavior. Rather, it is necessary to understand how the brain capitalizes on the dynamics of the body and how the body informs the brain in the construction of behavior. This has led to an emphasis on embodied cognitive dynamics (see Schöner, 2009; Spencer, Perone, & Johnson, 2009), that is, to a view of cognition in which brain and body are in continual dialogue from second to second.

A final strength of the DS approach is that it has generated a host of productive tools, including rich empirical programs (Samuelson & Horst, 2008; Smith, Thelen, Titzer, & McLin, 1999; Thelen & Ulrich, 1991; van der Maas & Dolan, 2006), formal modeling tools that can capture and quantify the emergence and construction of behavior over development (such as growth models, oscillator models, dynamic neural field models), and statistical tools that can describe the patterns of behavior observed over development (Lewis, Lamey, & Douglas, 1999; Molenaar, Boomsma, & Dolan, 1993; van der Maas & Dolan, 2006). These tools have enabled researchers to move beyond the characterization of what changes over development toward a deeper understanding of how these changes occur.

WHAT IS YOUR CRITICAL EVALUATION OF THE PROGRESS OF DS-INSPIRED EMPIRICAL RESEARCH?

DST has led to a revolutionary change in how people think about motor development, and this type of revolutionary thinking is starting to take hold in cognitive development as well. We review the basis for this optimistic assessment next. Note that we focus on motor and cognitive development because these are our "home" domains. We will leave it to the other authors in this issue to evaluate other fields.

The dominant view of motor development for much of the 20th century was that the development of action occurred in a series of relatively fixed motor milestones. The emphasis was on normative development, the concept of motor programs that controlled action, and a sequence of milestones that was largely under genetic or biological control (for review, see Adolph & Berger, 2006). The landscape has shifted dramatically in the last 20 years, thanks in large part to the work of Thelen (as well as other systems thinkers, most notably, Gibson, 1988; see Adolph & Berger, 2006). Today, the field views motor development as emergent and exploratory with a new emphasis on individual development in context. Although this revolution in thinking was spurred by DS concepts, it was also driven forward by a wealth of empirical research.

For instance, Thelen conducted a now-classic set of studies investigating the early disappearance of the stepping reflex. Thelen's early work on stepping revealed that the coordination patterns that underlie stepping and kicking were strikingly similar. The puzzle was that newborn stepping disappeared within the first 3 months, whereas kicking continued and increased in frequency. To explain the disappearance of stepping, several researchers had proposed that maturing cortical centers inhibit the primitive stepping reflex or that stepping was phylogenetically programmed to disappear (e.g., Andre-Thomas & Autgaerden, 1966).

To probe the mystery of the disappearing steps, Thelen conducted a longitudinal study that focused on the detailed development of individual infants. Thelen, Fisher, and Ridley-Johnson (1984) found a clue in the fact that chubby babies and those who gained weight fastest were the first to stop stepping. This led to the hypothesis that it requires more strength for young infants to lift their legs when upright (in a stepping position) than when lying down (in a kicking position). To test this idea, Thelen and colleagues conducted two ingenious studies. In one, they placed small leg weights on 2-month-old babies, similar in amount to the weight they would gain in the ensuing month. This significantly reduced stepping. In the other, they submerged older infants whose stepping had begun to wane in water up to chest levels. Robust stepping now reappeared. These data demonstrated that traditional explanations of neural maturation and innate capacities were insufficient to explain the emergence of new patterns and the flexibility of motor behavior.

Since this seminal work, Thelen and her colleagues have intensively examined the development of alternating leg movements (Thelen & Ulrich, 1991), the emergence of crawling (Adolph, Vereijken, & Denny, 1998), the emergence of walking (e.g., Adolph, 1997; Thelen & Ulrich, 1991), and the development of reaching (Corbetta, Thelen, & Johnson, 2000; Thelen, Corbetta & Spencer, 1996; Thelen et al., 1993). In all cases, these researchers have shown that new action patterns emerge in the moment from the self-organization of multiple components. The stepping studies elegantly illustrated this, showing how multiple factors cohere in a moment in time to create or hinder leg movements. Furthermore, these studies illustrate how changes in the components of the motor system over the longer time scale of development interact with real-time behavior.

In summary, DS concepts have led to a radical change in the conceptualization of motor development. But what about cognition? There have been a variety of DS approaches to cognitive development. For instance, researchers have used the concepts of DST to study early word learning (e.g., Samuelson, Schutte, & Horst, 2008), language development (e.g., van Geert, 1991), the development of intelligence (e.g., Fischer & Bidell, 1998), and conceptual development and conservation behavior (e.g., van der Maas & Molenaar, 1992). A survey of these different approaches is beyond the scope of this article (see Spencer, Thomas, & McClelland, 2009). We focus, instead, on one particular flavor of cognitive dynamics—dynamic field theory (DFT)—that emerged out of the motor approach that Thelen and colleagues pioneered (for discussion, see Spencer & Schöner, 2003).

The starting point for the DF approach was to consider several facts about neural systems. Neural systems are noisy, densely interconnected, and time dependent; they pass continuous, graded, and metric information to one another; and they are continuously coupled via both short- and long-range connections (Braitenberg & Schüz, 1991; Constantinidis & Steinmetz, 1996; Edelman, 1987; Rao, Rainer, & Miller, 1997). These neural facts raise deep theoretical challenges. How can a collection of neurons "represent" information amidst near-constant bombardment by other neural signals (Skarda & Freeman, 1987), and how do neurons, in concert with the body, generate stable, reliable behavior? To address these challenges, the DF framework emphasizes stable patterns of neural interaction at the level of population dynamics (see also Spivey, 2007). That is, rather than building networks that start from a set of spiking neurons, we have chosen to focus on the emergent product of the dynamics at the neural level—attractors at the level of the neural population.

The first steps toward a neurally grounded theory of cognitive development came from Thelen and Smith's studies of the Piagetian A-not-B error (see Smith et al., 1999; Thelen, Schöner, Scheier, & Smith, 2001). This early work formalized a DFT of infant perseverative reaching, arguably the most comprehensive theory of infants' performance in the Piagetian A-not-B task (Clearfield, Dineva, Smith, Diedrich, & Thelen, 2009; Smith et al., 1999; Spencer, Dineva, & Smith, 2009; Thelen et al., 2001). DFT has generated a host of novel behavioral predictions, and it explains how perseverative reaching arises as a function of (a) the infants' history of prior reaches to A (Smith et al., 1999), (b) a bodily feel and visual perspective of reaching to A (Smith et al., 1999), (c) the distinctiveness of the targets and perceptual cues in the task space (Clearfield et al, 2009), (d) the delay between the cueing and reaching events (Diamond, 1985), (e) the number of targets in the task space, (f) the characteristics of the hidden object (and whether there is any hidden object whatsoever; see Smith et al., 1999), and (g) changes in infants' reaching skill and working memory abilities over development (Clearfield, Diedrich, Smith, & Thelen, 2006; for related studies with older children, see Schutte, Spencer, & Schöner, 2003; Spencer, Smith, & Thelen, 2001).

More recently, we have extended the DF approach to a host of other topics in cognitive development. These topics include the processes that underlie habituation in infancy (Perone & Spencer, 2009; Schöner & Thelen, 2006), the control of autonomous robots and the development of exploratory motor behavior (Dineva, Faubel, Sandamirskaya, Spencer, & Schöner, 2008; Steinhage & Schöner, 1998), the development of visuospatial cognition (Simmering, Spencer, & Schutte, 2008), the processes that underlie visual working memory and the development of change detection abilities (Simmering, 2008), the processes that underlie early word learning behaviors (Samuelson et al., 2008), and the development of executive function (Buss & Spencer, 2008). This broad coverage of multiple aspects of development with the same theoretical framework underlies our optimism that the concepts of DST can have a revolutionary impact on cognitive development just as they had in motor development. Time will tell.

WHAT ARE THE CHALLENGES AND NECESSARY DIRECTIONS FOR THE NEXT 20 YEARS?

A major accomplishment of DS approaches has been to move beyond the conceptual level to establish a tight link between formal theory and empirical research, leading to a greater understanding of the processes that underlie developmental change. Although there have been many successful applications of DS concepts, significant challenges remain. For instance, soft assembly makes it difficult to define the components of the "system" or subsystem under study. Similarly, the multiply determined nature of dynamic systems makes it difficult to identify "cause" because different factors can lead to different outcomes depending on the context and history of the individual.

In addition to these conceptual challenges, researchers in the next 20 years will have to build theories that formally connect processes across multiple levels of analysis. Figure 1 shows the nested, interacting systems that contribute to the organization of behavioral development from genetic to social levels. Each of these levels and the interactions among them are highly complex; thus, understanding how development happens as these levels interact over time will require formal theories that specify the nature of those interactions (for related ideas, see Gottlieb, 1991; Johnston & Edwards, 2002; Johnston & Lickliter, 2009).

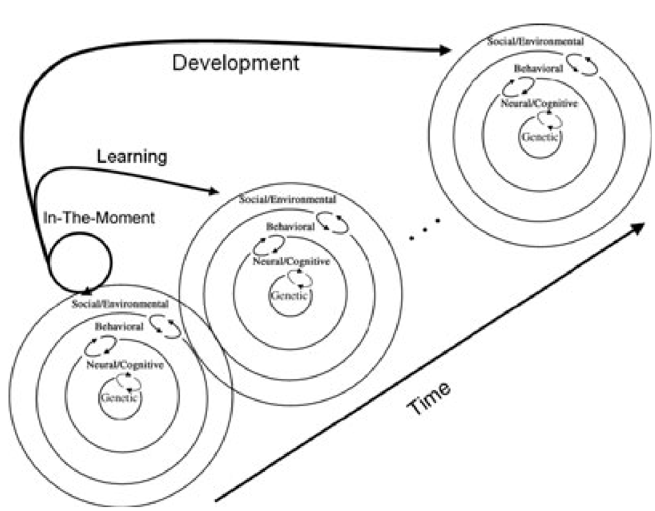

Figure 1. **A central challenge on the horizon for dynamic systems theory is to formally integrate across reciprocally interacting levels from genetic to social and to integrate these levels across multiple time scales from in-the-moment interactions to learning to development.**

To date, multiple approaches have attempted to understand behavioral development at the different levels shown in Figure 1, but these efforts have not been tightly integrated across levels.

In addition to the challenge of formally connecting processes at multiple levels, it will be important to tackle a second challenge: integrating time scales. Within DST, nested, interacting systems come together to create developmental change as those systems interact through time. In particular, the multiple systems in Figure 1 produce a coherent behavioral system in the moment, and those in-the-moment behaviors have consequences that carry forward across the longer time scales of learning and development (see Smith & Thelen, 2003, for a discussion). Our research using DFT has effectively integrated real-time behavior with changes over learning (see, e.g., Lipinski, Spencer, & Samuelson, 2010; Schöner & Thelen, 2006; Thelen et al., 2001). Other approaches have examined these time scales as well (e.g., French, Mareschal, Mermillod, & Quinn, 2004; McMurray, Horst, Toscano, & Samuelson, 2009), but the longer time scales of development have been more elusive (but, see Simmering et al., 2008; Schutte et al., 2003; Schutte & Spencer, 2009, for efforts in this direction).

One difficulty in this regard is that it is often hard to get a clear sense of developmental change empirically. Adolph, Robinson, Young, and Gill-Alvarez (2008), for example, showed how different views of developmental change are created simply by changing the sampling rate of observations. Developmental scientists also face deep theoretical challenges when trying to integrate behavior over very long time scales. Spencer and Perone (2008) have taken one step toward addressing this issue by probing changes in artificial neural dynamic systems. In particular, they showed that the gradual accumulation of neural excitation in a simple, dynamic neural system created qualitative changes in the state in which the system operated. That is, as the system gradually accumulated a history, the system was biased to settle into new neural attractor states. We believe that it is possible to generalize from these concepts, and we are currently working to scale up this demonstration guided by a rich, longitudinal empirical data set (see Perone & Spencer, 2009).

Integrating dynamics across multiple systems and time scales is a daunting task. Even more challenging is to achieve this integration at the level of the individual child in context. But this is a critically important goal because it opens the door for examining atypical development. If we understand the complex dynamics through which systems interact over time at the level of individual children, we will be well positioned to create individual interventions that help steer the child toward positive developmental outcomes. That would indeed be revolutionary. Perhaps, in the next 20 years we will realize this vision.

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